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Assessment of the Extra Capacity Required of Alternative Energy Electrical Power Systems to Completely Replace Fossil Fuels

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Abstract

This report addresses the challenges around the ambitious task of phasing out fossil fuels (oil, gas, & coal) that are currently used in vehicle Internal Combustion Engine technology (ICE) and for electrical power generation. A novel bottom-up approach (as opposed to the typical top-down approach) was used to make the calculations presented here. Previous studies have also tended to focus on estimated costs of production and CO_2 footprint metrics, whereas the present report is based on the physical material requirements. All data, figures and diagrams have been created or reproduced from publicly available sources and are cited appropriately.

Taking first the case for replacing all fossil fuel-based vehicles with Electric Vehicle Technology (EVT), it was believed that in 2019, around 7.2 million EV's were in use. However, the global fleet of vehicles at the time was estimated to be 1.416 billion vehicles, suggesting that only 0.51% of the global fleet was currently electric, and that 99.49% of the global fleet is yet to be replaced. Turning next to the global energy system, data from 2018 estimates that 84.7% was dependent on fossil fuels, whereas renewables (solar, wind, geothermal and biofuels) accounted for only 4.05% of global energy generation, and nuclear power accounted for 10.1%. This reinforces the scale of the many challenges we face.

The global strategic decision adopted by most nations to phase out fossil fuels systems and replace them with renewable energy generation systems is largely driven by CO_2 emissions and associated climate change, and not by dwindling resources, although it is well known that oil, gas, and coal reserves are finite. The general plan can be summarized as follows: ICE vehicles are to be phased out and substituted with Electric Vehicles (EV) and Hydrogen Fuel cell powered (H_2-Cell) vehicles. EV's are to be powered with lithium ion batteries. Coal- and gas-fired electrical power generation is to be phased out and substituted with by solar photovoltaic, wind turbine, hydroelectric, nuclear, geothermal or biowaste to energy power stations.

Knowledge around known mineral resources suggests the raw materials required for the manufacture and servicing of these renewable technologies will remain truly global in nature. There will not be one nation or geographic region that can be truly self-sufficient. The focus of this report therefore was to model the viability of the new global ecosystem using calculations made specifically for the three significant global players: the United States (US) economy; the European (EU-28) economy; and the Chinese economy.

Where possible, all data reported here were sourced for the year 2018. Due to the quarantine restrictions from the Covid-19 pandemic, 2019 could be the last year of 'normal' operation for the global ecosystem. Calculated models predict future scenarios for the next several decades. This approach acknowledges the typical long start-up times from exploration through to discovery and starting mineral extraction, which can be anywhere between 10 – 30 years, and that for every 1,000 deposits discovered, only one or two typically actually become viable mines. It is also in keeping with similarly long manufacturing cycles from invention to commercialization.

Calculations reported here suggest that the total additional non-fossil fuel electrical power annual capacity to be added to the global grid will need to be around 37 670.6 TWh. If the same non-fossil fuel energy mix as that reported in 2018 is assumed, then this translates into an extra 221 594 new power plants will be needed to be constructed and commissioned.

To put this in context, the total power plant fleet in 2018 (all types including fossil fuel plants) was only 46 423 stations. This large number reflects the lower Energy Returned on Energy Invested (ERoEI) ratio of renewable power compared to current fossil fuels.

The number of individual solar panel array farms, wind turbine farms, nuclear power plants, hydroelectric plants and biowaste to energy plants to deliver this additional power requirement was also calculated. The existing non-fossil fuel electrical power generation system (9 528.7 TWh) would have to expand by additional capacity, 4 times the existing scope. Each of the modelled non-fossil fuel systems have practical limitations to expansion, for example it was proposed to develop 16 504 new hydroelectric plants of average size but of course hydroelectricity can only be sited in very specific geographic conditions, and there may not by sufficient new sites globally that would be viable.

The first part of the report examines how every developed economy around the World is highly dependent on fossil fuels, which in turn is linked to industrial activity, economic GDP, food production (the price and quantity of oil, and oil derived products like petroleum in particular).

The second part of the report quantifies how fossil fuels are used and in what quantities they are consumed. The calculations were made based around the footprint one full year of operation for the entire industrial ecosystem, including fossil fuel consumption (oil, gas, & coal), heating, steel manufacture, electricity generation, number of vehicles in each class, and the distance they travelled.

The third part of the report documents the scale and system size of non-fossil fuel alternatives by examining 6 distinct scenarios, A – F. Scenario A examines the logistics and footprint to phase out petroleum fueled ICE vehicles and replace them with EV's. Scenario B builds upon Scenario A, where all other fossil fuel applications (gas heating of buildings, coal fired steel manufacture and fossil fuel power electricity generation) were substituted for non-fossil fuel systems. Scenario C examines the viability of a hydrogen-based economy. Scenario D looks at the viability of biofuels, which have often been referred to as the only truly renewable power source. Scenario E seeks to establish if the Nuclear Power Plant (NPP) fleet could be expanded fast enough to an electrical power generation capacity to deliver the needed electricity to power the non-fossil fuel systems substituting fossil fuel systems. Finally, Scenario F is a hybrid solution based on what was learned from Scenarios A to E.

In summary, it was found that each non-fossil fuel system has clear advantages and disadvantages when compared to all other systems. Recommendations are made for when a battery-powered EV should be used and when a H2-Cell vehicle is the better alternative technology and takes into account the required electrical power to charge the EV batteries and produce the hydrogen. Biofuels are recommended to fuel a small proportion of the aviation industry and biomass is recommended to produce bioplastics, replacing a proportion of the existing plastics industry. Nuclear power can be expanded moderately from the current capacity to support some industrial operations and heating buildings through winter, especially in the Northern Hemisphere.

Once the size and scope of the footprint of a non-fossil fuel energy and transport system was developed, it was compared to existing strategic studies that also examined future targets to phase out fossil fuels. It was found that previous work has significantly underestimated the number of vehicles to be replaced and supported, and this impacts the projected numbers for EV's, batteries and H_2-Cell vehicles to be manufactured, which in turn produces a lower estimate of the size of the required electrical power grid. Hence, the number of required new power stations estimated in this study is much larger than in any previous report. Also, current policy targets (for example European Parliament) hope to have 30% of the global energy and transport system to be renewable by the year 2030. This is only 8.5 years away, and the incubation time for the construction of a new power plant can range between 2 to 5 years (or 20 years for a nuclear plant).

The mass of lithium ion batteries required to power the 1.39 billion EV's proposed in Scenario F would be 282.6 million tonnes. Preliminary calculations show that global reserves, let alone global production, may not be enough to resource the quantity of batteries required. In theory, there are enough global reserves of nickel and lithium if they were exclusively used just to produce li-Ion batteries for vehicles. To make just one battery for each vehicle in the global transport fleet (excluding Class 8 HCV trucks), it would require 48.2% of 2018 global nickel reserves, and 43.8% of global lithium reserves. There is also not enough cobalt in current reserves to meet this demand and more will need to be discovered. Each of the 1.39 billion lithium ion batteries could only have a useful working life of 8 to 10 years. So, 8-10 years after manufacture, new replacement batteries will be required, from either a mined mineral source, or a recycled metal source. This is unlikely to be practical, which suggests the whole EV battery solution may need to be re-thought and a new solution is developed that is not so mineral intensive.

Electrical power generated from solar and wind sources are highly intermittent in supply volumes, both across a 24-hour cycle and in a seasonal context. A power storage buffer is required if these power generation systems are to be used on a large scale. How large this power buffer needs to be is subject to discussion. A conservative estimate selected for this report was a 4-week power capacity buffer for solar and wind only to manage the winter season in the Northern Hemisphere. From Scenario F, the power storage buffer capacity for the global electrical power system would be 573.4 TWh.

In 2018, pumped storage attached to a hydroelectric power generation system accounted for 98% of existing power storge capacity. If this power buffer was delivered with the use of lithium ion battery banks, the mass of lithium ion batteries would be 2.5 billion tonnes. This far exceeds global reserves and is not practical. However, it is not clear how this power buffered could be delivered with an alternative system. If no alternative system is developed, the wind and solar power generation may not be able to be scaled up to the proposed global scope.

Current expectations are that global industrial businesses will replace a complex industrial energy ecosystem that took more than a century to build. The current system was built with the support of the highest calorifically dense source of energy the world has ever known (oil), in cheap abundant quantities, with easily available credit, and seemingly unlimited mineral resources. The replacement needs to be done at a time when there is comparatively very expensive energy, a fragile finance system saturated in debt, not enough minerals, and an unprecedented world population, embedded in a deteriorating natural environment. Most challenging of all, this has to be done within a few decades. It is the author's opinion, based on the new calculations presented here, that this will likely not go fully to as planned.

In conclusion, this report suggests that replacing the existing fossil fuel powered system (oil, gas, and coal), using renewable technologies, such as solar panels or wind turbines, will not be possible for the entire global human population. There is simply just not enough time, nor resources to do this by the current target set by the World's most influential nations. What may be required, therefore, is a significant reduction of societal demand for all resources, of all kinds. This implies a very different social contract and a radically different system of governance to what is in place today. Inevitably, this leads to the conclusion that the existing renewable energy sectors and the EV technology systems are merely steppingstones to something else, rather than the final solution. It is recommended that some thought be given to this and what that something else might be.

Keywords Energy, ERoEI, fossil fuel, oil, gas, coal, nuclear, solar photovoltaic, solar thermal, wind, hydroelectric, Plastics manufacture, petrochemical fertilizer, land degradation, transport, vehicle fleet, kilometers driven, Electric Vehicle, hydrogen fuel cell, nuclear power, biofuel, grid capacity, consumption, power generation, ICE, rail, shipping, aviation, global, United States, Europe, China			
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1 INTRODUCTION

This report examines the viability of replacing fossil fuel energy systems with alternative sustainable energy systems. In context of the global scale and European scale industrial ecosystem, the three basic concepts this report seeks to examine are:

- How dependent on fossil fuels is the current industrial system?
- How are these fossil fuels used and in what applications?
- If fossil fuels were to be phased them out immediately, what would be required from alternative energy generation systems to replace lost capacity?

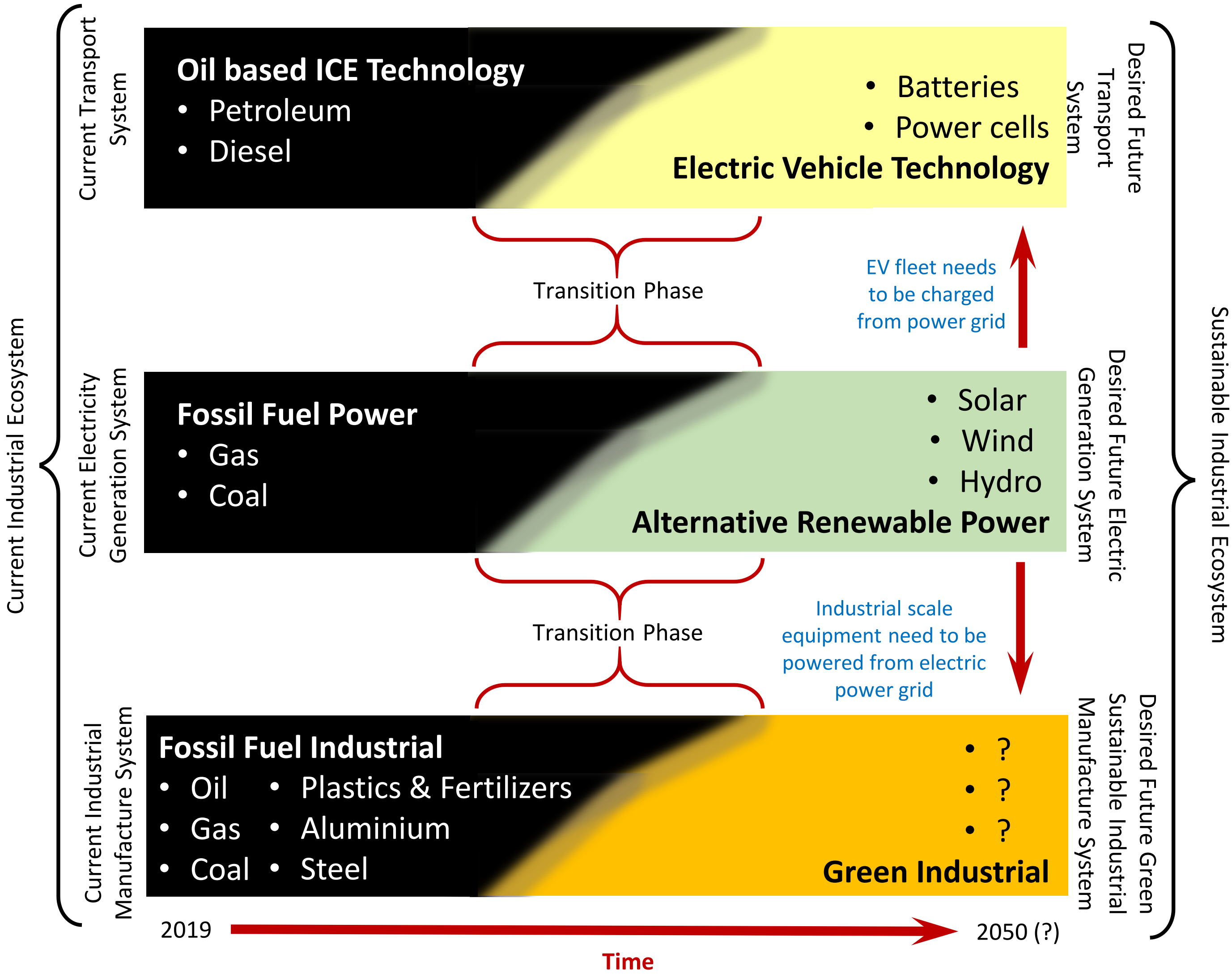

Figure 1.1. Transition from a fossil fuel based industrial system to a renewable power industrial system

There are a number of issues and concerns associated with the continued use of fossil fuels (oil, gas and coal). The use of fossil fuels has been linked to the production of CO^2 gases and carbon pollution, as a driving force behind climate change. Also, fossil fuel energy sources are finite natural resources. A school of thought is that all fossil fuels will deplete over time and reach peak production, thus become unreliable as a stable source of economically viable energy.

1.1 Energy is the master resource

Energy is the master resource. It allows and facilitates all physical work done, the development of technology and allows human population to live in such high density settlements like modern cities. Energy consumption correlates directly with the real economy (Bradley and Fulmer 2008). The real economy, which is the part of the economy that is concerned with actually producing goods and services, as opposed to the part of the economy that is concerned with buying and selling on the financial markets.

Future projections of global energy demand are usually developed on past behavior, with no understanding of finite limits or depleting resources. Generally, reserves have been projected on by past production and demand has been defined by population growth and economic GDP.

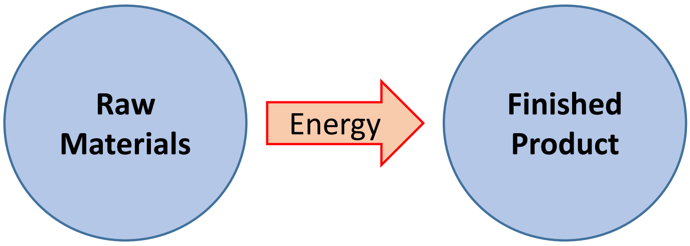

Figure 1.2. Relationship between raw materials and finished manufactured goods

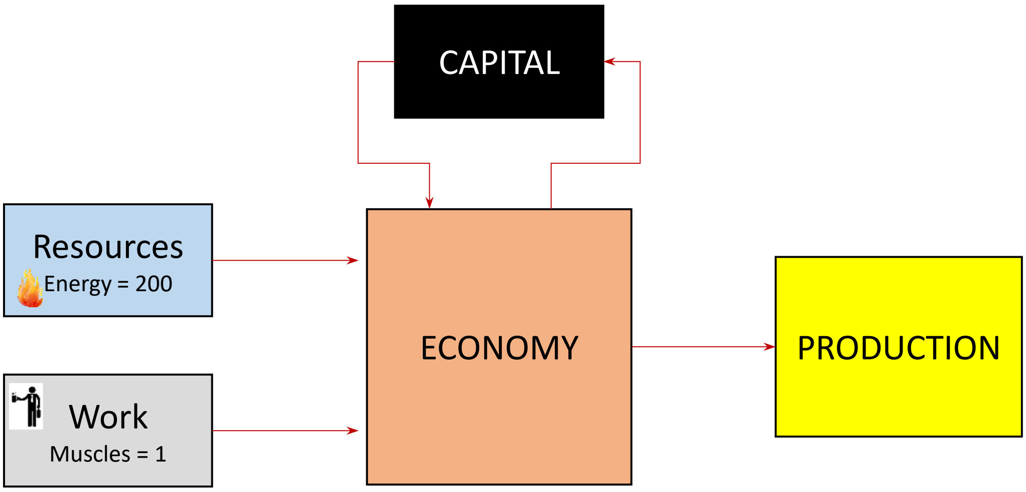

Figure 1.3. A simplified flow physical flows that sustain our productive system
(Source: Jancovici 2011)

The modern world is heavily interdependent. Many of the structures and institutions we now depend upon function in a global context. Energy as a fundamental resource underpins the global industrial system (Fizaine & Court 2016, Meadow et al. 1972, Hall et al. 2009, Heinberg 2011, Martenson 2011, Morse 2001, Ruppert 2004 and Tverberg 2014).

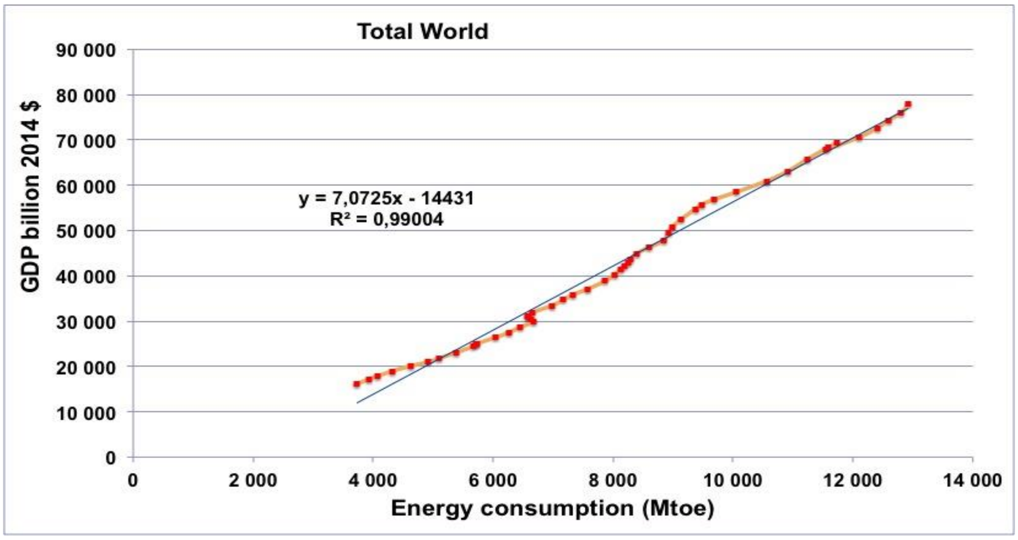

Figure 1.4. World GDP in constant dollars (vertical axis) plotted against the world energy consumption in million tonnes oil equivalent (horizontal axis), from 1965 to 2014.
(Source: BP Statistical Review, 2015, and World Bank 2015 (GDP), Jancovici 2011)

The economic progress of past decades has seen hundreds of millions of people enjoy major improvements in their material well-being (particularly noteworthy in the emerging economies, Brazil, Russia, India, and China). It is understood how economic globalization and market liberalization have underpinned these developments, but there is a crucial enabling role played by the energy sector (Tverberg 2014). This could be due to the falling cost of energy, particularly since the introduction of oil as an energy source and Internal Combustion Engine (ICE) technology. This has resulted in the widespread perception that energy is so abundant, that it does not really need to be considered (much like we now view oxygen in the air we breathe).

Without heat, light and power, society cannot build or run the factories and cities that provide goods, jobs, and homes, nor enjoy the amenities that make life more comfortable and enjoyable (Smil 2018). Energy is the “oxygen” of the economy and the life-blood of growth, particularly in the mass industrialization phase that all emerging economic giants are required to go through.

Beyond its direct contributions to the economy, energy is also deeply linked to other sectors in ways that are not immediately obvious. For example, each calorie of food we consume requires an average input of 10 calories of fossil fuel, and for high-end products like beef this rises to an average of 80 calories (Green 1978, Canning et al. 2017). This is driven by how we grow, then distribute food, between the farm and the domestic consumer kitchen table. The energy sector is also the biggest industrial user of fresh water, accounting for 40% of all freshwater withdrawals in the United States (EIA 2018). The energy industry significantly influences the vibrancy and sustainability of the entire economy – from job creation to resource efficiency and the environment. As a society becomes more developed, the higher the energy use per capita and complexity (Figures 1.5 to 1.8).

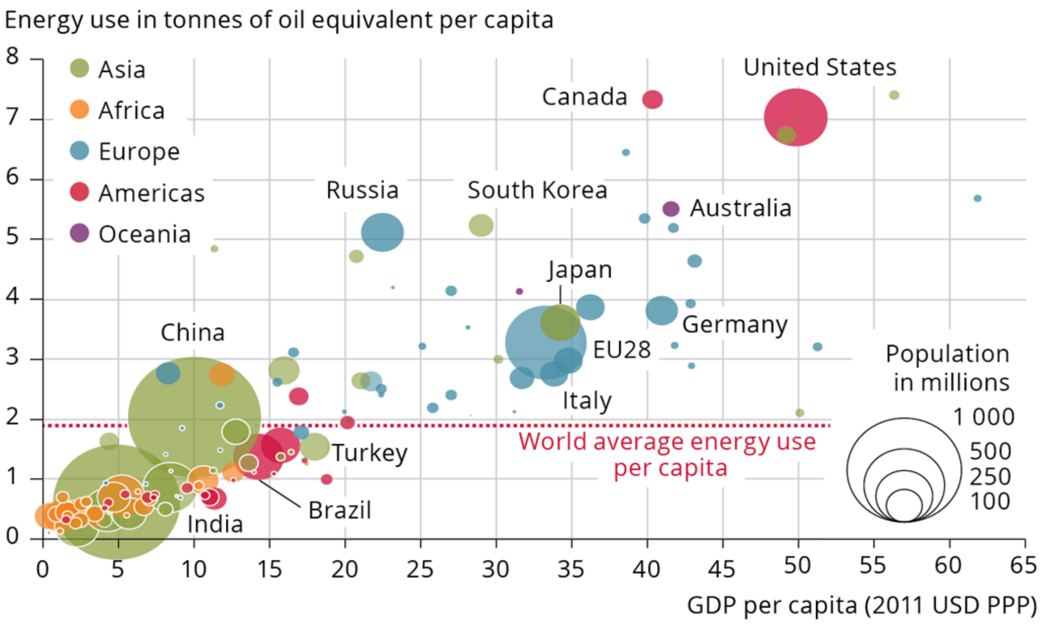

Figure 1.5. Per capita energy consumption (kg oil equivalent) vs. per capita GDP, PPP (2016 $USD). The size of the bubbles denotes total population per country. All values refer to the year 2011.
(Source: European Environment Agency)
(Copyright license: https://www.eea.europa.eu/legal/copyright)

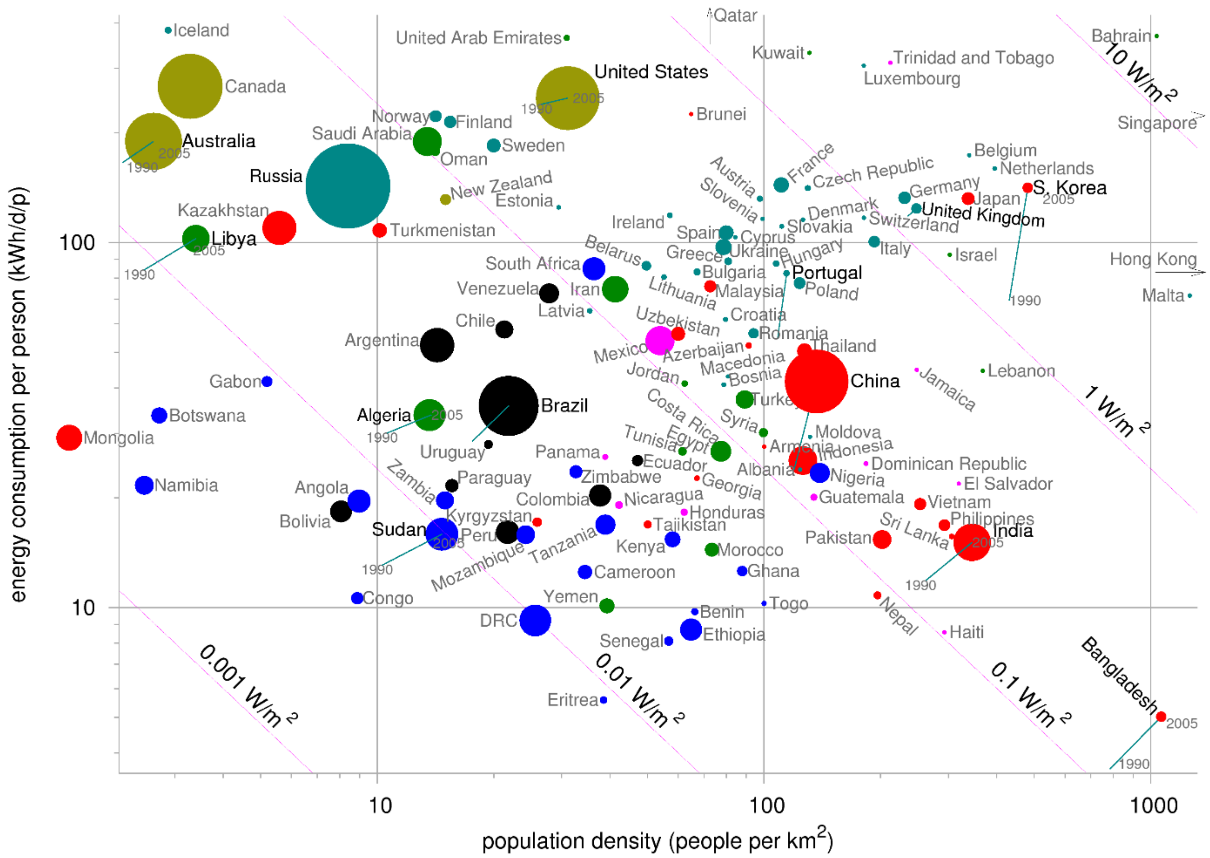

Figure 1.6. Nation power consumptions, population densities, and areas; and comparing power consumptions per unit area with the power production per unit area of various renewables (Source: Mackay 2013)
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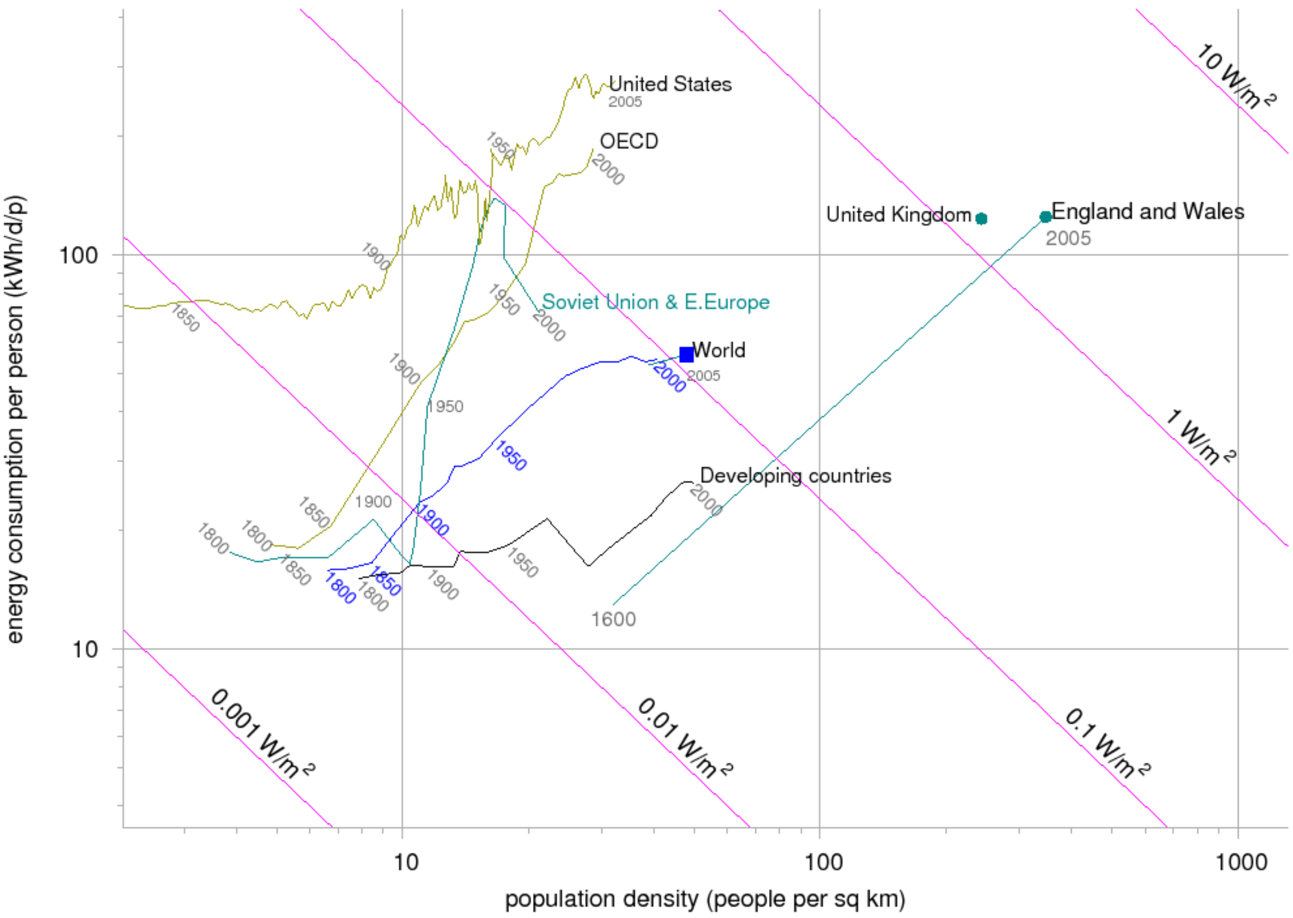


Figure 1.7. Power consumption per person versus population density, from 1600 or 1800 to 2005. OECD = Organization for Economic Cooperation and Development. (Source: Mackay 2013) (Data sources: Grubler, Arnulf (2008), "Energy transitions." In: Encyclopedia of Earth. Eds. Cutler J. Cleveland. Washington, D.C.: Environmental Information Coalition, National Council for Science and the Environment, and E. A. Wrigley (2010), Energy and the English Industrial Revolution, Cambridge University Press.)

Societies before the Industrial Revolution were dependent on the annual cycle of plant photosynthesis for both heat and mechanical energy (in addition to windmills, water wheels, etc.). The era before the first industrial revolution (IR1) was dependent largely on human labor and beasts of burden (horses, oxen etc.) in addition to the use of biomass as a fuel to develop society. The quantity of energy available each year was therefore limited, and economic growth was necessarily constrained. In the Industrial Revolution, energy usage increased massively, and output rose accordingly. The energy source continued to be plant photosynthesis but accumulated over a geological age in the form of coal, and later oil. This poses a problem for the future. Fossil fuels are a depleting stock, whereas in pre-industrial time the energy source, though limited, was renewed each year.

Major changes in the material culture of societies, and in particular in their ability to sustain larger populations, have been closely associated with changes in the scale and type of energy available to meet human needs for nutrition and to perform work (Smil 2018).

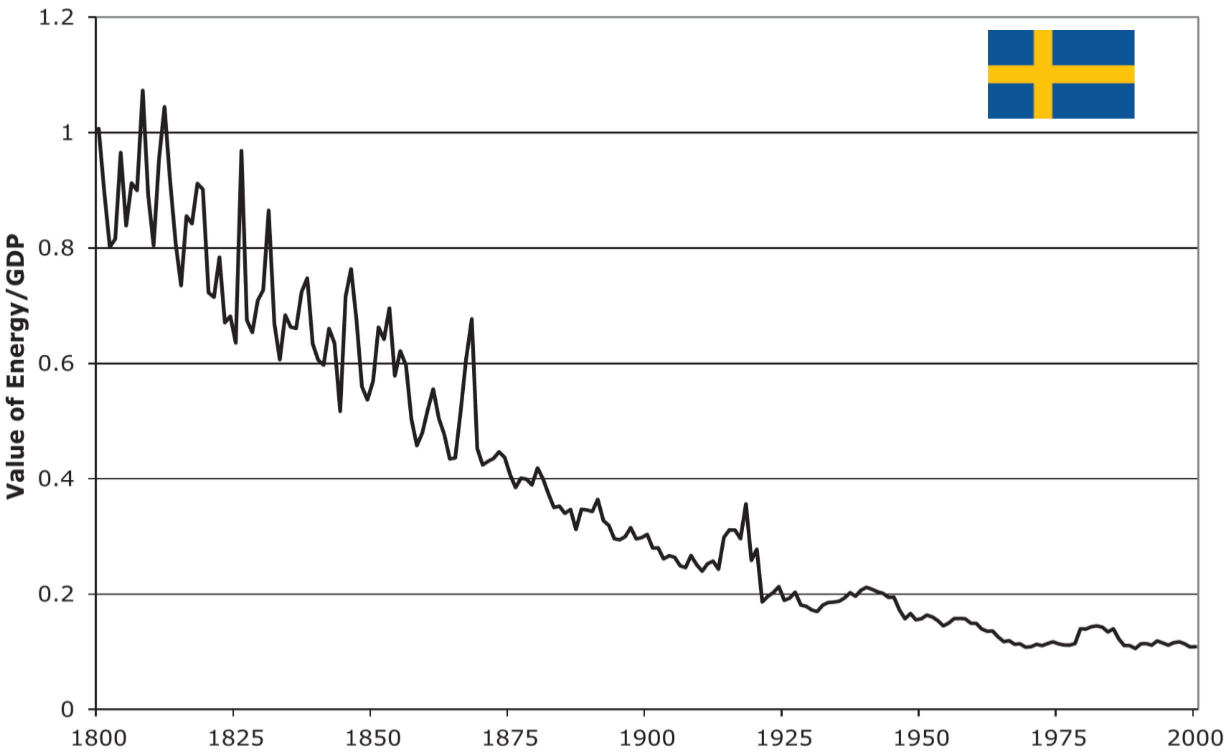


Figure 1.8. Sweden 1800-2000, value of Energy/GDP (Source: Stern & Kander 2012)

The expansion in the supply of energy services over the previous couple of centuries has reduced the apparent importance of energy in economic growth despite energy being an essential production input.

The current industrial system is heavily interconnected (Tverberg 2014, Martenson 2011, Ruppert 2004, Tainter 1988). Systems thinking can be used to understand it and successfully model its evolution.

Figure 1.9 shows a very simplistic model. Each of the sectors like raw material extraction or manufacture perform an important task. At the center of the whole system are three fundamental core sub-systems:

- Easily available financial credit
- Cheap and abundant energy of historically high calorific quality
- Complex information and data transfer systems that can connect all areas of the planet

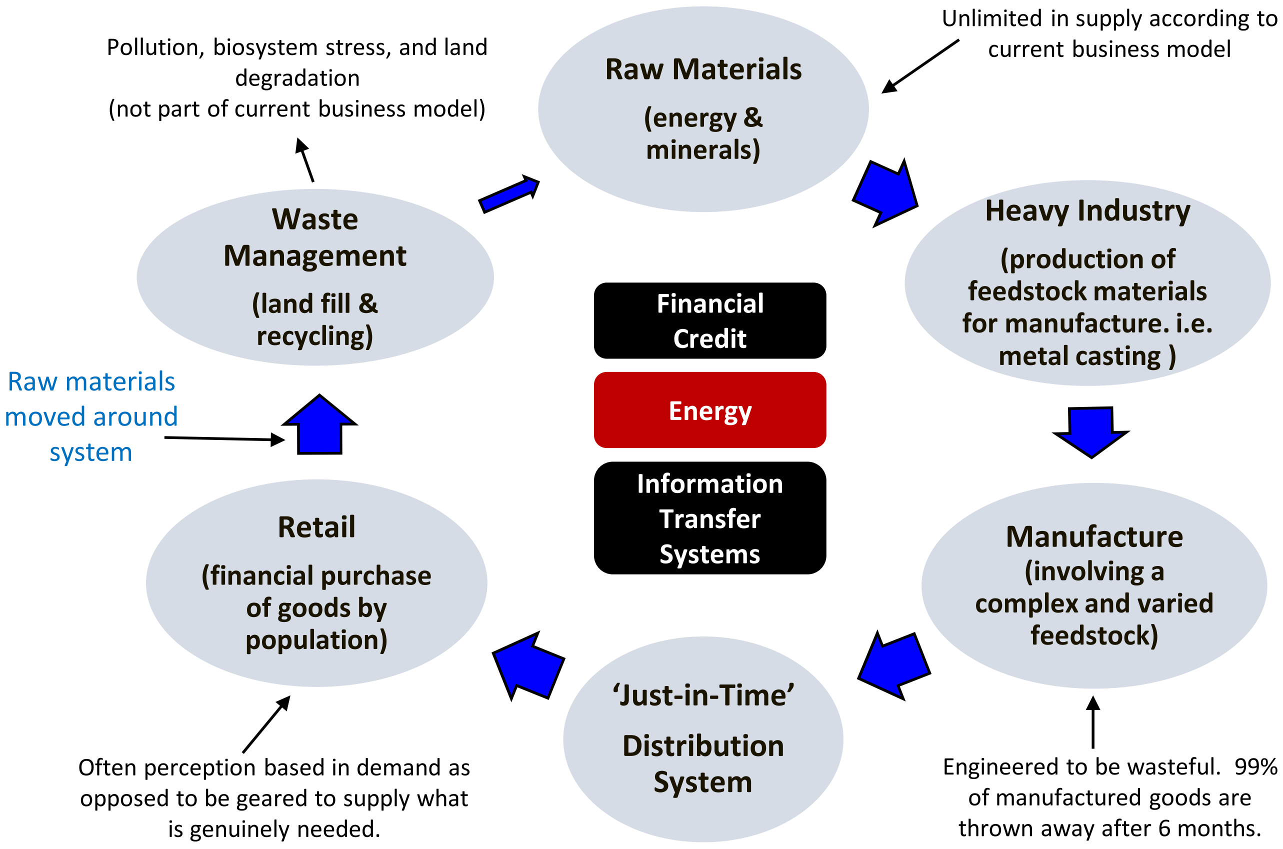
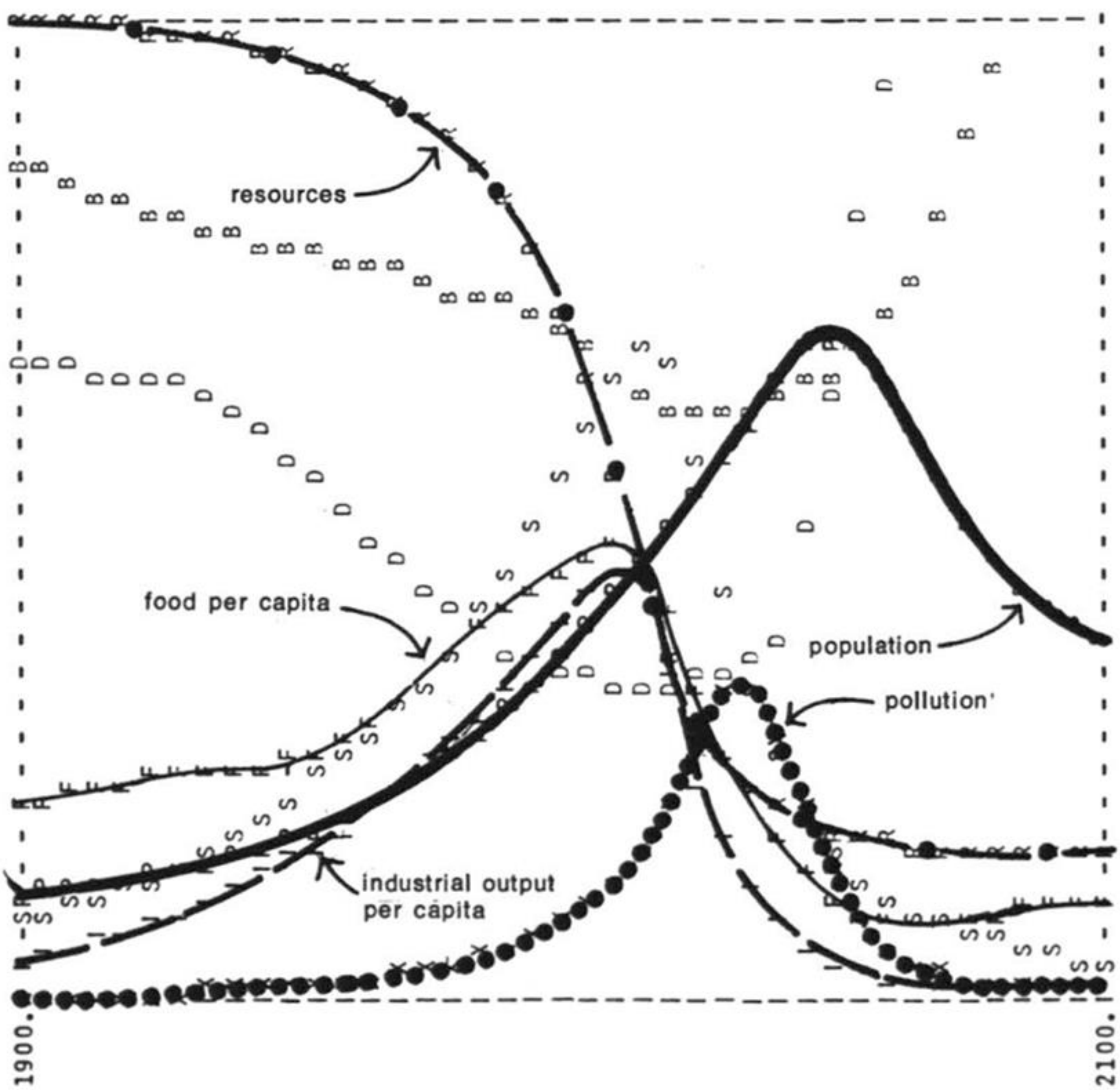


Figure 1.9. The macro scale structure of the current global industrial system
(Image: Simon Michaux)

The structure shown in Figure 1.9 is what the current industrial ecosystem has evolved into from what it was at the beginning of the industrial revolution IR1 (with its different energy and finance systems and very different information systems). What is most interesting is that in the current form, all three core systems are nearly interchangeable (Johnson 1995).

Figure 1.9 is not the first systems attempt to model the global industrial ecosystem. In 1968 the Club of Rome was formed to study the direction human society was developing. One of the technical outcomes was a sophisticated system dynamic based analysis of human society and its supporting resources, published as 'The Limits to Growth' (Meadows *et al.* 1972). During the course of this study, 13 scenarios were considered, where strategic changes in human society were made. The base case scenario is shown in Figure 1.10. This study highlighted the global systems dependence on non-renewable finite natural resources. Without a steady supply of those resources, the system crashed.



The "standard" world model run assumes no major change in the physical, economic, or social relationships that have historically governed the development of the world system. All variables plotted here follow historical values from 1900 to 1970. Food, industrial output, and population grow exponentially until the rapidly diminishing resource base forces a slowdown in industrial growth. Because of natural delays in the system, both population and pollution continue to increase for some time after the peak of industrialization. Population growth is finally halted by a rise in the death rate due to decreased food and medical services.

Figure 1.10. The base case projected outcome of 1972 systems analysis modelling of global industrial society (Source: Meadows *et al.* 1972)

The objective was to stabilize all inputs and outputs to human society. The base case scenario where the existing direction of human society development in the early 1970's was maintained with no change, then projected forward in time to the year 2100.

This remarkable study was one of the first of its kind in that it was conducted on one of the first computers available to civilians. Using a well thought out network of systems in an elegant experimental simulation design, the rates of consumption, population growth and associated pollution were each predicted. While this study was done in the early 1970's, an update that compare historical data mapped against the model predictions, show that the base case scenario model was conceptually correct (Turner 2008).

Figures 1.11 to 1.13 shows some actual historical data from 1970 to 2000 projected onto the original 1970 study. The implications of Figures 1.10 to 1.13 are that the basic prediction of the original limits to Growth systems study was conceptually correct. Just so, it should be considered that the industrial ecosystem and the society it supports may soon contract in size.

The underpinning paradigm of this study was to look at the resource limitations in context of growing human population. Figure 1.11 shows the 1972 study human population growth scenarios (with a model future prediction between 1970 and the year 2000), overlaid with historical data from 1970 to the year 2000 as measured (Turner 2008). The historical data shows that human population is following the Standard Run model from the 1972 Limits to Growth study. This is most pertinent as human population is one of the fundamental underpinning parameters in mapping resource consumption.

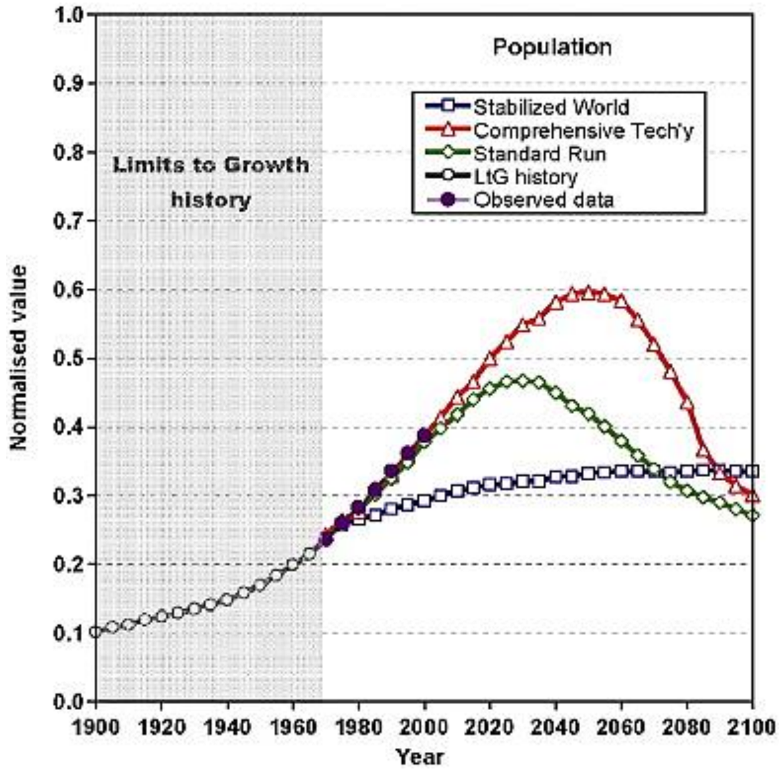


Figure 1.11. Comparing 'Limits to Growth' scenarios to observed global data – human population (Source: Turner 2008)

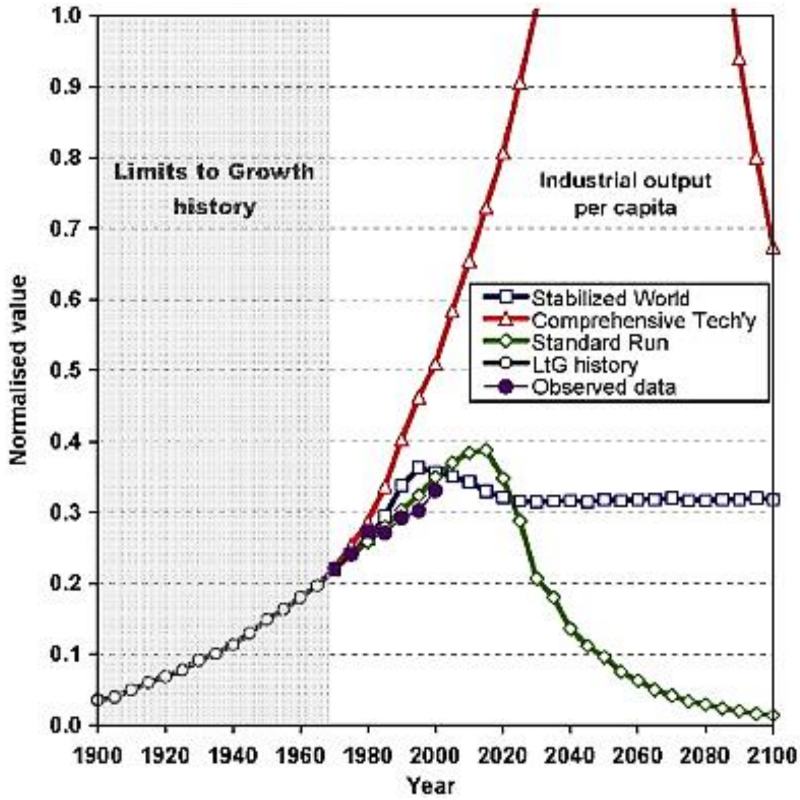


Figure 1.12. Comparing 'Limits to Growth' scenarios to observed global data – industrial output (Source: Turner 2008)

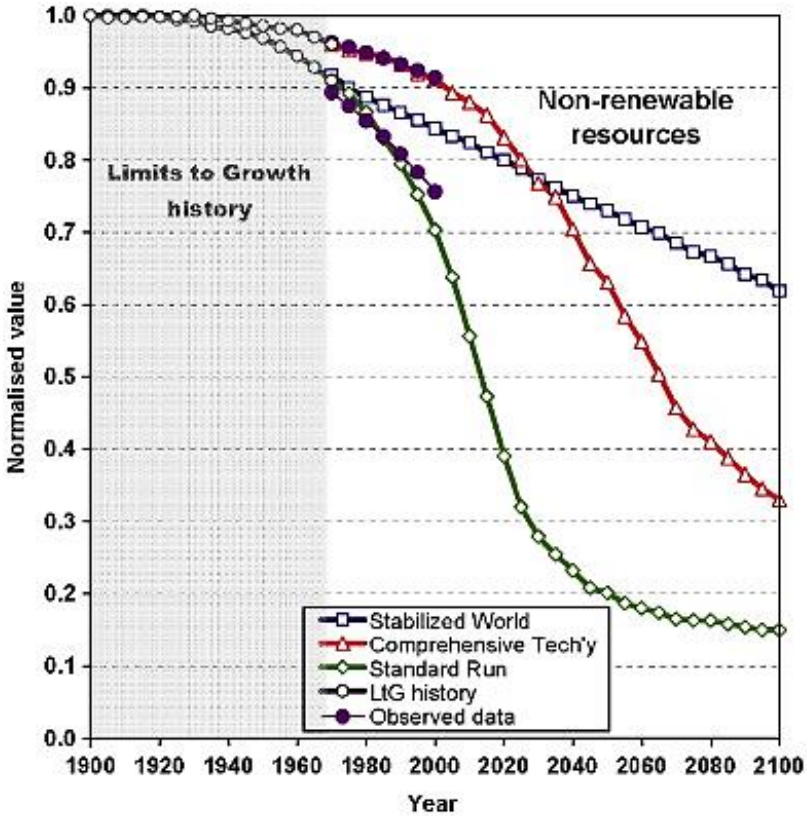


Figure 1.13. Comparing 'Limits to Growth' scenarios to observed global data – Non-renewable resources (Source: Turner 2008)

Figures 1.11-1.13 shows the 1972 study industrial output per capita scenarios (with a model future prediction between 1970 and the year 2000), overlaid with historical data from 1970 to the year 2000 as measured (Turner 2008). The historical data shows that industrial output per capita is following the Standard Run model from the 1972 Limits to Growth study.

All of this implies that the global industrial ecosystem is going through the Limits to Growth standard run. This means that industrial production per capita is about to peak and decline, and non-renewable resources will continue to deplete. This has very serious implications to the global population. It also very clearly shows that the industrial ecosystem is about to transform into something else entirely.

In the current industrial ecosystem, the underlying metric for operational success is growth. Current economic ecosystems are geared to a growth of 2% per annum. Growth in all its forms is a metric of the current system (The Linear Economy). Just so, the consumption of natural resources has steadily increased. Figure 1.14 shows how resource consumption has increase on a global scale between the year 2000 and the year 2018.

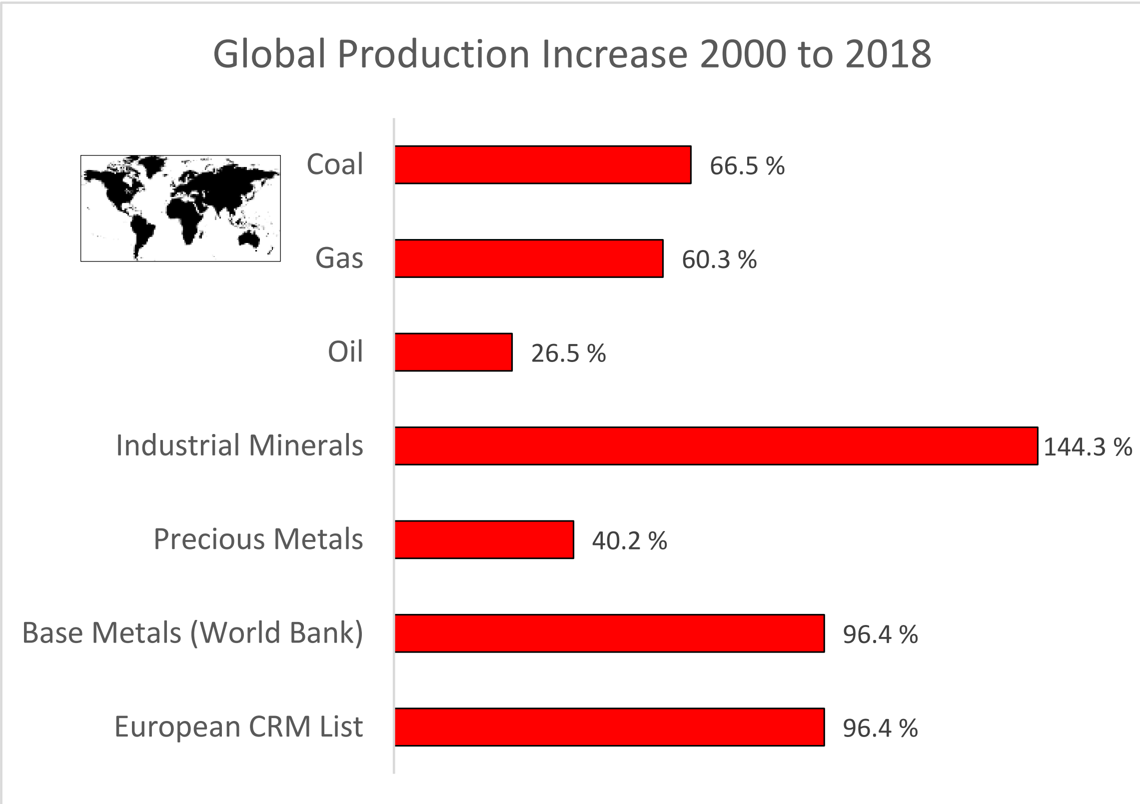


Figure 1.14. Global annual consumption of mineral resources between the year 2000 and 2018
(Source: USGS data, World Bank data, BP Statistics 2011, BP Statistics 2019)
(World Map Image by Clker-Free-Vector-Images from Pixabay)

Since the acceptance of the petrodollar agreement in 1973, where all oil purchases are to be done in $US dollars (Emerson 1985) and the $US dollar decoupled from the gold standard in 1971 (Bytheway & Metzler 2016) and became a fiat currency, the world reserve currency and the most dominant energy resource have become heavily interdependent (Bytheway & Metzler 2016 and Rickards 2014). A fiat currency in 2019 is mostly stored in the form of numbers in a computer file, as in the currency itself is electronic (Rickards 2014). This means that modern money is really indistinguishable from information from a database. Zero's and ones recorded against a name and an address (although now a physical address is now often not needed, and a name is often an alias). From a physics perspective, information can be considered as energy stored (Johnson 1995). Johnson (1995) describes the outcome of a discussion between physicists at the Los Alamos National Laboratory about the nature of information in abstract terms. They developed the idea that stored information could be modelled as a form of battery storing energy. This abstract concept may not appear useful at first glance but consider what the global reserve currency (United States Dollar, $USD) has become since the decoupling of the gold standard in 1971.

In addition to this the complexity of the current technology system has become dependent on the rapid transfer of information. Since the development of the worldwide internet, this system has grown more complex at a geometric rate. It is now inconceivable for current technology to function without an information system. What is intriguing is the potential applications of the successful development of block chain technology.

The concept of crypto currencies show that the function of money and an information system can conceivably merge. It is worth noting that one of the criticisms of crypto currencies is the large quantities of electricity consumed to mathematically identify (or ‘mine’) new currency tokens (Vincent 2019). Thus money, information systems and energy once again can be considered as a merged concept. The social contract behind the modern fiat currency is not that different to the possible social contract behind a crypto currency.

Currently Europe (EU-28) is heavily dependent on the use of fossil fuels as an energy source. The current European Union, evolved from a previous union of nations, the ECSC. The European Coal and Steel Community (ECSC) was an organization of six European countries created after World War II to regulate their industrial production under a centralized authority (Europa Web portal, ECSC Treaty). It was formally established in 1951 by the Treaty of Paris, signed by Belgium, France, Italy, Luxembourg, the Netherlands, and West Germany. The ECSC was the first international organization to be based on the principles of supra-nationalism and started the process of formal integration which ultimately led to the European Union. In particular, oil, gas, and coal support most industrial and economic activities. Section 2 discusses what energy sources are used in Europe, in what application and in what quantities.

Energy is utilized by many sectors including residential, commercial, industrial, and transportation sectors. The industrial sector may be the most difficult to address as it requires large quantities of concentrated power that is sinusoidally clean and of consistent supply. Energy-supply reliability is expressed via long-term preservation of energy resource availability at a level comparable with the present level of electrical-energy supply from domestic energy resources, i.e. at least 75% of the present consumption. A great deal of work has been done to develop alternative systems of energy generation and delivery. Solar power generated from photovoltaic panels and also solar thermal systems involving using the focused heat of the sun to make steam. The used of moving water in hydro power generation. Wind turbines in linked arrays. Also, there is a school of thought that the future of power generation should be nuclear.

Use of fossil fuels like coal, gas, and oil to generate energy in its various forms, all results on carbon pollution. Use of nuclear power to generate electricity, has a very different carbon footprint, but has its own challenges to remain viable at a large scale of application. The most significant being the disposal of spent fuel rods, which are highly radioactive and require specialized storage requirements. Renewable power sources like wind and solar, while traditionally seen as producing no carbon pollution, require extensive mineral resources to manufacture the required infrastructure. Renewable sources like hydroelectricity have a very small materials footprint and produces very little carbon pollution (if at all) but can only be applied in specific and unusual geographic circumstances.

So each of these power generation systems were examined in the context of what the major economic blocks need (Europe, United States, China, then the global requirements), then in the context of the Energy Returned on Energy Invested (ERoEI) for each of the energy systems being considered for industrial power supply. This is the effective efficiency in the process of extracting and then generating the energy. ERoEI is only part of what needs to be understood. What is also needed the quantity of energy at the point of application.

Then it is appropriate to examine what would happen if oil, gas, and coal were phased out and other energy systems were to be applied to make up the short fall.

1.2 The objective of this report

This report has been developed around the simple premise of what is needed first, then compared to what is available second. Also, a basic assumption is that the sustainable revolution will have proven to be successful and that all vehicles are to become EV based technology, and that all fossil fuels are phased out entirely.

As GTK is a geological survey, the primary focus is minerals. The question was asked for what kinds of minerals and in what quantities will be required to supply the incoming Gigafactories of Europe (Figure 1.15). This question was expanded to include what minerals would be required to completely phase out fossil fuels and deploy a full system replacement with carbon free technology, powered with renewable energy systems. These mineral groups were to be the primary raw material source for technology metals.

This research question was founded on how long the mining cycle is. For every 1000 mineralized ore deposits discovered, only one or two become operating mines. Of those operating mines many of them become unviable and are not profitable, resulting in mine closure. From the time where a mineralized deposit is discovered, it can take 20 to 25 years to develop into a producing mine, assuming that the deposit is viable. What this shows is that mining is not that flexible in increasing production. It will take decades to expand with current methods of industrial/economic operation.

There is a requirement to know more precisely what will be required for future supply of minerals.

While there were multiple studies reporting on what would be required for the transition away from fossil fuels, the information provided was not in a form that allowed the direct quantification of minerals required in a long term context. What is required is an estimate for the number of Electric Vehicles, lithium ion batteries, hydrogen fuel cells, solar panels, wind turbines, nuclear fuel rod assemblies, graphite moderation rods, in 30 years, 50 years and 100 years into the future.

The current paradigm is examined in Section 2. The outcomes of the studies shown in Section 2 are forming the basis of much of the strategic development of the future industrial eco-system. Unfortunately, many of these studies have seriously underestimated the size and scope of the task at hand. The following has been significantly underestimated:

- The number of vehicles in the global transport fleet
- The number of lithium ion batteries to be manufactured
- Extra power production capacity that will be required in the future
- The capability for renewable power generations system to replace fossil fuel power generation systems
- The time required to develop, construct and commission a non-fossil fuel industrial ecosystem
- The current industrial and economic dependency on fossil fuels (oil, gas, and coal)
- Long term and medium term reliability of the fossil fuel industry

What is also clear that the current paradigm is to focus exclusively on lithium ion battery chemistry, to the exclusion of all other possible chemical systems that could be resourced with different minerals. There are many examples of alternative systems like vanadium or sodium chemistry battery systems being presented conceptually, but when it comes to the serious development of large scale applications, for the last 5-10 years, the focus has been Li-Ion batteries.

Preliminary and approximate calculations show that 2018 global mineral reserves will not be sufficient to supply enough metals to manufacture the planned non-fossil fuel industrial systems. This implication requires a more precise and in-depth examination of what will be required to make this transition from fossil fuels a reality.

This report summarizes the current paradigm of the global system first, then examines the major economic blocks separately. The consumption of fossil fuels, the number of vehicles, distance travelled and what that might mean if it all was replaced with an EV solution is considered at a global scale. Then as a subset the same calculations are done for the European Union, United States and China.

All nation states are either attempting or are considering strategic options to phase out fossil fuels at the same time (Munroe 2010 and BTC 2010). The industrial value chain for most metals and manufacture of vehicles, batteries, solar panels, and wind turbines is international in form. No one nation state has the capability to develop a replacement energy system on its own (with the possible exception of China). If phasing fossil fuels out is such an important task, but all nations cannot do it together, then conflict becomes inevitable. This is why scopes of calculation of Global, United States, Chinese and European Union have been chosen.

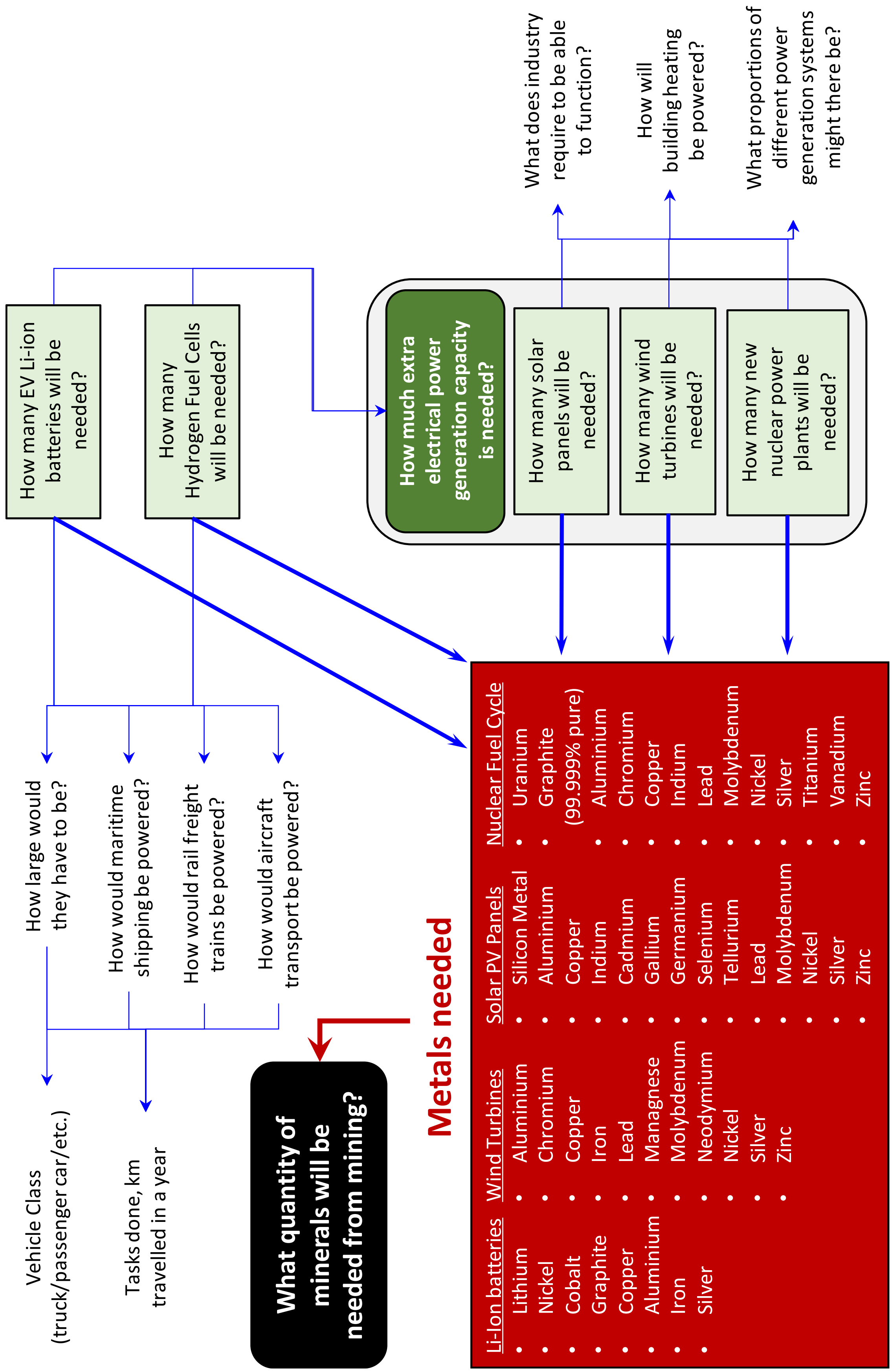


Figure 1.15. What quantity of minerals will be required to phase out fossil fuels and at what application? (Minerals list: Hund *et al* 2020) (Image: Simon Michaux)

The fossil fuel energy system is global in nature. All nations depend on it. The European Union for example does not produce its own petroleum and gas, it buys it from a global market. The sourcing of raw materials to make batteries, solar panels and wind turbines mainly comes from Chinese production facilities (either mined in China itself, mined in Chinese corporate investment controlled mines around the world, and then processed in China).

While most similar studies examine how quickly renewable energy systems can be implemented (and their efficiency), this report will examine what a full replacement of the existing system will involve. It is thought that there will be a ramp up phase of transition, but when all existing vehicles and power generation systems are replaced, the ecosystem will stabilize into a much slower growth rate (Figure 1.16). So, the approach is to estimate what is needed in terms of activity and actions done, for full system replacement, then work backwards to estimate the required extra power capacity.

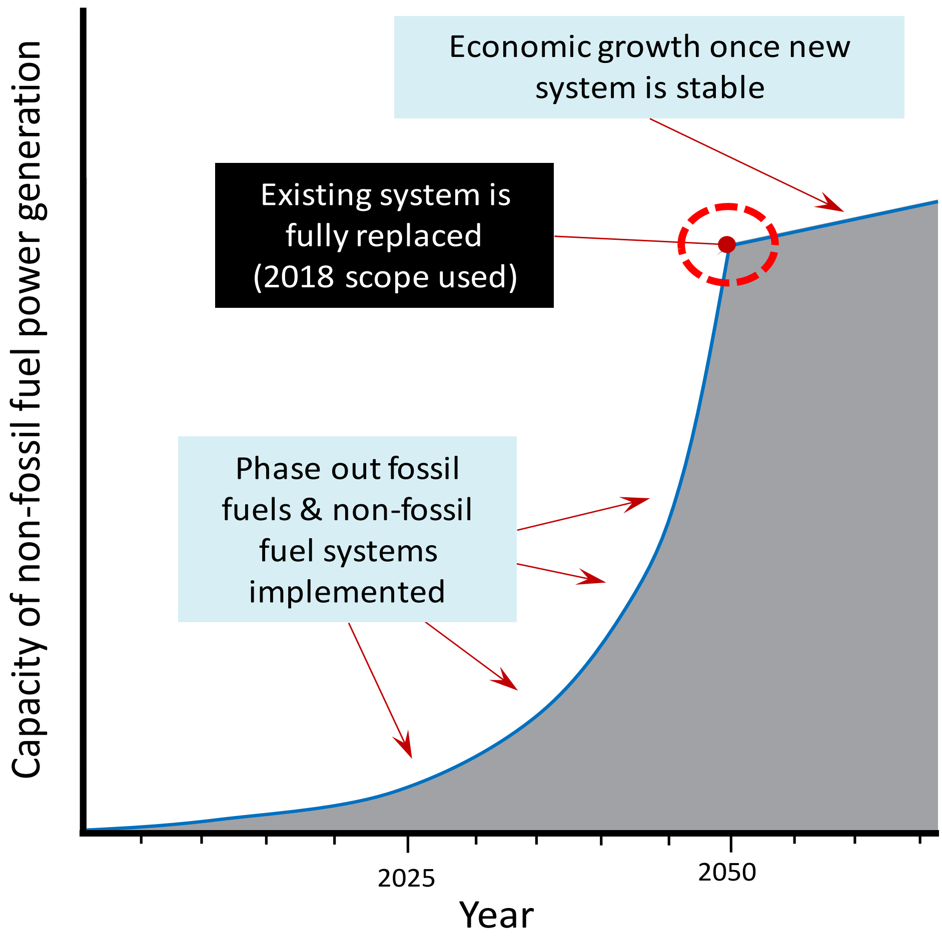


Figure 1.16. Full system replacement of the existing ICE vehicle fleet and fossil fuel power generation systems (Image: Simon Michaux)

The first half of this report will attempt to answer the following questions:

- How much of each of the fossil fuels is consumed at a global scale, EU scale, US scale and Chinese scale?
    - How is the existing industrial ecosystem dependent on them?
- What applications are those fossil fuels used for?
    - Quantify each application in context of its replacement.
- How many cars, trucks, ships, trains & aircraft are there, and what do they do?
- How many batteries will be needed?
- How many hydrogen cells will be needed?
- How much extra electrical power capacity is required to phase out fossil fuels completely?
- What are the alternatives to fossil fuel power generation?
    - What quantity of those alternatives is required to arrange a successful complete replacement of fossil fuels?
- How many new power stations will be needed and of what kind?
- Could biofuels contribute?
- How many solar panels will be needed?
- How many wind generator turbines will be needed?
- What quantity of minerals will be needed to do this?

In the second half of the report, six scenarios and the pertinent calculations will be presented (using a 2018 scope of operations):

- Scenario A – phase out ICE and substitute with EV (Section 18)
- Scenario B – phase out fossil fuels completely are replaced with non-fossil fuel power and EV's (Section 23)
- Scenario C – phase out ICE and substitute with hydrogen cells (Section 20)
- Scenario D – phase out petroleum as a fuel and substitute with biofuel (Section 22)
- Scenario E - phase out fossil fuel power generation and substitute with nuclear power (Section 25)
- Scenario F – A hybrid solution based on the learnings of A-E (Section 26)

Shown in Section 26, Scenario F is a data supported recommendation put forward as the most useful approach to this fundamental task. A direct comparison between the estimate predictions of the current paradigm (shown in Section 2) will be done with numbers calculated in this report in the end of Scenario A (Section 18), the end of Scenario B (Section 23) and in the end of Scenario C (Section 20). Scenario E examines the viability of the nuclear power plant fleet expansion to supply the required extra power, which in turn can be compared to what current thinking would be required in the future regarding the nuclear power industry.

Figure 1.17 shows the development of why six scenarios to phase out fossil fuels were selected, and how the Scenario F Hybrid solution was developed.

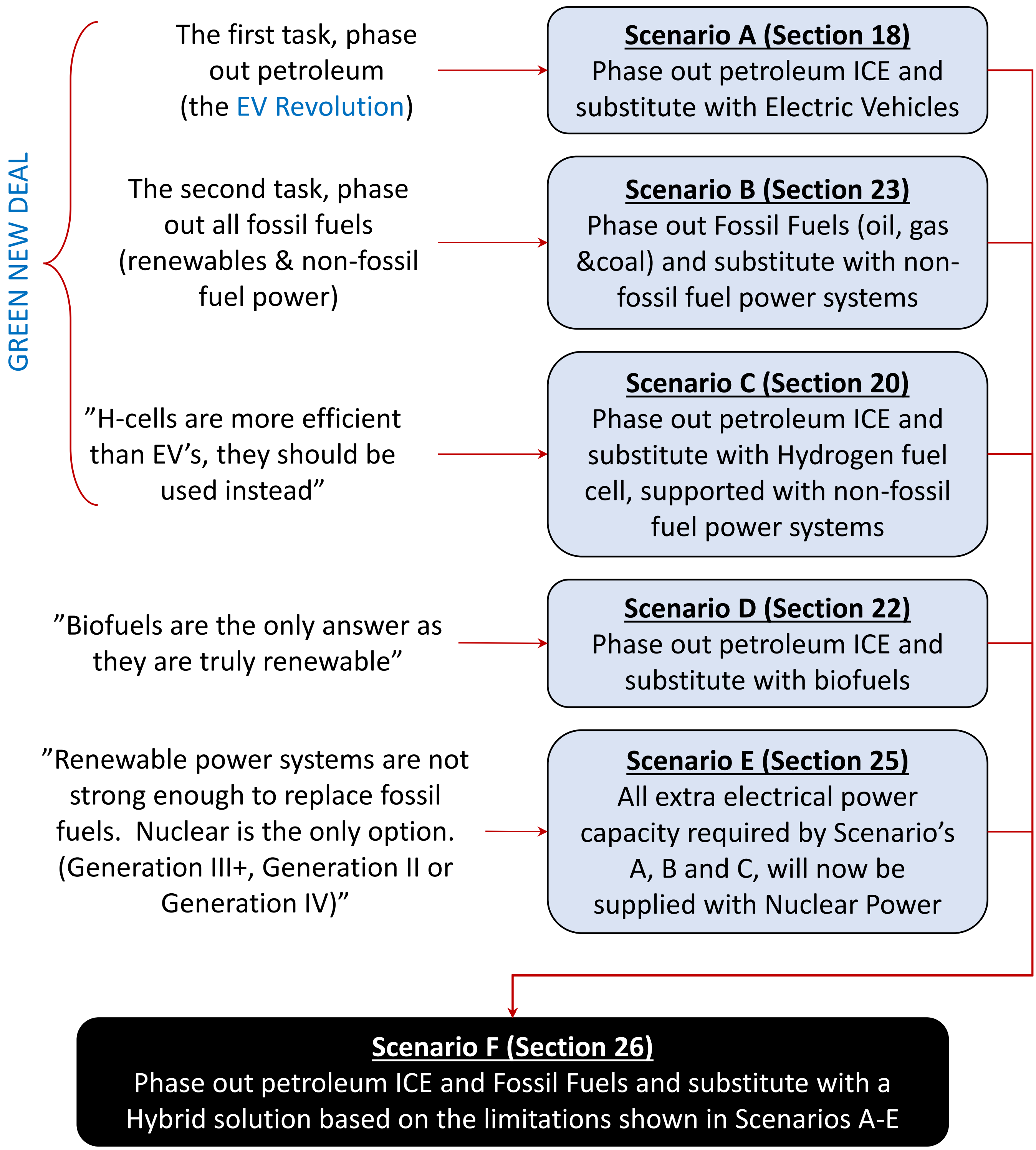


Figure 1.17. The development of the six scenarios to phase out fossil fuels in this report
(Image: Simon Michaux)

1.3 Difference between this report and other previous studies

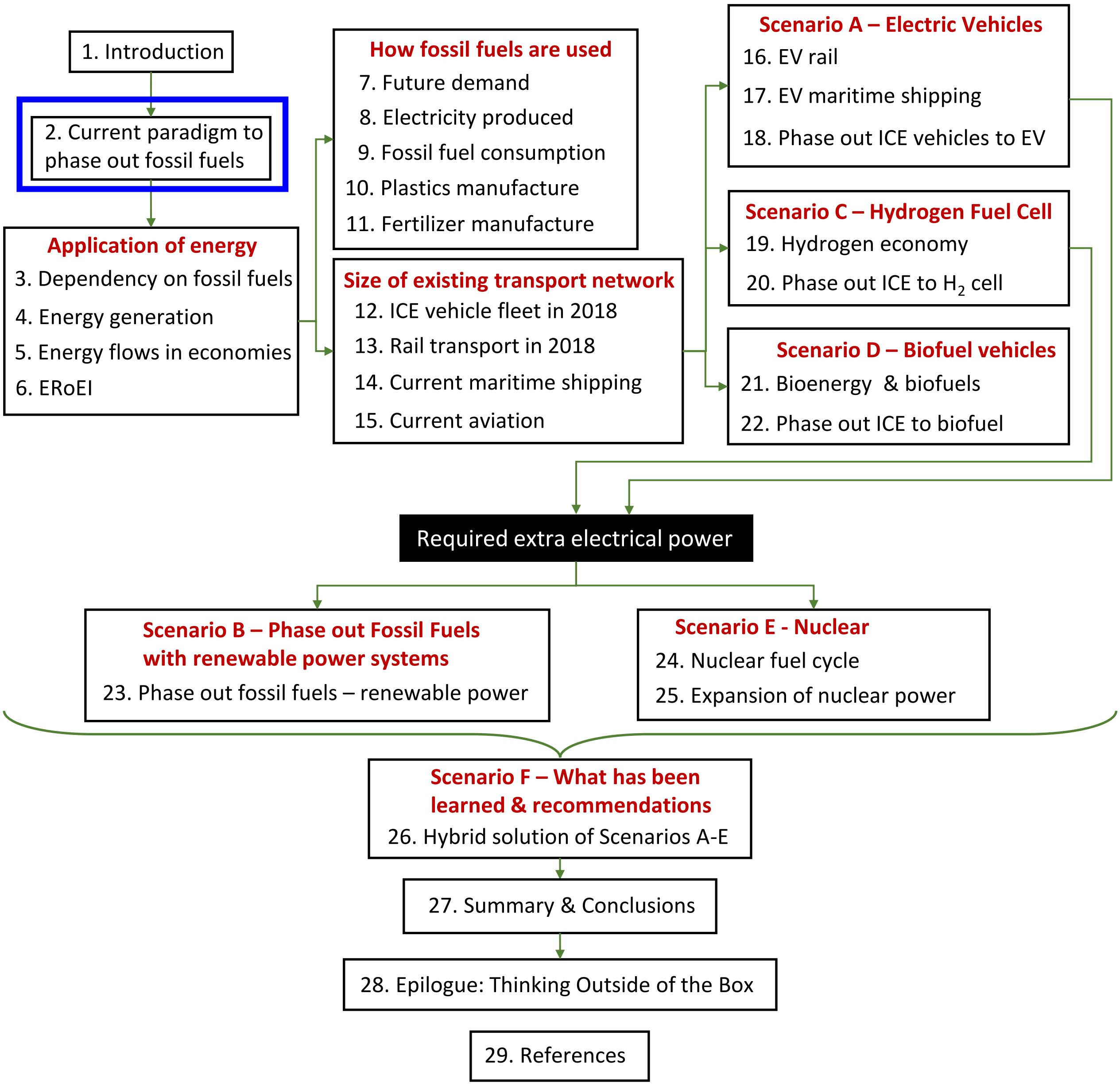
Most other studies that examine the issue of phasing out fossil fuels do not address the practical aspects. Very few reports quote the number of vehicles in context needed expanded power grid capacity. If they do, it is in context of one nation state only, or the European Union only. The task to establish the total number of vehicles in the global vehicle fleet (Appendix J), highlighted this. The distance travelled by these vehicles is also not considered.

Usually, the conventional approach in studying the substitution of fossil fuels examines the carbon pollution, and climate change mitigation aspect. This report will not look at carbon emissions being saved in the interest of reducing the length of this document. It is recommended that another analyst could take the numbers presented in this report and use them to do a parallel study.

Also, discussion often goes straight to economic considerations like required investment levels, or the rate of transition. This report will not examine market fluctuations and forces. It will focus on the physical material needs to construct and service the existing ecosystem without fossil fuels. Just so it will form a boundary condition in market forces studies.

2 CURRENT PARADIGM TO PHASE OUT FOSSIL FUELS

The purpose of Section 2 is to examine and if possible, quantify the accepted paradigm being discussed in the literature and in policy making conferences. This chapter will examine what the outcomes are of studies done by the World Economic Forum (World Economic Forum 2019), International Energy Agency (IRENA Global Renewables Outlook 2020) and the European Commission (European Commission 2019a Going climate-neutral by 2050 and European Commission 2019e). The numbers collected are to show what international policy makers believe what will be done and by what year. These numbers will be compared against numbers developed in this report in Sections 18 and 23.



Assessment of the Extra Capacity Required of Alternative Energy Electrical Power Systems to Completely Replace Fossil Fuels

Fossil fuels are to be phased out as they are widely recognized to be the origin of the industrial pollution that causes global warming the generation anthropogenic greenhouse gas (GHG) emissions, also termed climate change. Climate change has happened in the planetary system through many geological cycles. A school of thought, now backed by legislation for mitigation, proposes that human industrialization is driving the current warming cycle (IPCC 2013). The largest driver of warming is the emission of greenhouse gases, of which more than 90% are carbon dioxide (CO_2) and methane. Fossil fuel burning (coal, oil, and gas) for energy consumption is the main source of these emissions, with additional contributions from agriculture, deforestation, and industrial processes.

The European Union adopted a climate change strategy as early as 1992 and endorsed the goal of limiting global warming to 2 degrees Celsius above pre-industrial levels in 1996. In 2001, the Kyoto Protocol developed the legislation recommendation approach further (Parker *et al* 2017).

In 2015, the Paris Climate Agreement of December 2015, was an agreement within the United Nations Framework Convention on Climate Change (UNFCCC), on climate change mitigation, adaptation, and finance was signed in 2016 (UNFCCC 2016 and United Nations 2016).

A number of useful reports and studies have been released since then, documenting how the objectives of the Paris Agreement will be delivered.

The approach to be developed in Europe is, where possible (technological and economically viable), any industrial or physical activity that can be electrified will be electrified, thus making battery technology one of the most important key enablers for the green energy transition facilitating existing and new technologies (European Commission 2020 Strategic Research Agenda for batteries). The ambitious target to get this done by is 2030. Applications will vary widely, with most of the incoming change will be in the transport sector:

- electric bikes, scooters, and motorcycles
- passenger cars
- commercial vans
- trucks and buses
- boats, and maritime shipping
- trams and metros

A developing area that needs to be operational is battery energy storage technologies supporting and strengthening the power grid to facilitate greater intermittency. Other applications to change could be:

- heavy duty machinery
- robotics
- currently unseen vectors

In 2018 the European Commission released a strategy to become climate neutral by the year 2050 (European Commission 2019a Going climate-neutral by 2050). Carbon neutrality refers to producing net zero carbon dioxide emissions in the European region on an annual basis. This is to be achieved by balancing carbon dioxide emissions with removal (often through carbon offsetting) or simply eliminating carbon dioxide emissions altogether, followed by the transition to the post-carbon economy. In 2019, the European Green Deal strategy was released (European Commission 2019e), which are a set of policy initiatives by the European Commission with the overarching aim of making Europe climate neutral in 2050.

2.1 Phase out petroleum fueled ICE and substitute with EV and/or H-cell vehicles

It is recognized that the most pertinent task to be undertaken to phase out fossil fuels is to phase out petroleum fueled Internal Combustion Engine (ICE) vehicles. This is often referred to as 'The Electric Vehicle Revolution'. In the year 2017, the European Union, emissions from transport are considered to be approximately 25% of the total European CO_2 emissions (European Commission 2020 Strategic Research Agenda for batteries). The fossil fueled electrical power generation fleet of power stations contributed to 23 % of global emissions in 2017. By enabling electrification of transport and the use of renewables as a reliable source of energy, the use of battery technology has the enormous potential to reduce global emissions by roughly 30% (World Economic Forum 2019) by 2030 in addition to contributing to numerous UN Sustainable Development Goals.

In 2019 there was 7.2 million EVs registered in the global vehicle fleet, which represented 2.6% of the total passenger car market share. This was a 6% growth from the previous year (IEA 2020, Global EV Outlook 2020).

It is recognized that legislation and regulation policies will drive the EV market share, not subsidies. To this end, the sale of ICE vehicles and/or petroleum products could be taxed so high that they become not economically viable compared to the alternative EV technology. Europe is currently strengthening its CO2 emissions standards, thus indirectly supporting a move towards EV.

To further incentivize the market, France adopted the phase-out of internal combustion vehicles by 2040's, while another 17 countries announced similar intentions targeting a 2050 timeframe (IEA 2020 Global EV outlook).

The scope of needed batteries exceeds just EV vehicles. They will also be needed to manufacture stationary energy storage battery banks. In 2017, global cumulative installed capacity of electrochemical energy system storage was at 3.5 GWh in scope. This capacity is expected to rapidly increase to approximately 400 GWh by 2030 and further to 1300 GWh by 2040 (Tsiropoulos *et al* 2018).

By, 2030 it is forecasted that PV solar power will service more than half of the required global installed power storage capacity, while frequency regulation, transmission, distribution, and others account for the remaining (Tsiropoulos *et al* 2018).

If technologically possible, batteries will be used in maritime shipping and aviation applications. Globally, around 250 maritime vessels are currently operating with EV batteries propulsion systems, and over 150 more being commissioned (DNV-GL Alternative Fuel Insight'. https://afi.dnvgl.com/). Many of these vessels are passenger ferries, with the first electric ferry being launched in 2015, demonstrating the rapid transition and adaptation of battery technology in this sector. Other types of vessels are following this trend, and the first hybrid cruise ship was introduced in 2019 by Color Line, allowing for full electric operation in and out of the ports (https://www.colorline.com/about-us/worlds-largest-plug-in-hybrid-ship). It is hoped that fully EV maritime ships will be made viable to phase out diesel fueled ICE maritime shipping vessels.

It is also an objective to have all rail transport to be fully electric, where all passenger trains and freight locomotives became electric EV based technology.

Batteries for aviation have a fundamental limitation for implementation of electric aircrafts is the energy density. Current LiB technology allows small aircrafts with up to 4 passengers to operate distances up to 100 km. According to Rolls Royce, "the world's most energy-dense flying battery pack," is currently at 160 Wh/kg (https://cleantechnica.com/2020/01/29/rolls-royce-claims-its-latest-electric-airplane-battery-has-the-highest-energydensity/).

The European automotive industry is driving the demand for batteries which today is the fastest growing market in the world for plug-in vehicles. The European Battery Alliance reports that there is a total of 25 announced/planned projects on Li-Ion factories in Europe ranging from pilot plants to Gigafactory's, in various stages of development. If these projects are commissioned in their planned schedules, they will provide an additional total of approximately 500GWh production capacity for Europe by 2030.

A summary of these planned batteries manufacturing operations is shown in Figure 2.1. It is foreseen that Europe will have a 16% share of the 2550 GWh global battery market by 2029 compared to just under 6% of todays 450 GWh (World Economic Forum 2019).

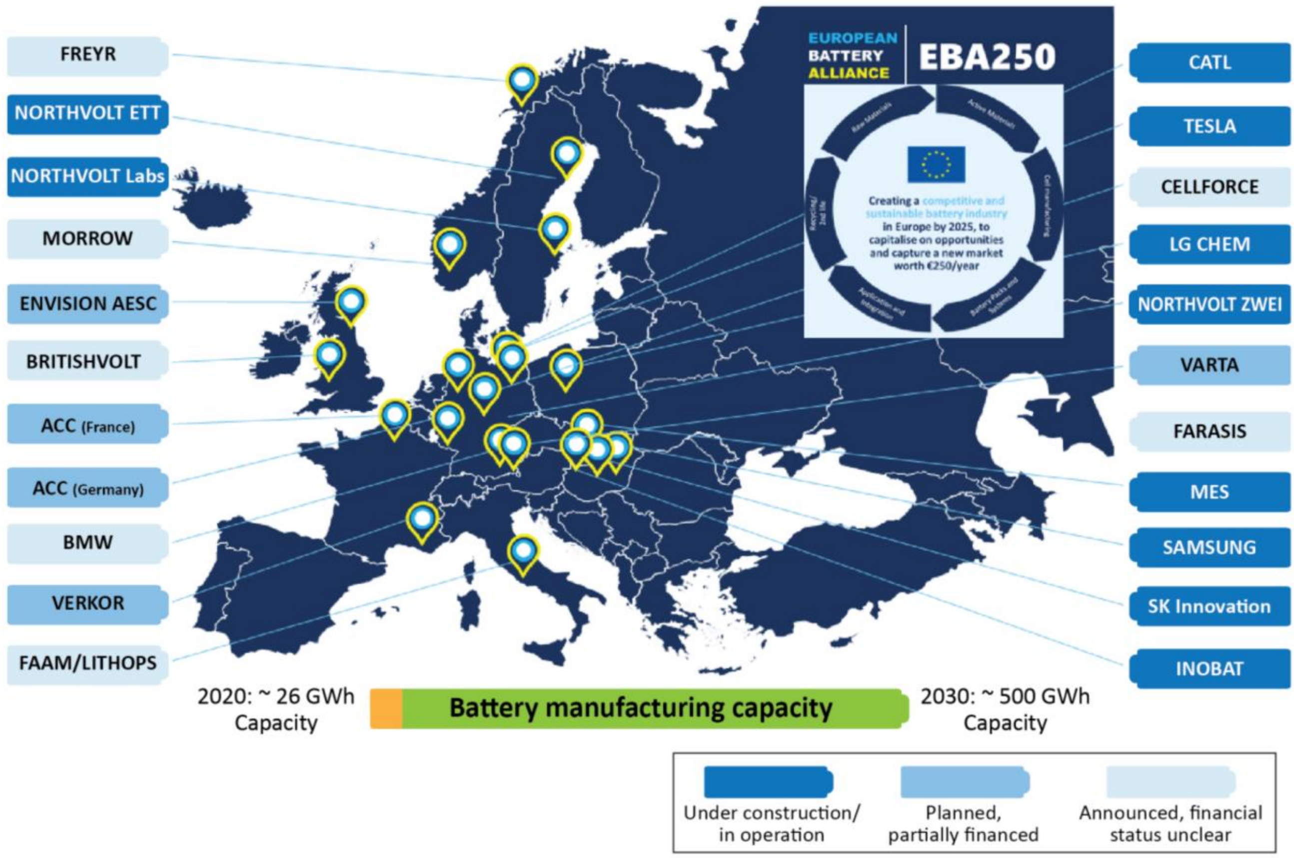


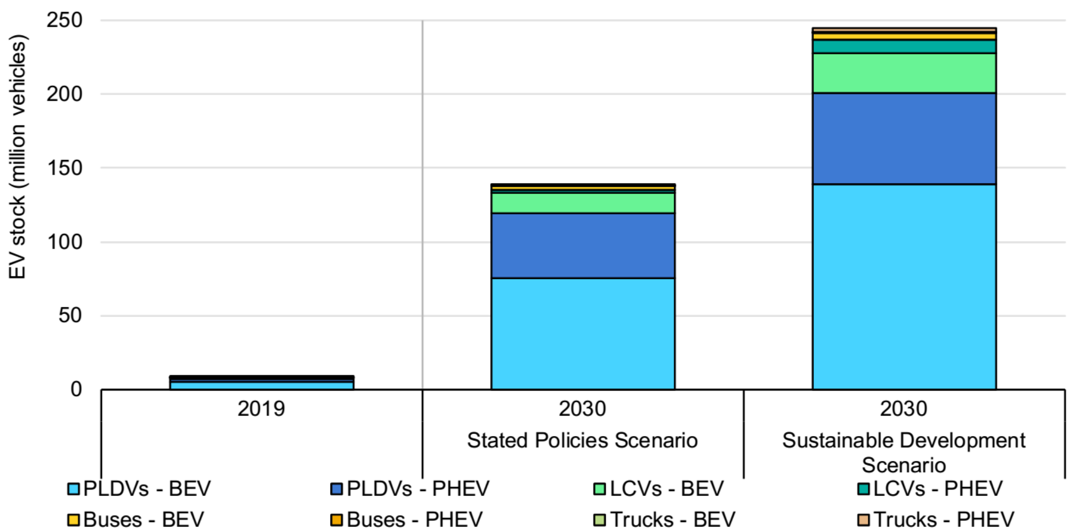
Figure 2.1. Planned European battery manufacturing factories
(Source: Global EV Outlook 2020, copyright IEA)

The Global EV Outlook report published by the IEA (IEA 2020) examines the electric mobility outcomes of two IEA scenarios.

1. The Stated Policies Scenario, which incorporates existing government policies (SP)

2. The Sustainable Development Scenario, which is fully compatible with the climate goals of the Paris Agreement. The Sustainable Development Scenario incorporates the targets of the EV30@30 Campaign to collectively reach a 30% market share for electric vehicles in all modes except two-wheelers by 2030 (SD).

The EV30@30 Campaign was launched at the Eighth Clean Energy Ministerial in 2017. The participating countries are Canada, China, Finland, France, India, Japan, Mexico, Netherlands, Norway, Sweden, and United Kingdom (IEA 2020).

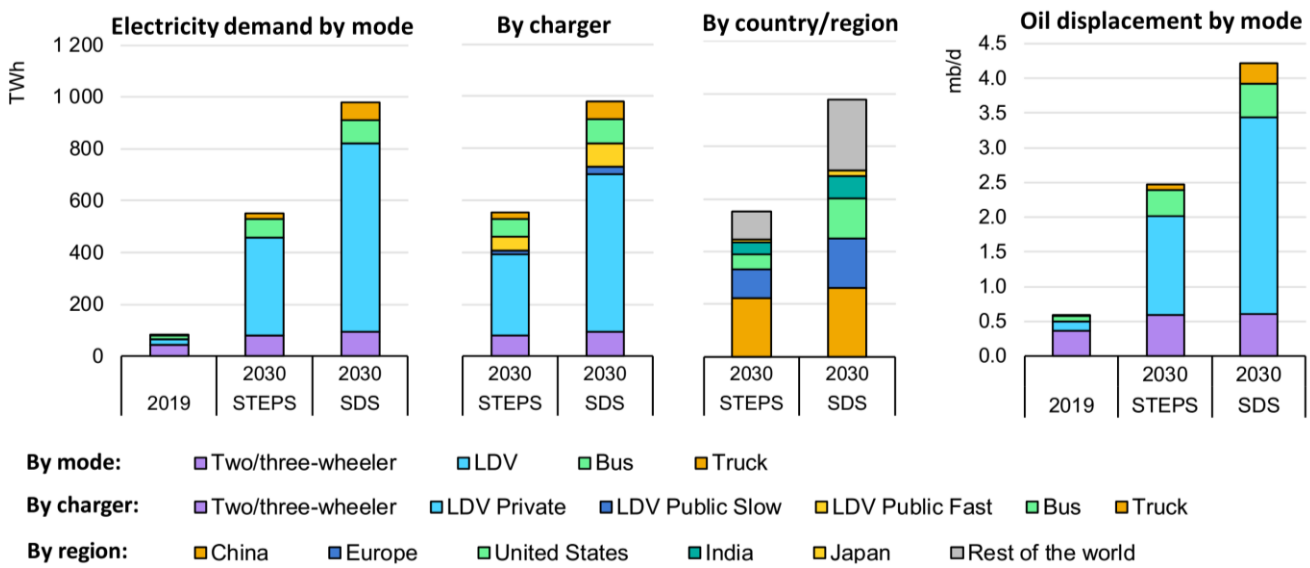


Notes: PLDVs = passenger light-duty vehicles; LCVs = light commercial vehicles; BEV = battery electric vehicle; PHEV = plug-in hybrid electric vehicle.

Source: IEA analysis developed with the IEA Mobility Model.

By 2030, the global electric vehicle stock (excluding two/three-wheelers) is about 140 million in the Stated Policies Scenario, while the more ambitious Sustainable Development Scenario projects about 245 million electric vehicles.

Figure 2.2. Global electric vehicle stock by scenario, 2019 and 2030 (Source: Global EV Outlook 2020, IEA)



Notes: Mb/d = million barrels of oil per day; STEPS = Stated Policies Scenario; SDS = Sustainable Development Scenario; LDV = light-duty vehicle. For more details, see figure 3.5 in the main report.

Source: IEA analysis developed with the IEA Mobility Model.

Figure 2.3. Electricity demand from electric vehicle fleet by mode, charger type, country/region, and oil displacement, 2019 and 2030 (Source: Global EV Outlook 2020, IEA)

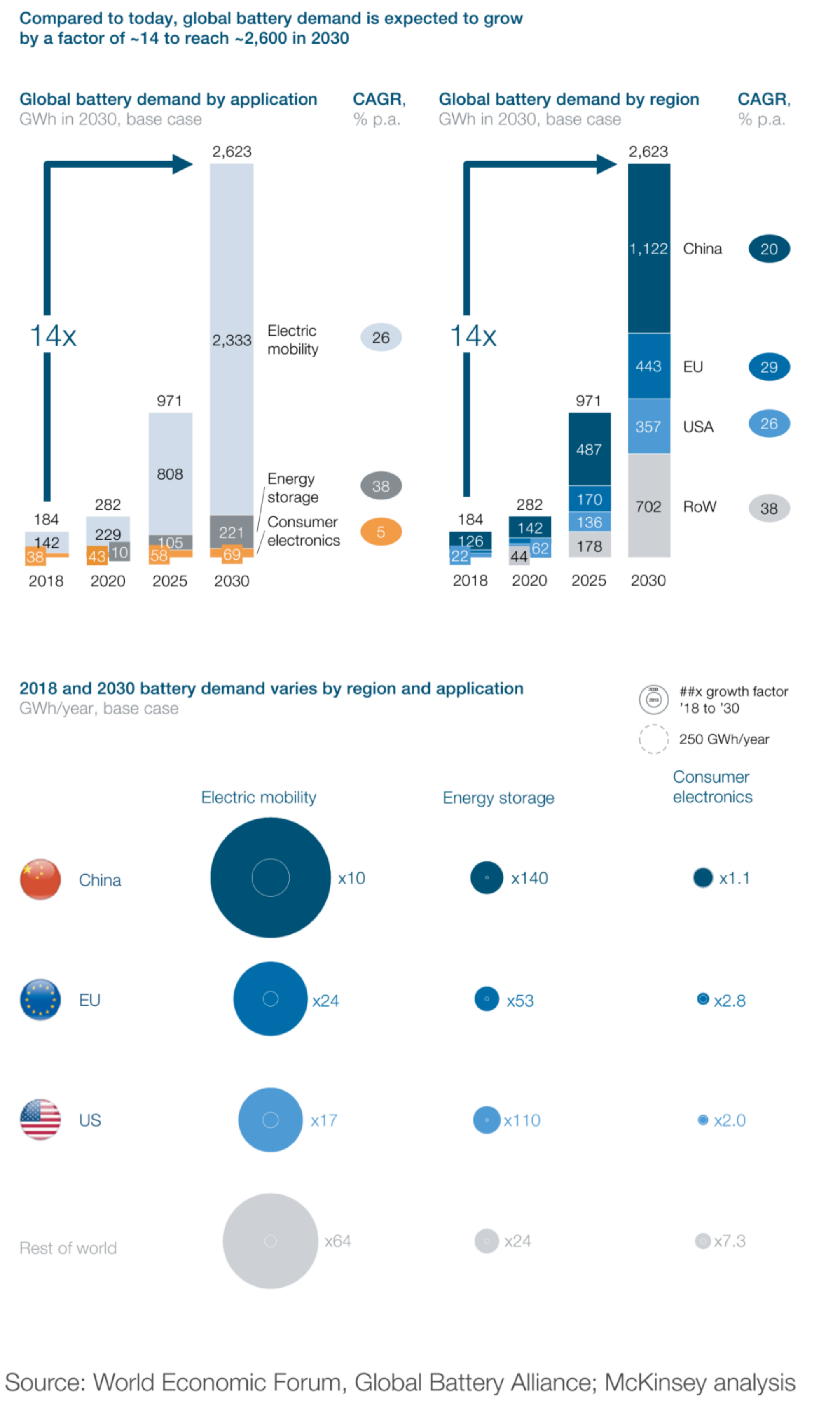


Figure 2.4. Global battery industry growth by application and region by 2030 (Source: World Economic Forum 2019)

As shown in Figure 2.3, the IEA Global EV Outlook 2020 Stated Policies Scenario, global electricity demand from electric vehicles (including two/three-wheelers) will reach 550 TWh. This is a six-fold rise from 2019 EV power requirements. This represents 140 million EV vehicles in the global vehicle fleet (Figure 2.2).

In the Sustainable Development Scenario, demand due to electric vehicles in total electricity consumption at a global level grows rising nearly eleven-fold relative to 2019, to almost 1 000 TWh. The IEA scenarios varied by national/regional areas, then compiled a global estimate. This represents 245 million EV vehicles in the global vehicle fleet (Figure 2.2).

Figure 2.4 shows the outcomes of the study done by the World Economic Forum (World Economic Forum 2019). Between 2010 and 2018, battery demand grew by 30% annually and reached a volume of 184 GWh in 2018. In the WEF study base case, the market is expected to keep growing, at an estimated 25% annual rate, to reach a volume of 2,623 GWh in 2030, which is a 14 fold increase in market volume (World Economic Forum 2019).

By 2030, passenger cars will account for the largest share (60%) of global battery demand, followed by the commercial vehicle segment with 23%. Geographically, China is the biggest market with 43%. Consumer electronics, which account for more than 20% of the market today, will represent only a marginal share of the global battery market in 2030.

In summary, the EV vehicle market share is expected to increase exponentially, where eventually they completely replace petroleum fueled ICE vehicles.

2.2 Phase out fossil fuel electrical power generation systems and substitute with renewable power generation systems

There have been several studies done and documented to predict the transition to renewable power systems to meet climate change targets. The electrical power energy transition away from fossil fuel systems like coal and gas to renewable electrical power systems is considered vital to significantly reduce GHG emissions. The renewable (clean) energy transition would result in a system in which the largest share of the EU-28 primary energy supply being sourced from renewable energy systems (Figure 2.5).

The EU had recently agreed a new renewables target of 32 % by 2030 (European Commission 2019a Going climate-neutral by 2050). Europe's energy import dependence currently stands at around 55 % and is forecast to fall to 20 % in 2050 with the transformation to a climate neutral economy. The large-scale deployment of renewables will decentralize and increase electricity production. By 2050, more than 80 % of electricity will be coming from renewable energy sources, with electricity providing for half of the final energy demand in the EU. The International Renewable Energy Agency released a study in 2020 (IRENA 2020) that not only predicted the share of renewable energy to increase, but overall global energy consumption was to decrease (Figure 2.6). Several scenarios were developed, two of which were:

1. **The Planned Energy Scenario (PES).** This is the primary reference case for the IRENA study, providing a prediction outcome based on current energy plans and other planned targets and policies (as of 2019). This was based on an estimation of Nationally Determined Contributions under the Paris Agreement for signatory nation states.

2. **The Transforming Energy Scenario (TES).** The TES is an ambitious but achievable, energy transformation pathway based largely on renewable energy sources and steadily improved energy efficiency (though not limited exclusively to these technologies).

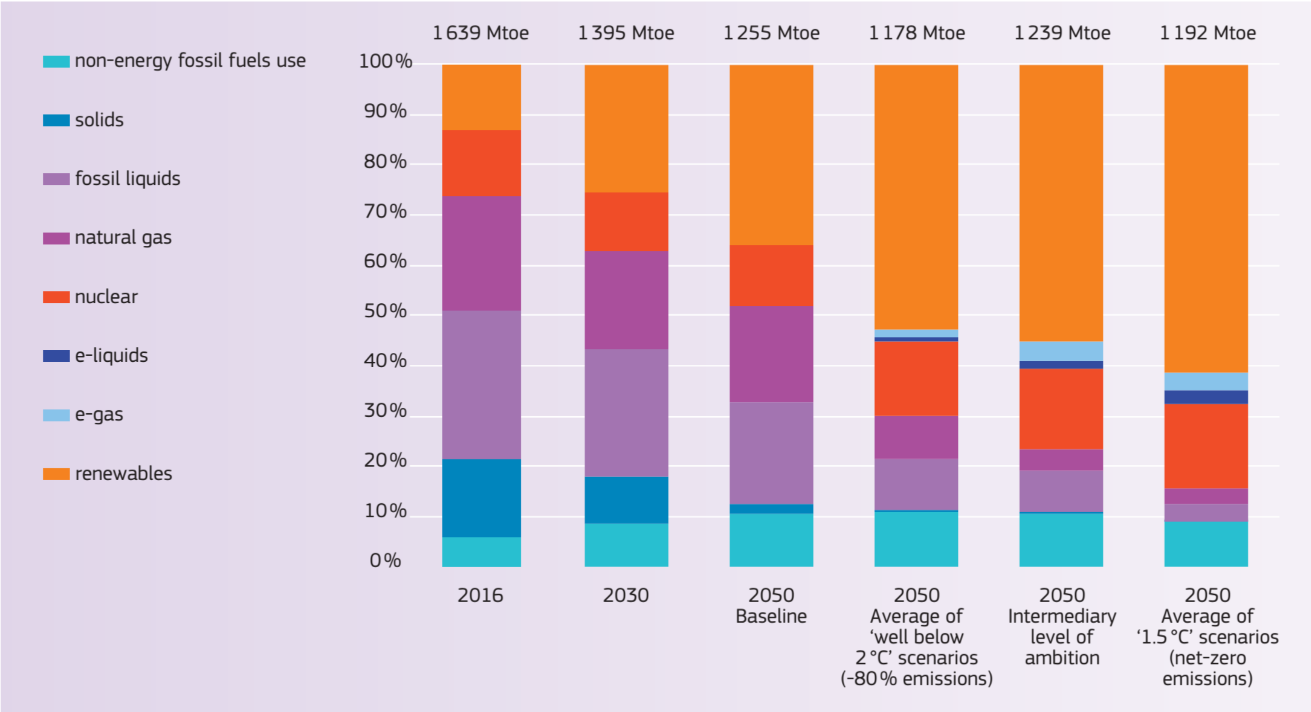


Figure 2.5. Global gross consumption of energy (Source: European Commission 2019a - *Going climate-neutral by 2050)*

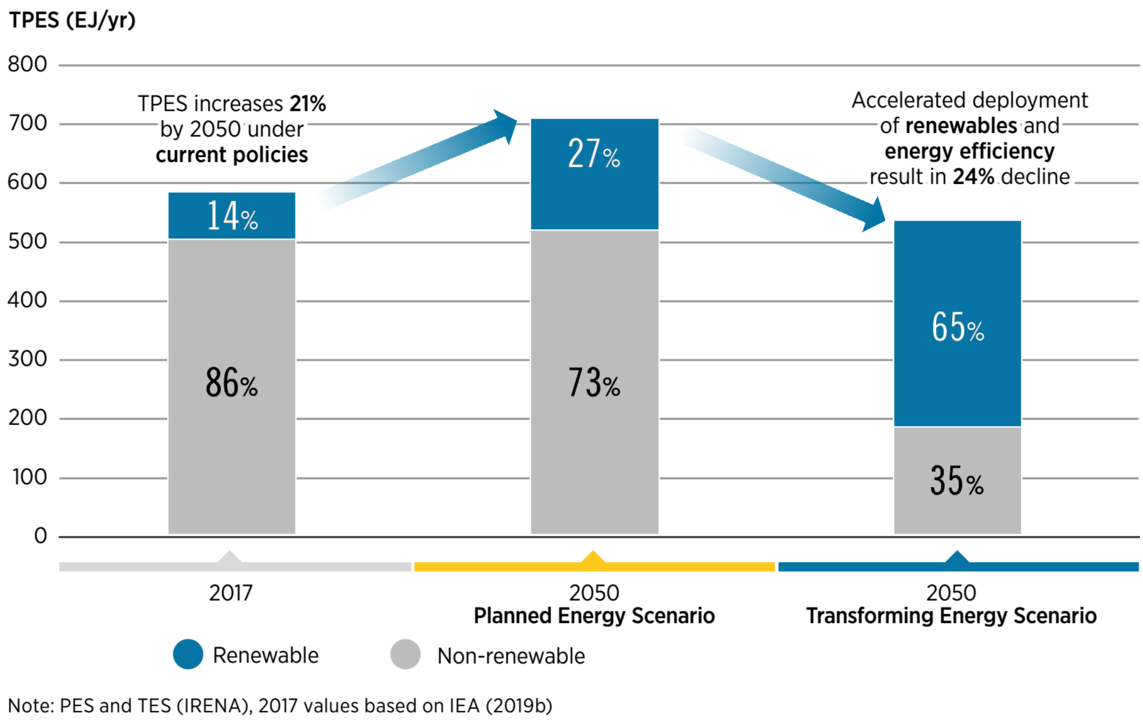


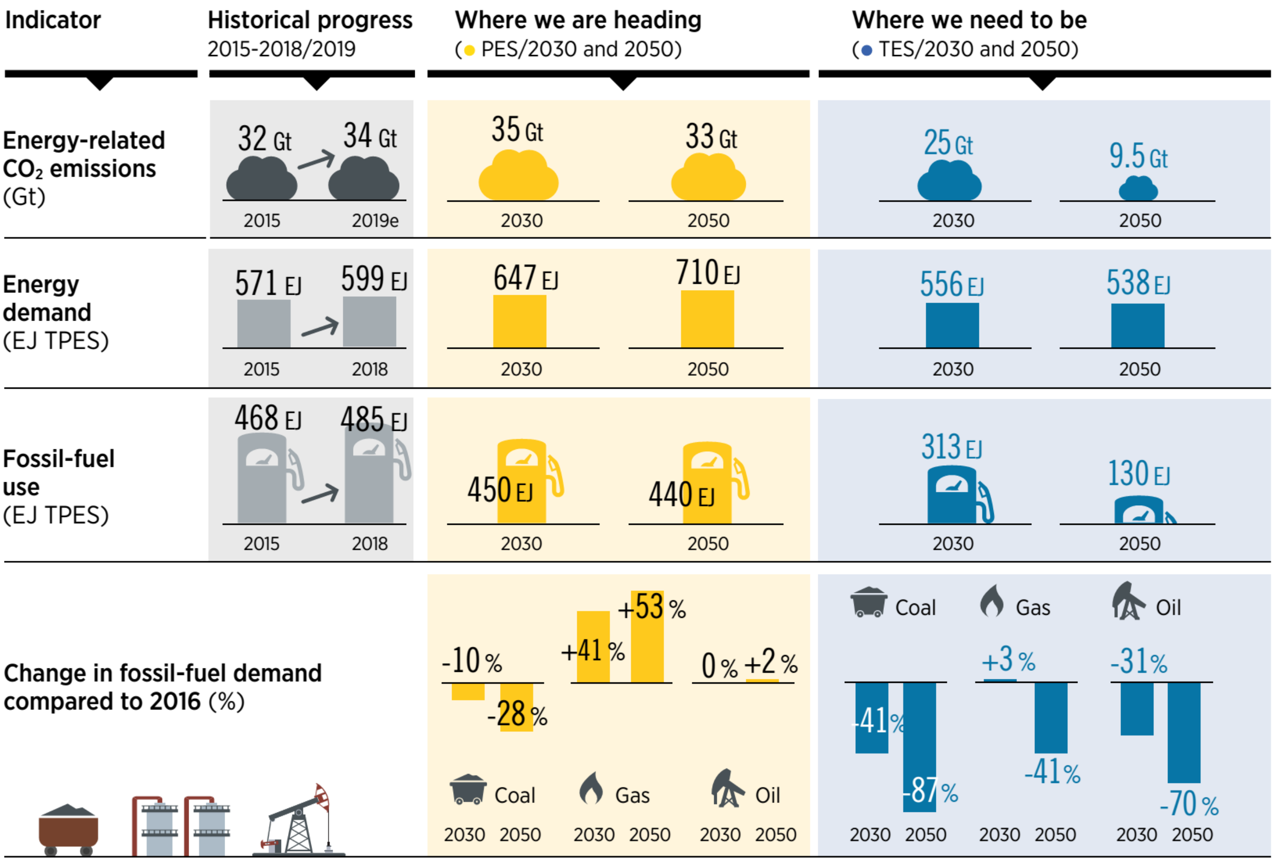
Figure 2.6. Total primary energy supply, renewable and non-renewable share, for the Planned Energy Scenario (PES) and the Transforming Energy Scenario (TES), for years 2017 and 2050
(Source: IRENA Global Renewables Outlook 2020)

To meet the agreed global climate goals (Paris Agreement 2016), renewable power systems would need to provide two-thirds of the world's energy supply.

Renewable energy power systems, operational efficiency gains, and electrification of all systems provide a clear focus for where to develop actions to cut the bulk of emissions at the regional and country levels.

In the Planned Energy Scenario, primary energy demand increases from around 600 exajoules (EJ) in 2017, to an estimated 710 EJ by 2050 (Figure 2.6). The focus of the PES is the rapid increase of renewable energy power generation systems to make up for the phasing out of gas and coal electrical power generation. In the same PES, the amount of fossil fuels remains approximately similar to 2017 level, due to practicalities of how much of the current system is dependent on fossil fuel. The PES does show an increasing market share for renewable energy.

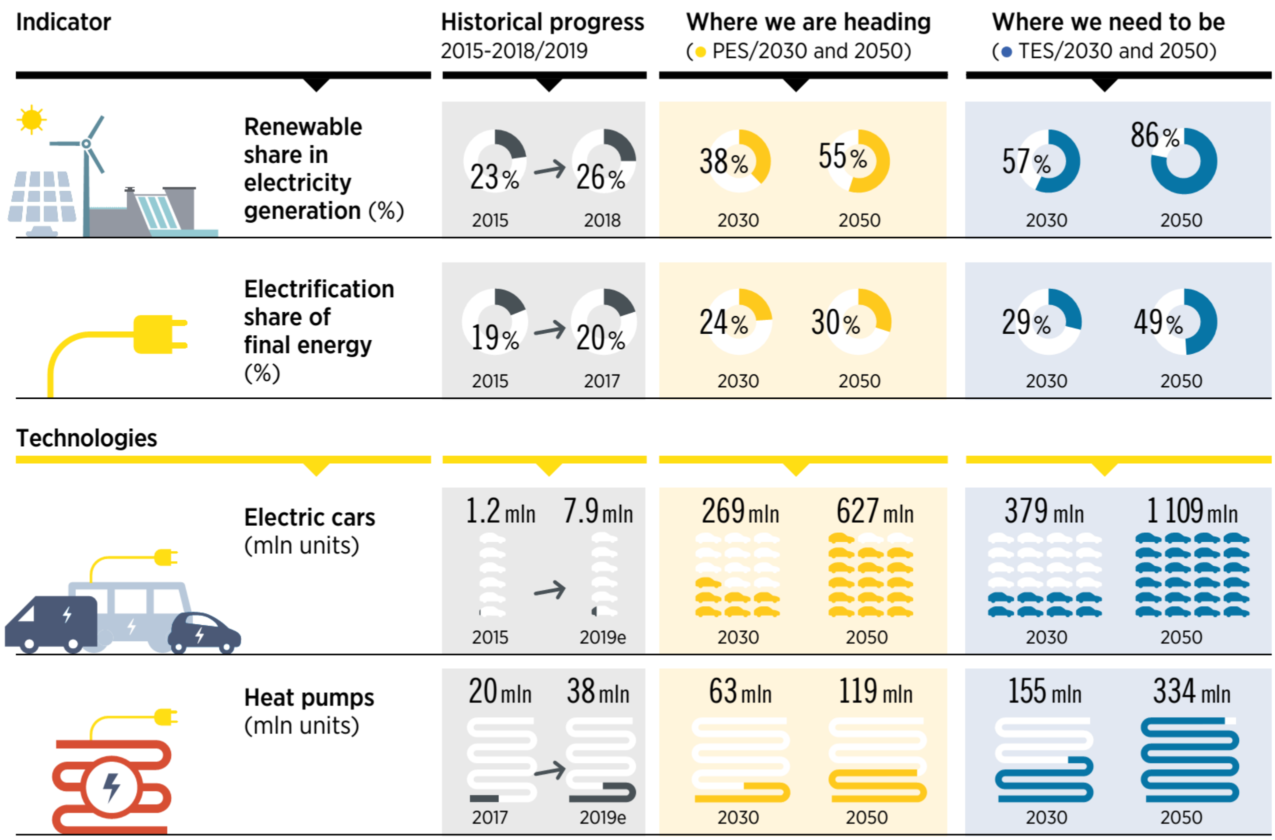
However, given the need to reduce emissions, fossil-fuel consumption cannot stay at the 2017 level of consumption. In the Transforming Energy Scenario (TES), fossil fuel consumption declines by 75% compared to the 2017 level, to 130 EJ by 2050. This is approximately equivalent to just the energy demand of the nation state of China. How this could happen will vary greatly from nation to nation. that being stated, all regions would see higher shares of renewable energy use, with Southeast Asia, Latin America, the European Union, and Sub-Saharan Africa all predicted to reach 70-80% renewable shares in their total energy mixes by 2050 (Figures 2.7 and 2.8). Similarity, electrification of end uses like heat and transport would rise everywhere, exceeding 50% in East Asia, North America and much of Europe (IRENA Global Renewables Outlook 2020).



Note: TPES = total primary energy supply. e = estimate; Gt = gigatonnes; EJ = exajoules.

Based on IRENA scenarios (PES and TES), along with IEA (2019a, 2019b) for 2015-2018 historical progress of energy demand and fossil-fuel use.

Figure 2.7. Energy-related CO_2 emissions, energy demand and fossil-fuel outlook, historical progress, Planned Energy Scenario (PES) and Transforming Energy Scenario (TES) (Source: IRENA Global Renewables Outlook 2020)



Based on IRENA scenarios (PES and TES), along with Spiegel (2020), IEA (2019a, 2019b), IEA and IRENA (2017) and IRENA (2019a) for 2015-2018 historical progress.

Figure 2.8. Renewable electricity share in electricity generation, electrification share, and select technologies (Source: IRENA Global Renewables Outlook 2020)

In the Transforming Energy Scenario, electricity would become the central energy carrier by 2050, growing from a 20% share of final consumption to an almost 50% share; as a result, gross electricity consumption would more than double. Renewable energy and energy efficiency together could offer over 90% of the mitigation measures needed to reduce energy-related emissions in the Transforming Energy Scenario (TES). To achieve this reduction energy-related CO_2 emissions need to fall by 3.8% per year on average until 2050, to 70% below the 2019 level of consumption. In contrast, that compares to an average annual increase of 1% over the last decade (IRENA Global Renewables Outlook 2020).

A number of studies have been done to look at the implications of the predicted reduction on costs on the renewable power market share. These studies examine only market forces around cost reductions in the deployment of new technology. From this paradigm, it is both physically possible and economically viable to meet 100% of electricity demand with the combination of solar, wind, and batteries (SWB) by 2030 across the entire continental United States as well as the overwhelming majority of other populated regions of the world (Dorr & Seba 2020).

- Solar PV capacity costs have fallen over 80% between 2010 and 2020.
- Onshore wind capacity costs have fallen more than 45%
- Lithium-ion battery capacity costs have fallen almost 90%

These technologies will continue to become more efficient and effective, such that by 2030 their costs will have decreased a further 70%, 40%, and 80% respectively (Dorr & Seba 2020). This paradigm suggests that market forces will be sufficient to make fossil fuels in general obsolete in the next few years.

2.3 Summary of predictions to phase out fossil fuels

To summarize the different studies that have been proposed to phase out fossil fuels and transition to a non-fossil fuel system, the following statements have been assembled.

The EU has recently agreed a new renewables target of 32 % by 2030 and by 2050, more than 80 % of electricity will be coming from renewable energy sources, with electricity providing for half of the final energy demand in the EU (European Commission - Going climate-neutral by 2050).

- In the Sustainable Development Scenario (IEA Global EV Outlook 2020)
- By 2030, 30% of global fleet is EV
- By 2030, 245 million cars in global fleet are EV
- By 2030, demand due to electric vehicles in total electricity consumption at a global level grows to almost 1 000 TWh.

- Global battery demand by 2030 - 2623 GW (World Economic Forum 2019)

Table 2.1 shows a summary of the IRENA 2020 PES and TES scenarios. There are several studies that propose this is viable and practical (Jacobson *et al* 2015a and Jacobson *et al* 2015b).

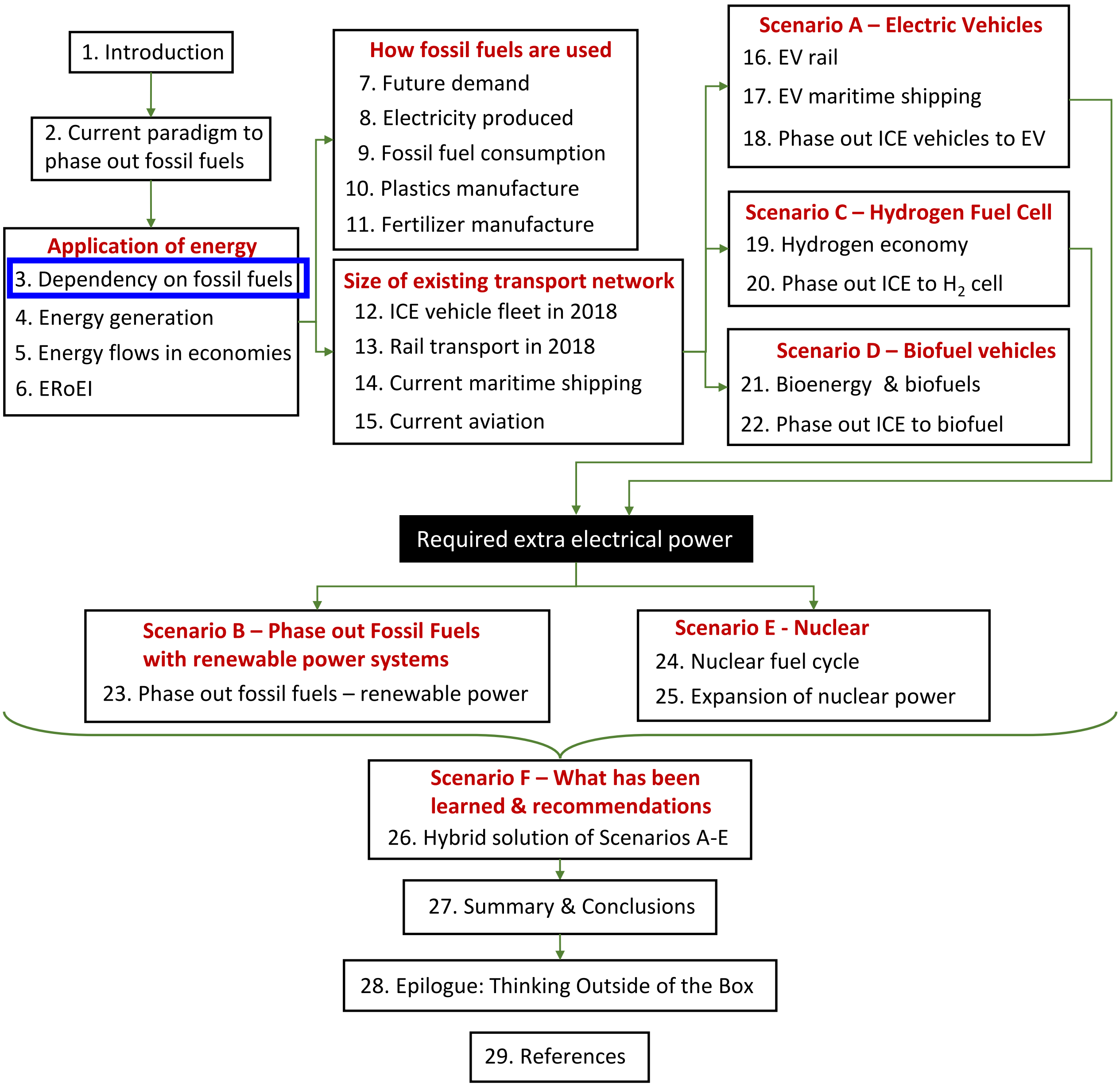
Table 2.1. Scenario's for 2030 and 2050 (Source: IRENA 2020)

Planned Energy Scenario	**2030**	**2050**
Energy demand (EJ TPES)	647	710
Fossil fuel use (EJ TPES)	450	440
Oil consumption (compared to 2017)	0%	2%
Gas consumption (compared to 2017)	41%	53%
Coal consumption (compared to 2017)	-10%	-28%
Renewable share in electricity generation (%)	38%	55%
Electrification share of final energy	24%	30%
Electric vehicles (millions of units)	269	627
Heat Pumps (millions of units)	63	119
Transforming Energy Scenario	**2030**	**2050**
Energy demand (EJ TPES)	556	538
Fossil fuel use (EJ TPES)	313	130
Oil consumption (compared to 2017)	-31%	-70%
Gas consumption (compared to 2017)	3%	-41%
Coal consumption (compared to 2017)	-41%	-87%
Renewable share in electricity generation (%)	57%	86%
Electrification share of final energy	29%	49%
Electric vehicles (millions of units)	379	1 109
Heat Pumps (millions of units)	155	334

These numbers will be compared to outcomes in Scenario A (Section 18), Scenario B (Section 23) and Scenario C (Section 20), in the relevant chapters.

3 CURRENT INDUSTRIAL DEPENDENCY ON FOSSIL FUELS

The purpose of Section 3 was to demonstrate how most energy consumption applications in the global industrial ecosystem are dependent on fossil fuels (oil, gas, and coal). To assess what will be required to phase out fossil fuels, the existing scope and size of the fossil fuel dependent systems was mapped out.



Assessment of the Extra Capacity Required of Alternative Energy Electrical Power Systems to Completely Replace Fossil Fuels

Current industrialization has a foundation in the continuous supply of natural resources. The methods and processes associated with this foundation have significant momentum. This paradigm will not be undone easily. Human nature and human history make it so. Currently, our industrial systems are absolutely dependent on non-renewable natural resources for energy sources. Oil, gas and coal, and will continue to do so for some time. A group of economists (Covert 2016) explored whether market forces alone would cause a reduction in fossil fuel supply or demand. By studying the history of fossil fuel exploration and technological progress for both ‘clean’ (solar, hydro, geothermal and wind) and ‘dirty’ technologies (oil, gas and coal), they concluded that it is unlikely that the world will stop primarily relying on fossil fuels soon.

Over the last 100 years western society has evolved into a petroleum driven economy. Economic activity correlates strongly with the transport of goods. All industrial activity, energy use in general and economic indicators like GDP all correlate strongly with energy consumption (Figure 9, 10 and 11#) (Heinberg and 2012, Ruppert 2004, Martenson 2011), oil in particular. Figure 3.1 shows the global energy consumption by source between 1820 and 2018. As can be seen, the Industrial Revolution was powered by fossil fuels, where the first Industrial revolution (IR1) was made possible with the use and application of fossil fuels. In 2018, the global system was still 84.7% dependent on fossil fuels, where renewables (including solar, wind, geothermal and biofuels) accounted for 4.05% of global energy generation (Figure 3.2). Figures 3.3 to 3.10 show the relative energy consumption proportions of different nation states.

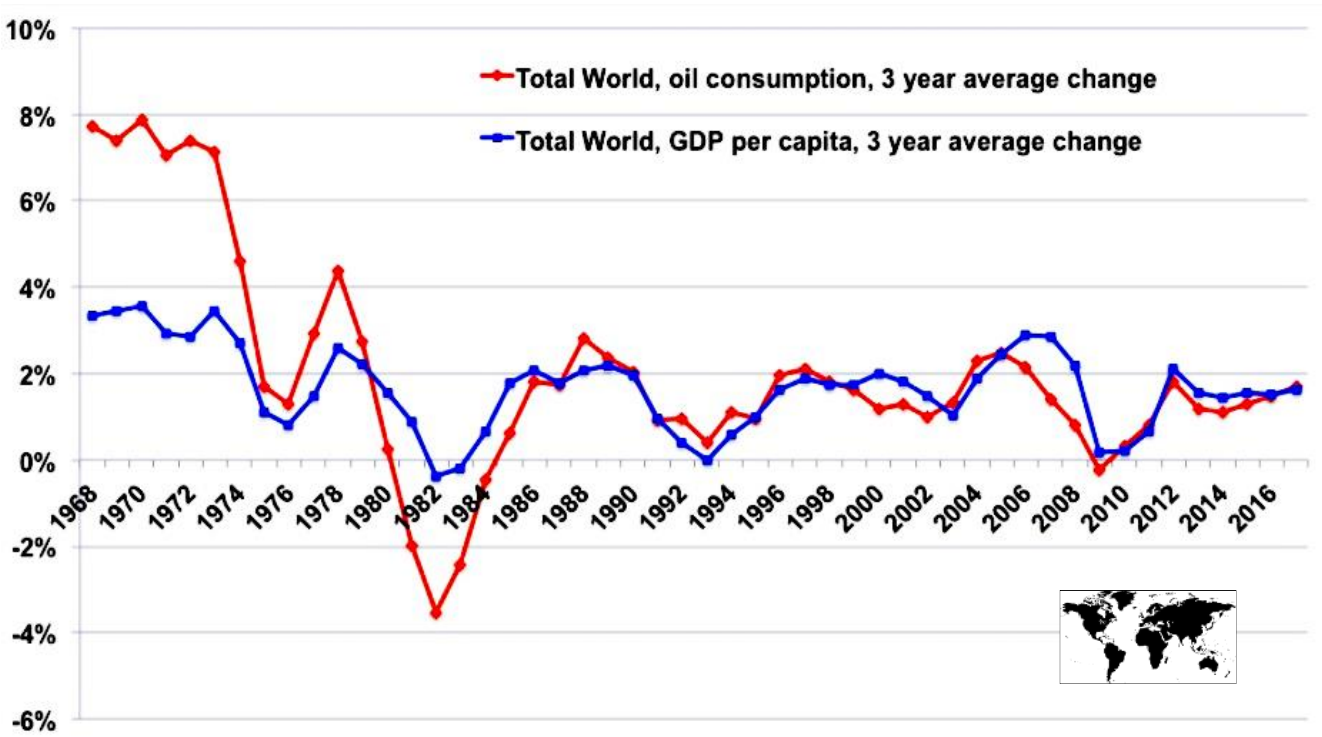


Figure 3.1. The annual relative change in world oil consumption and GDP per capita averaged over three years (Source: Data from BP Statistical Review 2019, World Bank) (World Map Image by Clker-Free-Vector-Images from Pixabay)

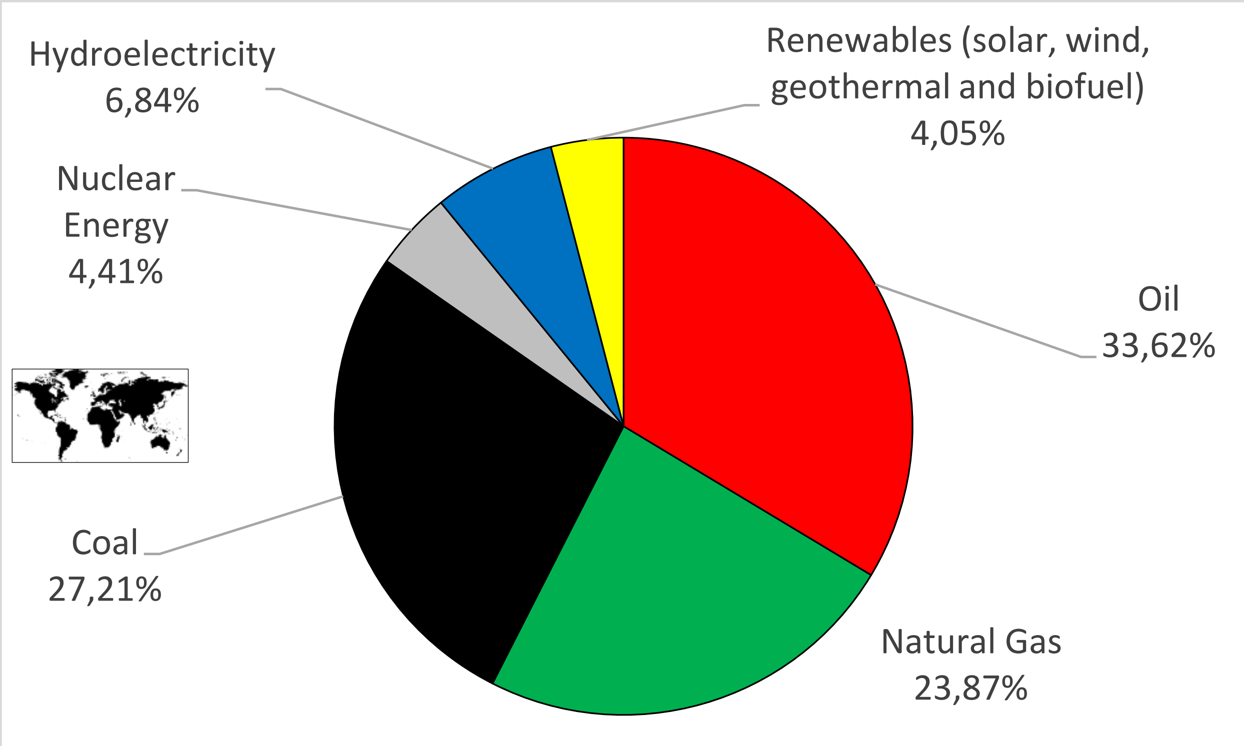


Figure 3.2. Global primary energy consumption by source in 2018
(Source: Appendix A and BP Statistical Review of the World Energy 2019) (World Map Image by Clker-Free-Vector-Images from Pixabay)

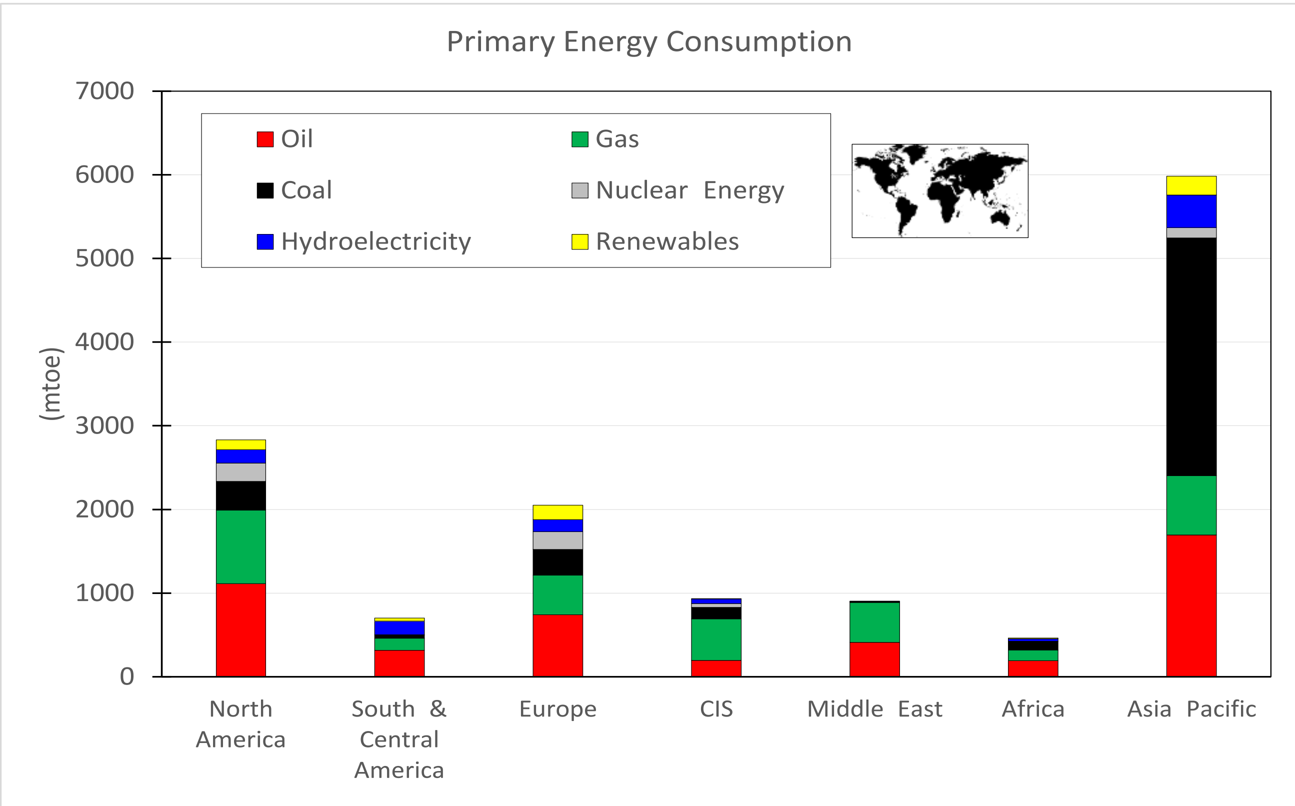


Figure 3.3. Primary energy consumption in 2018, by fuel type and geographical region
(Source: BP Statistical Review of World Energy 2019 & Appendix A)
(World Map Image by Clker-Free-Vector-Images from Pixabay)

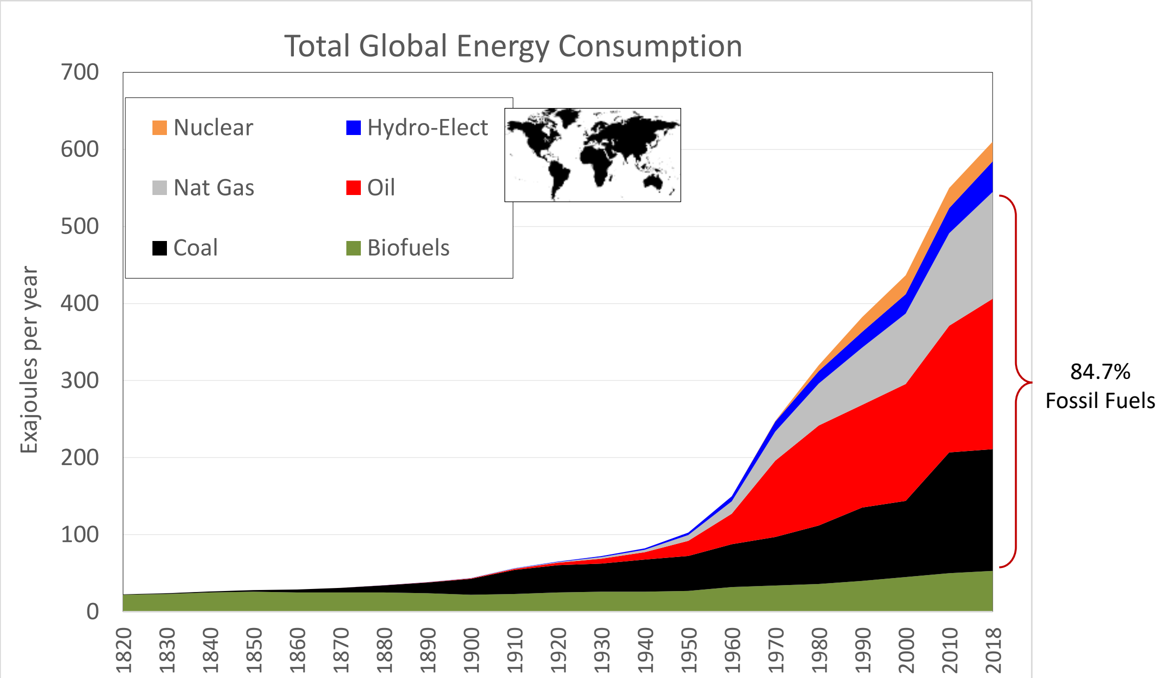


Figure 3.4. Global energy consumption by source 1820 to 2018 (excluding solar and wind)
(Source: Data from Tverberg, G. https://ourfiniteworld.com/, and BP Statistical Review of the World Energy 2019, US Census Bureau)
(World Map Image by Clker-Free-Vector-Images from Pixabay)

Uranium is classified as a nuclear fuel, in context that it is a geological resource, not a fossil fuel (World Nuclear Association). Fossil fuels are formed from the remains of organic matter (plant, animal, and microbial) and are composed primarily of various combinations of hydrocarbons. In this report, oil, gas, and coal are treated as fossil fuels and uranium is treated as a different geological resource.

Figure 3.5 shows the increase per capita for individual energy resources.

- Oil has sharply increased since its inception and then declined per capita since 1970
- Natural gas has increased steadily since its inception
- Coal rose steadily from the start of the industrial revolution and plateaued in 1910, was stable till it sharply increased in the year 2000

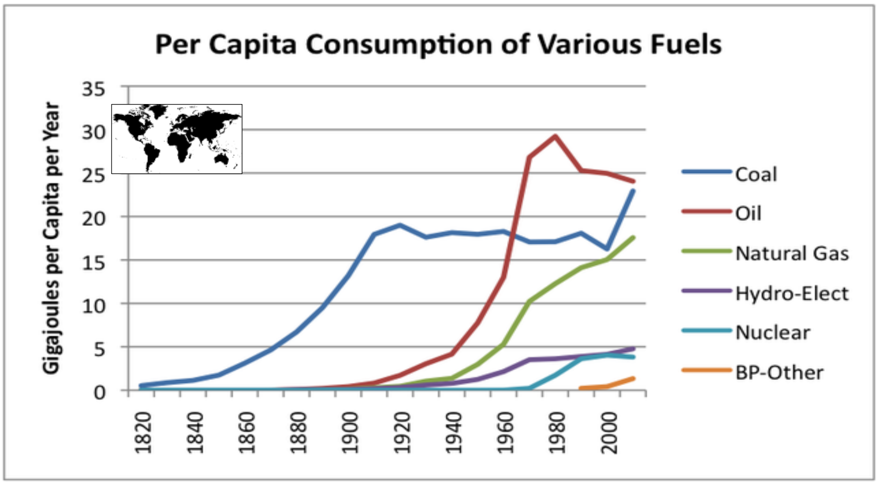


Figure 3.5. Per capita consumption of various fuels
(Source: Tverberg 2015, OurFiniteWorld.com) (World Map Image by Clker-Free-Vector-Images from Pixabay)

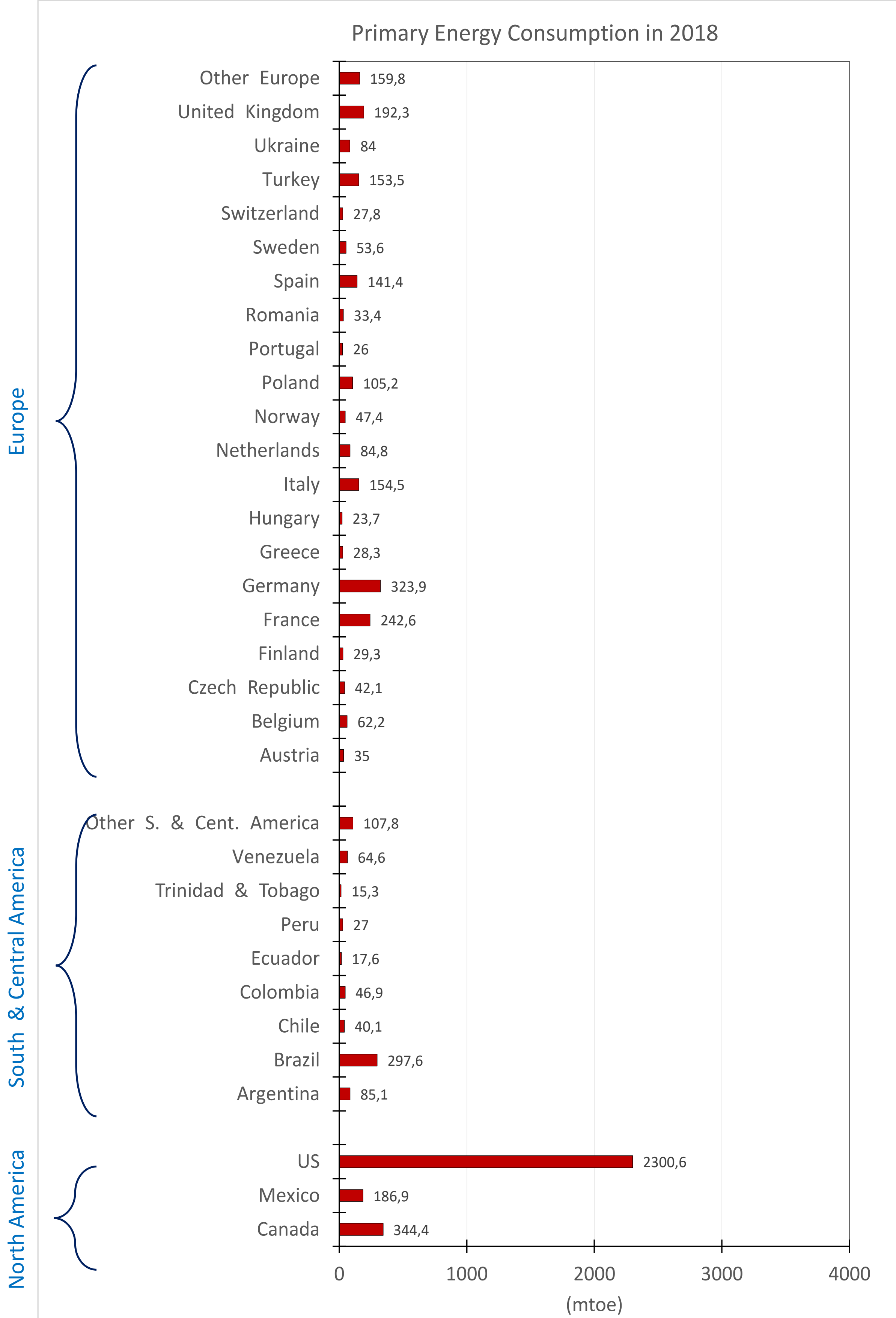


Figure 3.6. Primary Energy Consumption by Country, Part 1, units in Million tonnes of oil equivalent (mtoe) (Source: BP Statistical Review of World Energy 2019 & Appendix A)

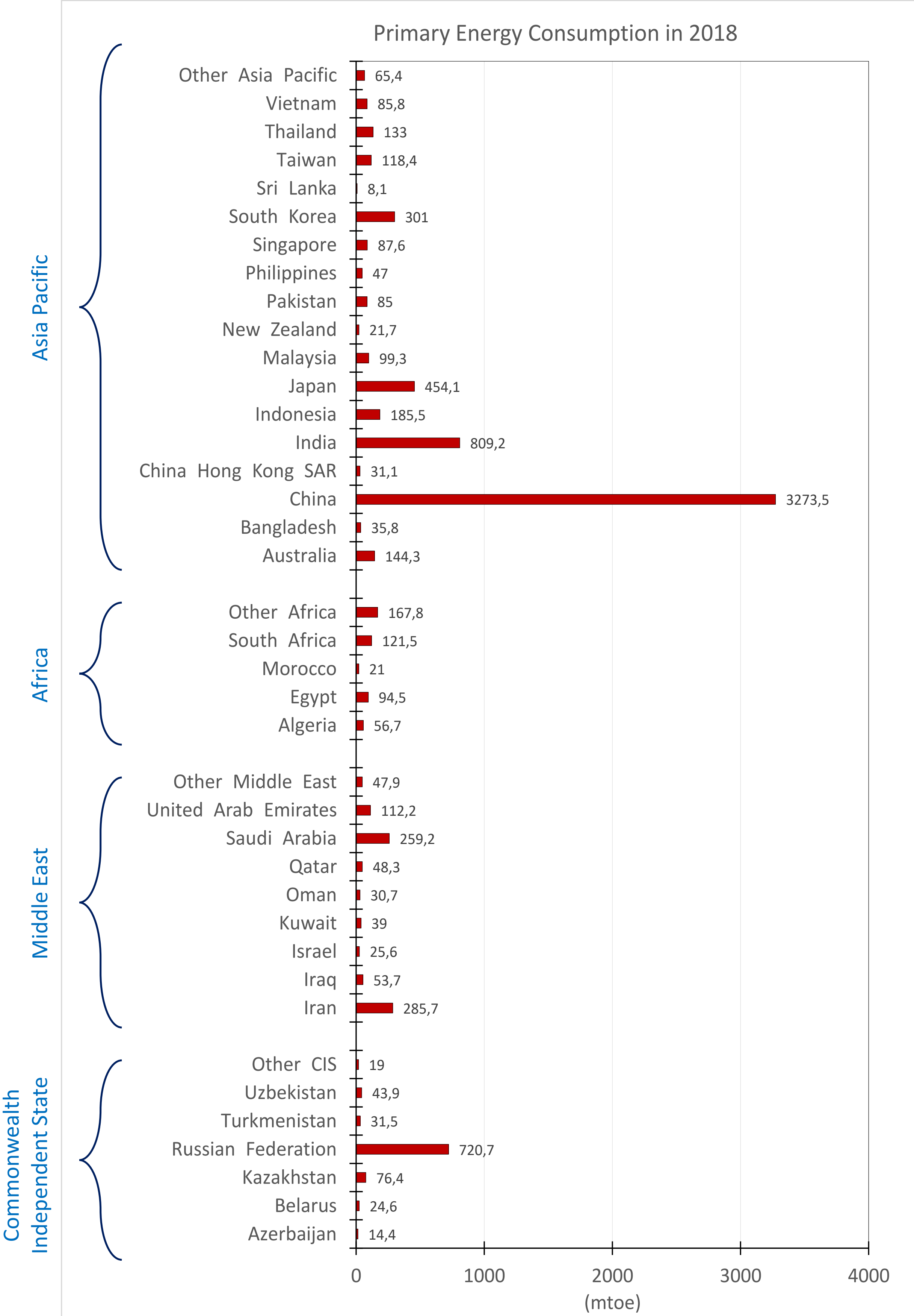


Figure 3.7. Primary Energy Consumption by Country, Part 2, units in Million tonnes of oil equivalent (mtoe) (Source: BP Statistical Review of World Energy 2019 & Appendix A)

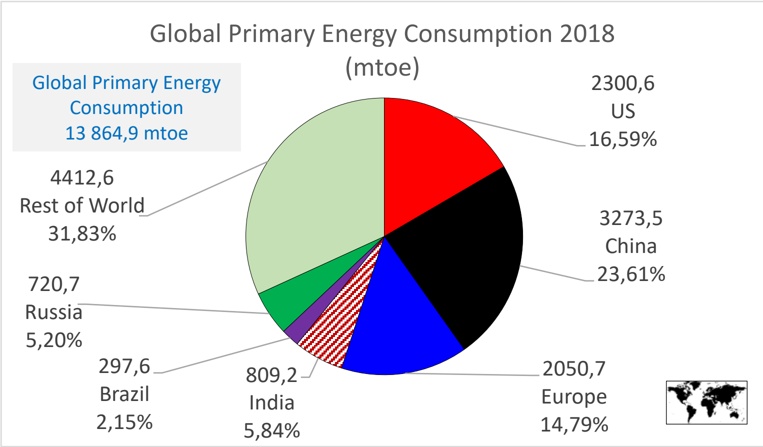


Figure 3.8. Global primary energy consumption in 2018
(Source: BP Statistical Review of World Energy 2019 & Appendix A) (World Map Image by Clker-Free-Vector-Images from Pixabay)

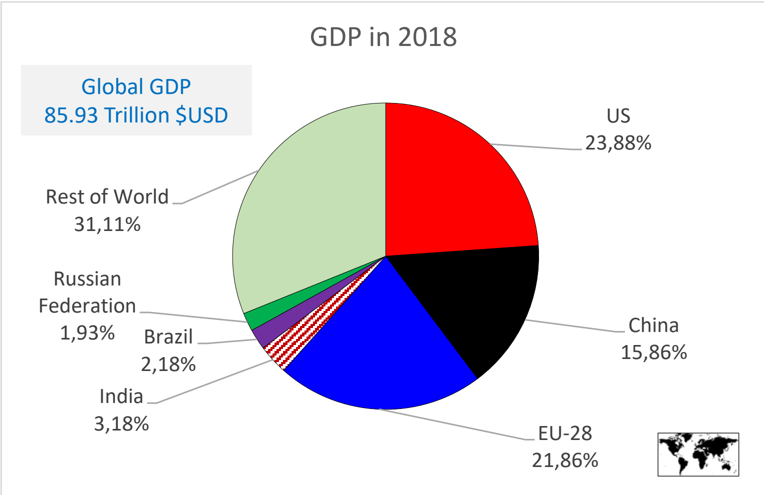


Figure 3.9. GDP in 2018, calculated in $USD 2018,
(Dollar figures for GDP are converted from domestic currencies using single year official exchange rates.)
(Source: World Bank national accounts data, and OECD National Accounts data files.)
(World Map Image by Clker-Free-Vector-Images from Pixabay)

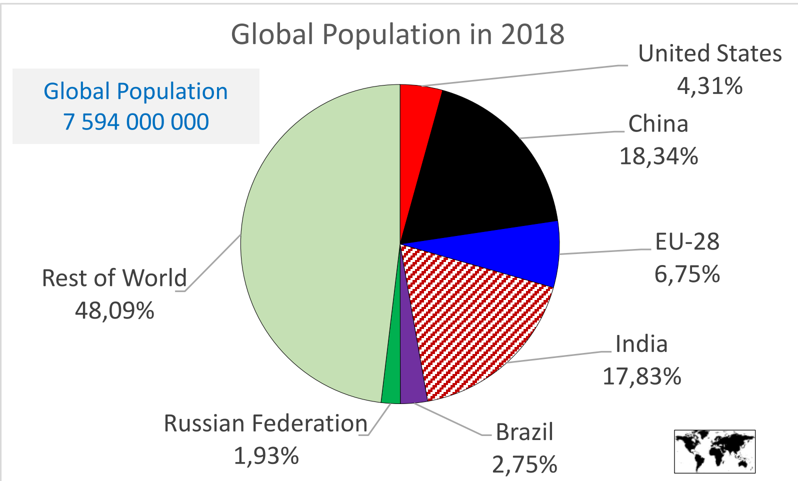


Figure 3.10. Global human population in 2018 (Source: World Bank Data)
(World Map Image by Clker-Free-Vector-Images from Pixabay)

Figure 3.8 shows the global energy market share for countries in 2018. The three main consumers are the United States, European Union and China, accounting for 54.99% of the global market. To illustrate the point that oil consumption is linked to GDP, compare the proportions shown in Figure 3.9 to Figure 3.10. Gross Domestic Product (GDP) is a monetary measure of the market value of all the final goods and services produced in a specific time period, usually annually. GDP at purchaser's prices is the sum of gross value added by all resident producers in the economy plus any product taxes and minus any subsidies not included in the value of the products. It is calculated without making deductions for depreciation of fabricated assets or for depletion and degradation of natural resources. Data are in 2018 U.S. dollars. Note that 3 major GDP market values are the same countries as the 3 major oil consumers.

Figures 3.6 and 3.7 show that a small number of nation states dominate the international energy consumption. These nations are China, United States, India, Russia, and Japan. The European Union EU-28 collectively consumed 2050.7 mtoe of energy in 2018, which if was placed on these charts, would make it the third largest consumer block behind China and the USA.

To put this in context, consider Figure 3.10, where human population proportions between those nations that dominate energy consumption and GDP are clearly different. Population growth is another fundamental driver to this current set of circumstances. Consumption is a function of the number of people who consume. An increase in production or an achieved efficiency has to be put in context of the population growth across that time frame. Population has grown in a manner that strongly correlates with the increase in energy consumption once all sources have been summed together (Bartlett 1994). Since the start of the industrial revolution, population has been empowered by technology coupled with increased energy density (coal vs biomass wood, followed by the introduction of oil).

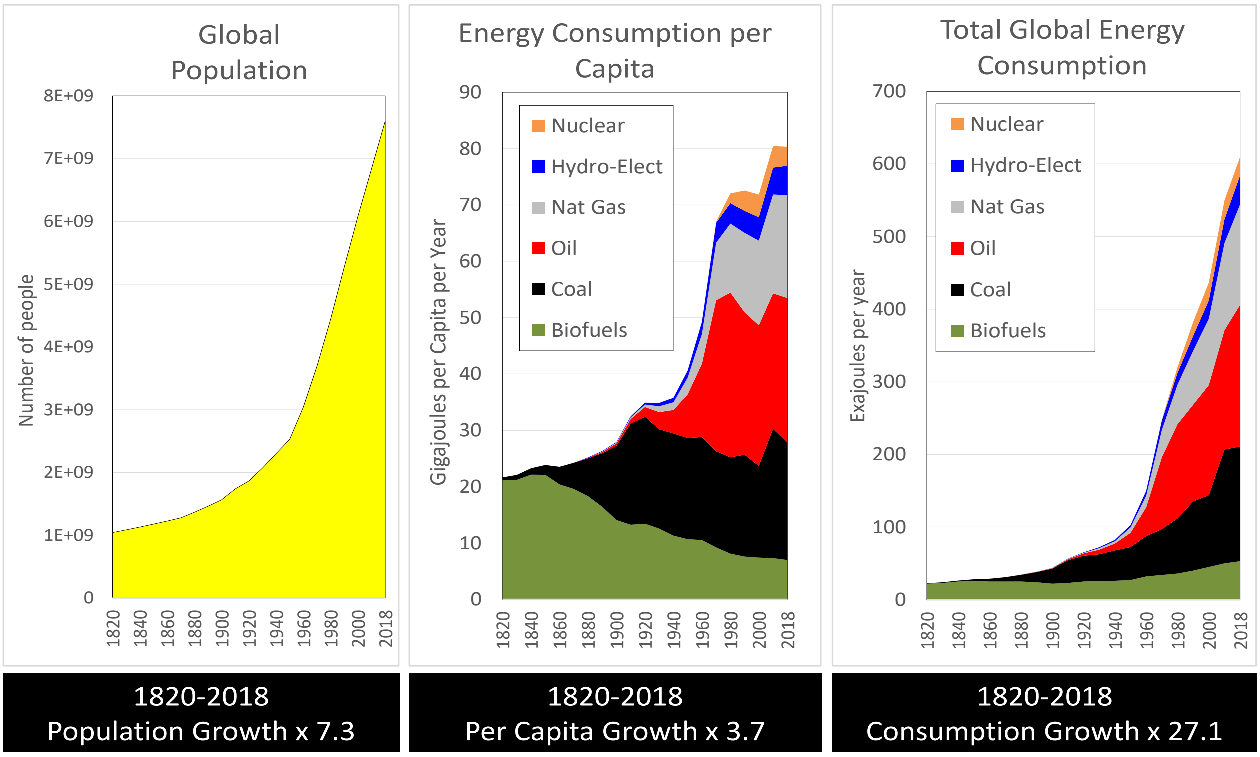


Figure 3.11. World population, per capita-, and total energy consumption, 1820-2018
(Source: Data from Tverberg, G. https://ourfiniteworld.com/, and BP Statistical Review of the World Energy 2019, US Census Bureau)

Note in Figure 3.11 how the middle chart has Per Capita Consumption for energy. This highlights how increasing complexity of technology has resulted in an increase per person in terms of energy requirements (the same can be shown for all natural resources). In summary, the energy requirements per capita have increased over time in line with technological development and complexity (middle chart in Figure 3.11). In conjunction to this, human population consuming and operating this technology is growing at an exponential rate. The RHS chart in Figure 3.11 shows that the combination of the two have resulted in a multiplication times 27.1, the demands on our energy resource sector. It can be observed that most of these charts showing fundamental support concepts like energy consumption or human population take the exponential mathematical form. It also can be observed that global energy systems are still sourced from finite non-renewable natural resources.

Figure 3.12 shows the Commodity Indices as collected by the World Bank and IMF (International Monetary Fund). Figure 3.12 shows the indices for food, crude oil, and metals. These three indices correlate well. They show a fundamental relationship between the three of them. It is postulated that the relationship is actually us, as in human society managing its needs and requirements through the movements of the industrial ecosystem.

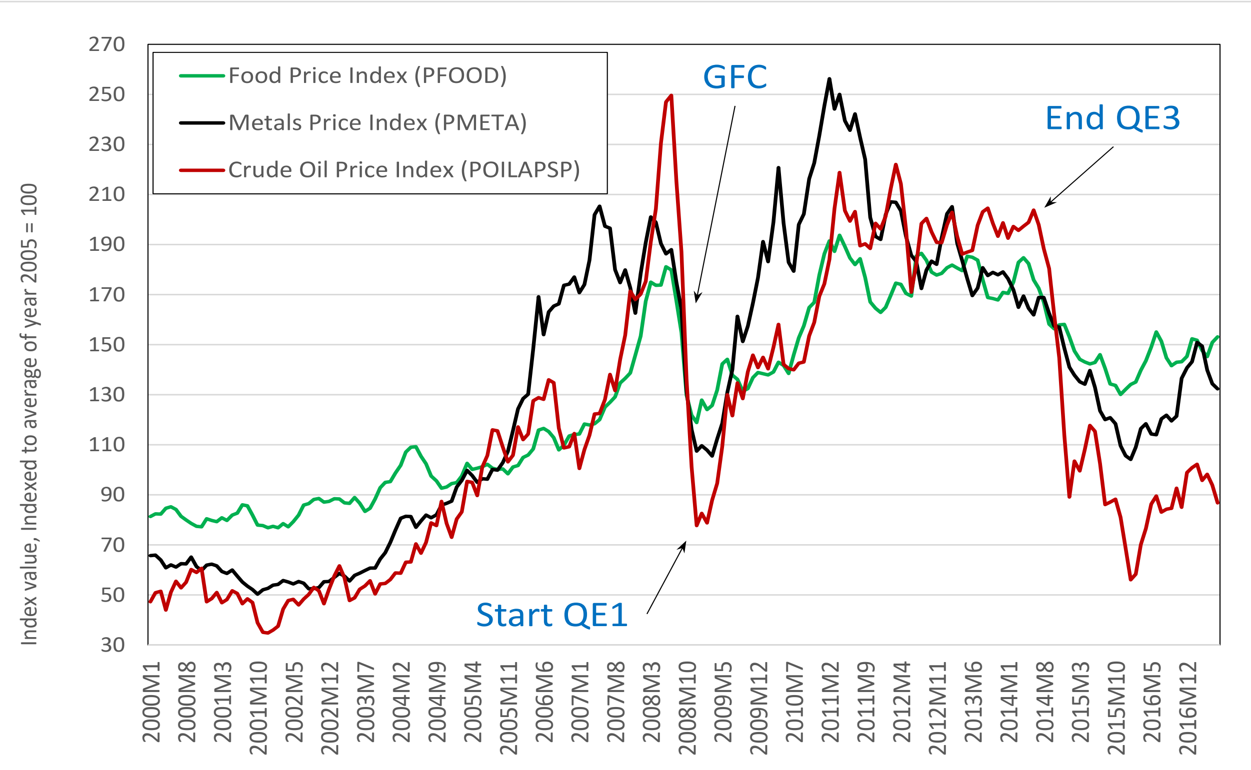


Figure 3.12. Correlation between global food price, metal price and crude oil
(Source: IMF Primary Commodity Price System, http://www.imf.org/external/np/res/commod/External_Data.xls)

GFC: Global Financial Crisis of 2008

QE1: Quantitative Easing Stage 1, the creation of $USD by the U.S. federal Reserve to mitigate the GFC

QE3: Quantitative Easing Stage 3

3.1 Energy, Industrialization, and the Goods Distribution System

The vast amount of products that are used in the homes of domestic consumers, and what is seen if one was to walk through a shopping mall, was delivered through the goods distribution system and was transported there on a truck (most probably a diesel fueled truck). Prior to delivery by a freight truck, 90 percent of those same/similar items were transported on a ship and/or a train. If trucks, trains, and ships (most of which run on fossil fuels) were to cease operation, the global economy and modern Western way of life would also cease (Friedemann 2016).

In the current 'just in time' supply grid, ships, trucks, and trains form the backbone of industrial civilization. Most of the truck transport fleet in the United States is powered by Diesel ICE (MDOT 2012). Their use of diesel combustion engines is engineered and optimized to burn petroleum-based diesel fuel. These engines and the fuels that fire them have been among the most transformative yet disruptive technologies on the planet in context of the beginning of the industrial revolution. Most of the consuming members of society around us take this for granted (Friedemann 2016).

Yet modern society have become absolutely dependent on its basic needs as serviced from this just in time supply grid (SARHC 2009). The supply grid operating 100 years ago was warehouse based, where as much as 6 months' supply of most requirements was stored in warehouses. Currently, the supply gird is so optimized that that there is only 2-9 days of capacity stored. In Australia, at any given time, there is in storage on a nation scale (Australian Dept. Environment and Energy 2019):

- 9 days of dry goods
- 7 days of chilled/frozen goods
- 3 days of hospital pharmacy supplies

The current economic paradigm is that any scarcity would lead to an increase in product price, resulting in more economic activity viable, which would address any shortage. This has been a successful model until now as energy has been abundantly available and classified as 'merely' a basic cost. This would continue to be successful if energy was infinite in supply, but for some time now, industrial energy has been mostly sourced from finite non-renewable resources.

Since oil reserves are finite (as are all fossil fuels), one day supplies will be diminished to where the cost of moving freight and goods with our present oil-fueled fleet will not be economically viable.

To demonstrate the concept that energy raw materials are connected to industrialization, global oil consumption is then examined in context of industrial output. Figure 3.13 shows the global steel production plotted against global oil consumption. There clearly is a correlation, but that correlation is interrupted by structural change as an external influence. The years 2009 to 2014 correlate in a consistent relationship, then there was a structural setback (possibly the end of the third round of Quantitative easing by the U.S. Federal bank QE3). The years 2016 to 2018 have a similar relation (similar gradient in Figure 3.13). This suggests that oil consumption can be used as a proxy for industrial activity when there is no global scale structural change (like the Global Finance Crisis).

What is interesting is that 71% of steel is produced using coal. Oil has no clear relationship to its production of steel or application of steel in industrial applications. Figure 3.14 shows global steel production to global coal consumption. Compared to Figure 3.13 (oil to steel), the relationship shown in Figure 3.14 (coal to steel) is not in the same form, while the same structural turning points can be seen. The oil to steel (Figure 3.13) relationship, with the exception of the 2015 anomaly (possibly related to the Chinese financial reset) and the 2008 GFC, would have been almost a straight line.

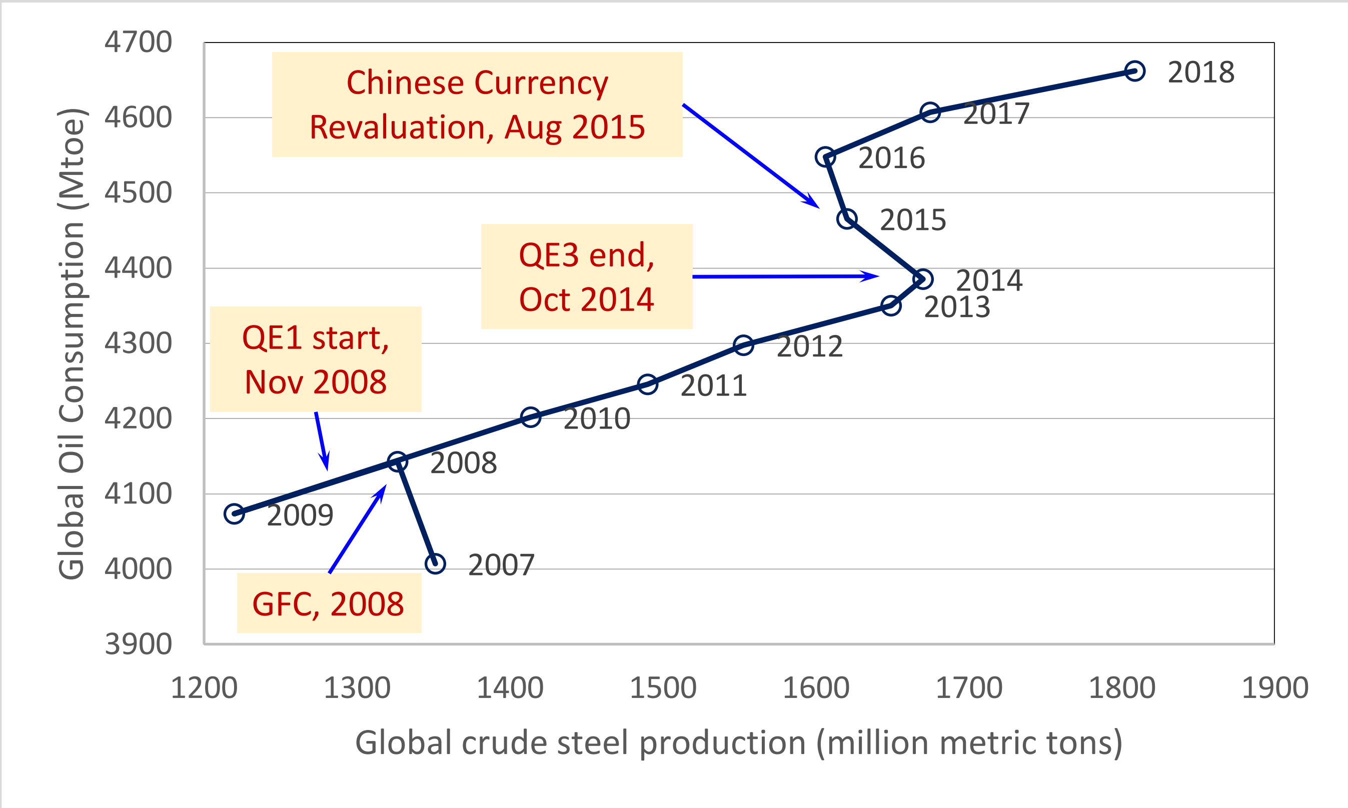


Figure 3.13. Global oil consumption compared to global steel production. (Source: BP Statistical Review of the World Energy 2019, BP Statistical Review of the World Energy 2011, World Steel Association)

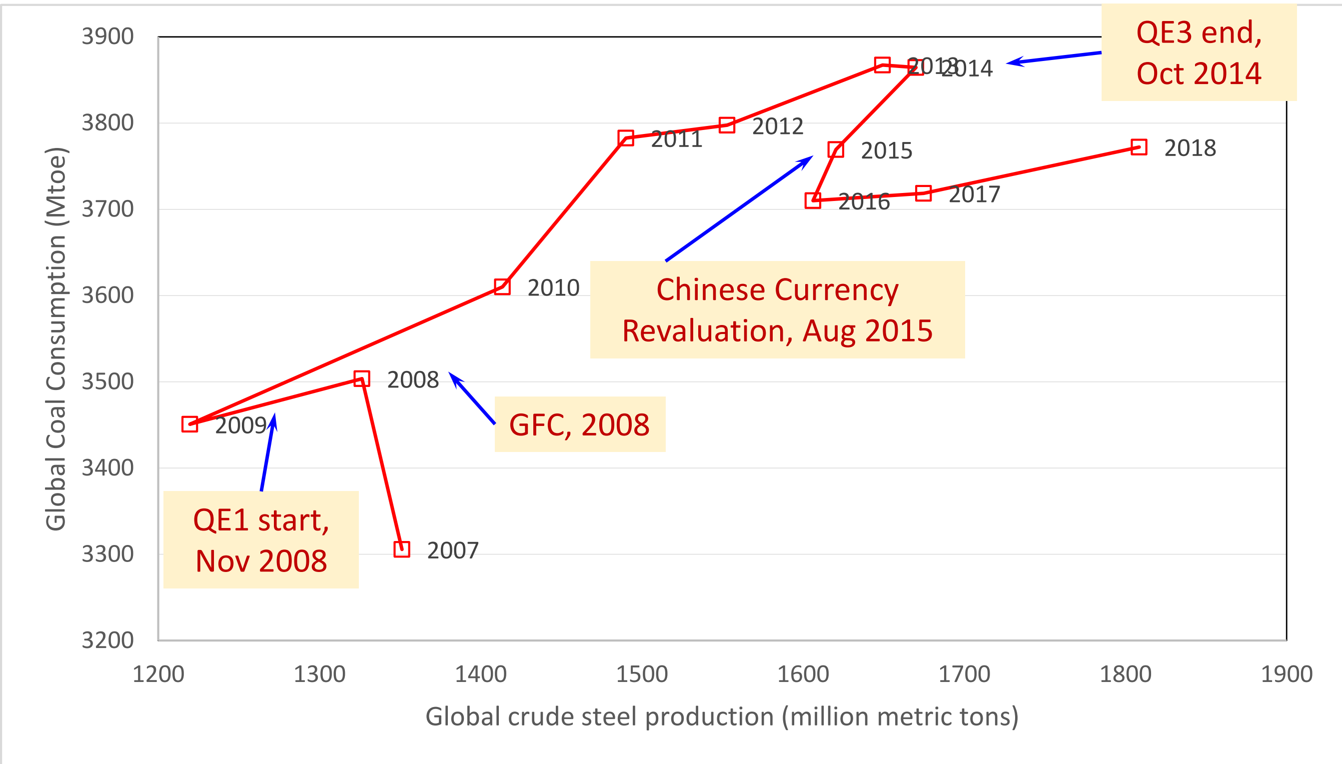


Figure 3.14. Global coal consumption compared to global steel production. (Source: BP Statistical Review of the World Energy 2019, BP Statistical Review of the World Energy 2011, World Steel Association)

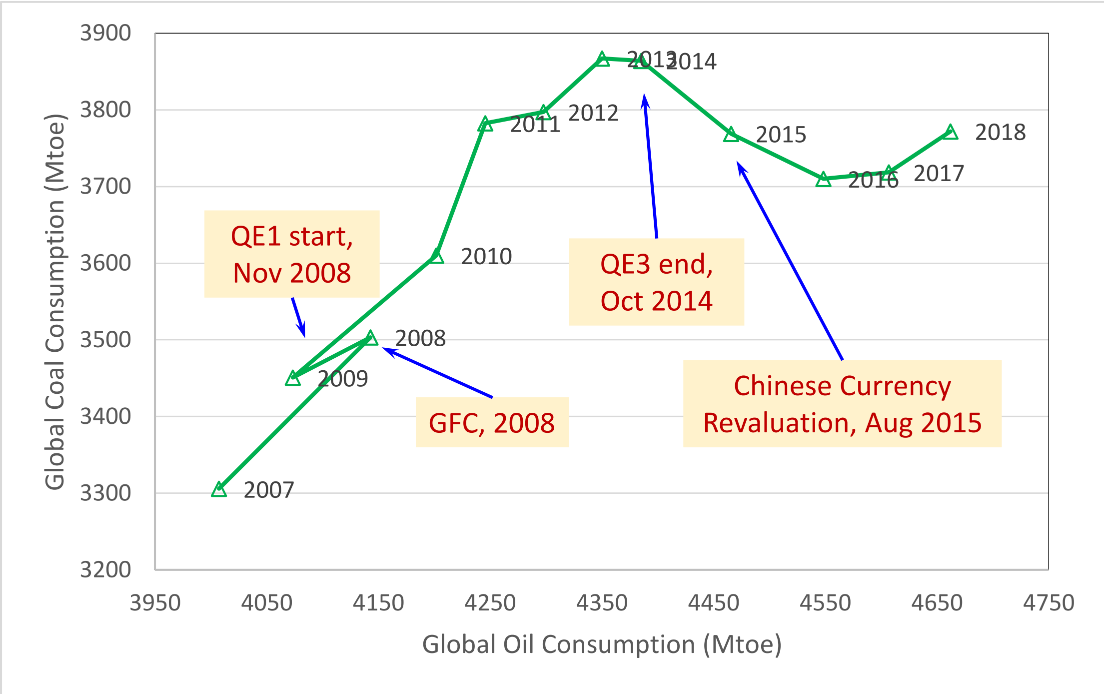


Figure 3.15. Global oil consumption compared to global coal consumption. (Source: BP Statistical Review of the World Energy 2019, BP Statistical Review of the World Energy 2011, World Steel Association)

3.2 China as a Proxy for the Global Industrial Ecosystem

China dominates not only the global manufacture of goods, but consumption of raw materials of all kinds. Figures 3.16 to 3.18 shows the industrial global market share of China. Figures 3.19 and 3.20 shows the link between the oil market and Chinese industrial output. Thus, oil can be linked to a proxy to the global industrial market.

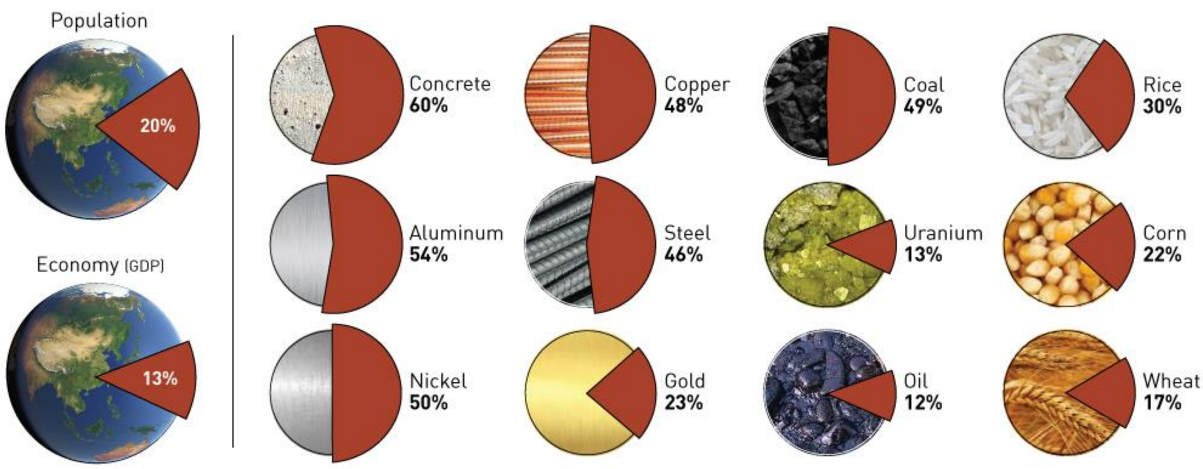


Figure 3.16. Chinese consumption of natural resources in 2015 as a fraction of global consumption (Source: visualcapitalist.com) (Copyright: https://www.visualcapitalist.com/frequently-asked-questions/)

Figure 3.16 shows the market share of global consumption of raw material resources. As can be seen China consumes enough raw materials and dominates enough heavy industry (steel and cement production are proxies for this) that Chinese industrial output could be considered as a proxy for the global industrial market.

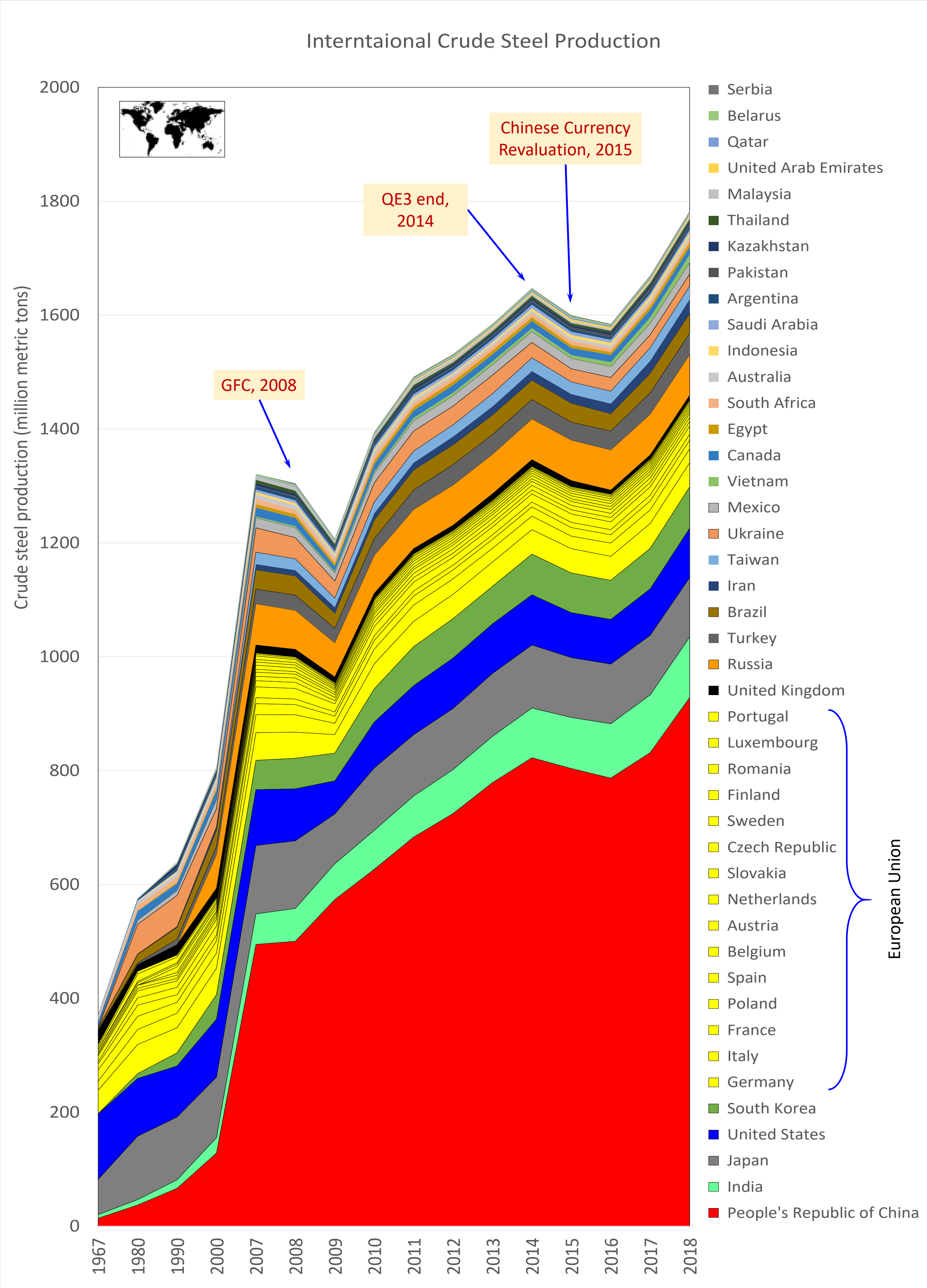


Figure 3.17. Crude steel production in 1967, 1980, 1990, 2000 and from 2007 to 2018.
All countries with annual production of crude steel at least 2 million metric tons are listed.
(Source: based on data provided from World Steel Association 2018) (World Map Image by Clker-Free-Vector-Images from Pixabay)

The production of steel is a useful proxy for industrial activity (as is cement production). The combination of steel and cement (concrete) forms the basic foundation or structure of most industrial actions. Figure 3.17 shows the international production of steel by country.

At the end of World War II, the global industrial capacity was distributed across all continents. In the 1950's, the United States, United Kingdom, parts of Europe and Australia had industrial and manufacturing capability. Mining of minerals had (still has) a different distribution than refining, smelting, and manufacturing. Now, industrialization and large scale heavy industry manufacture is dominated by just one nation state: China. In the 1970's and 1980's, many industrial operations across the western world, shut down operations and moved to South East Asia (China in particular), where the cost of production was much cheaper. In 2018, China accounted for 48% of global crude steel production. This makes China a useful proxy for the global industrial market.

The purpose of this section is to examine the nature of the industrial ecosystem in context of its structure. The industrial ecosystem is no longer homogenously distributed across the planet. China now dominates industrial activity. This is relevant in context of understanding what the energy requirements of the industrial ecosystem are. The energy consumption of China has a different profile and purpose that the energy consumption of Europe (EU-28). This will diagnose the form and applications for any non-fossil fuel energy system in replacement.

Figure 3.18 shows the supply from the global market to the European Union for Critical Raw Materials. As can be observed, China is by far the largest provider in the global market. Figure 3.19 and 3.20 shows the correlation relationship between the change in Chinese industrial output (Year on Year % change) and a change in Brent oil price on the international market (Year on Year % change).

Industrial activity represents real physical work, and the YOY % (% change at the month date, Year Over Year) Industrial output is a measured index of physical work done and goods manufactured by Chinese heavy industry. China dominates the industrial activity in the global market, controlling the majority of mining, refining recycling and manufacture (Wübbeke *et al* 2016). This means that a change in Chinese industrial activity is a useful proxy for global industrial activity. Energy is the ability to do work, and the YOY % change in the price of oil is a proxy for the stability of the energy system. A correlation between the two strongly in conjunction with the Chinese market share of global industry (See Figures 14, 15 and 16) supports the concept that Chinese industrial output can be used as a proxy for global industrial activity.

As can be observed these is a correlation. It can also be noted in Figures 3.19 and 3.20 that there are three different time periods that have different signatures. The correlation between Chinese industrial output and oil price seems to become strong enough to be recognized sometime in the early 2000's. Chinese industrial output started to become a global major provider in approximately the year 2000.

During the crash of 2008 (Global Financial Crisis), there is a strong correlation as both indices dip sharply followed by temporary recovery (this signature is the most prominent in the whole data set from 1991 to 2018), followed by a steady decrease. Prior to the GFC crash in 2008, there is a second time period where the two indexes correlate (but not as strongly). The relation between the two proxies is clearly involving multiple parameters. After the GFC is a third time period were the two indexes do not correlate at all. The change in Chinese industrial output decreases steadily, where the change in oil price does not. This is another signature of the contraction of the real economy.

On August 11, 2015, the People's Bank of China (PBOC) conducted three consecutive devaluations of the yuan renminbi or yuan (CNY), removing over 3% off its value. Between 2005 and 2015, China's currency had appreciated 33% against the U.S. dollar, and the first devaluation marked the most significant single drop in 20 years (Investopedia 2019).

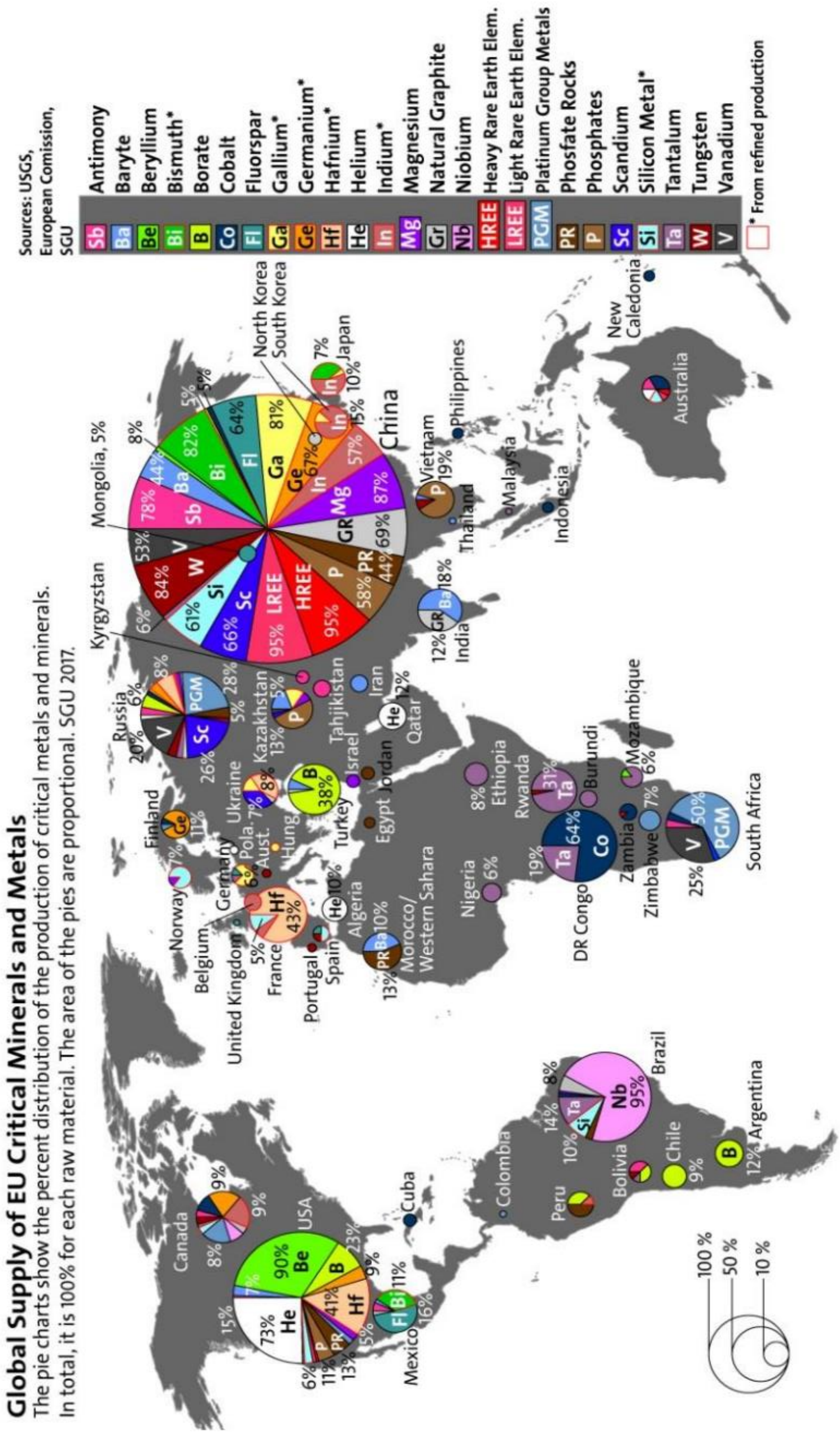


Figure 3.18. Global supply of European Union Critical Minerals and Metals (Source: SGU 2016)

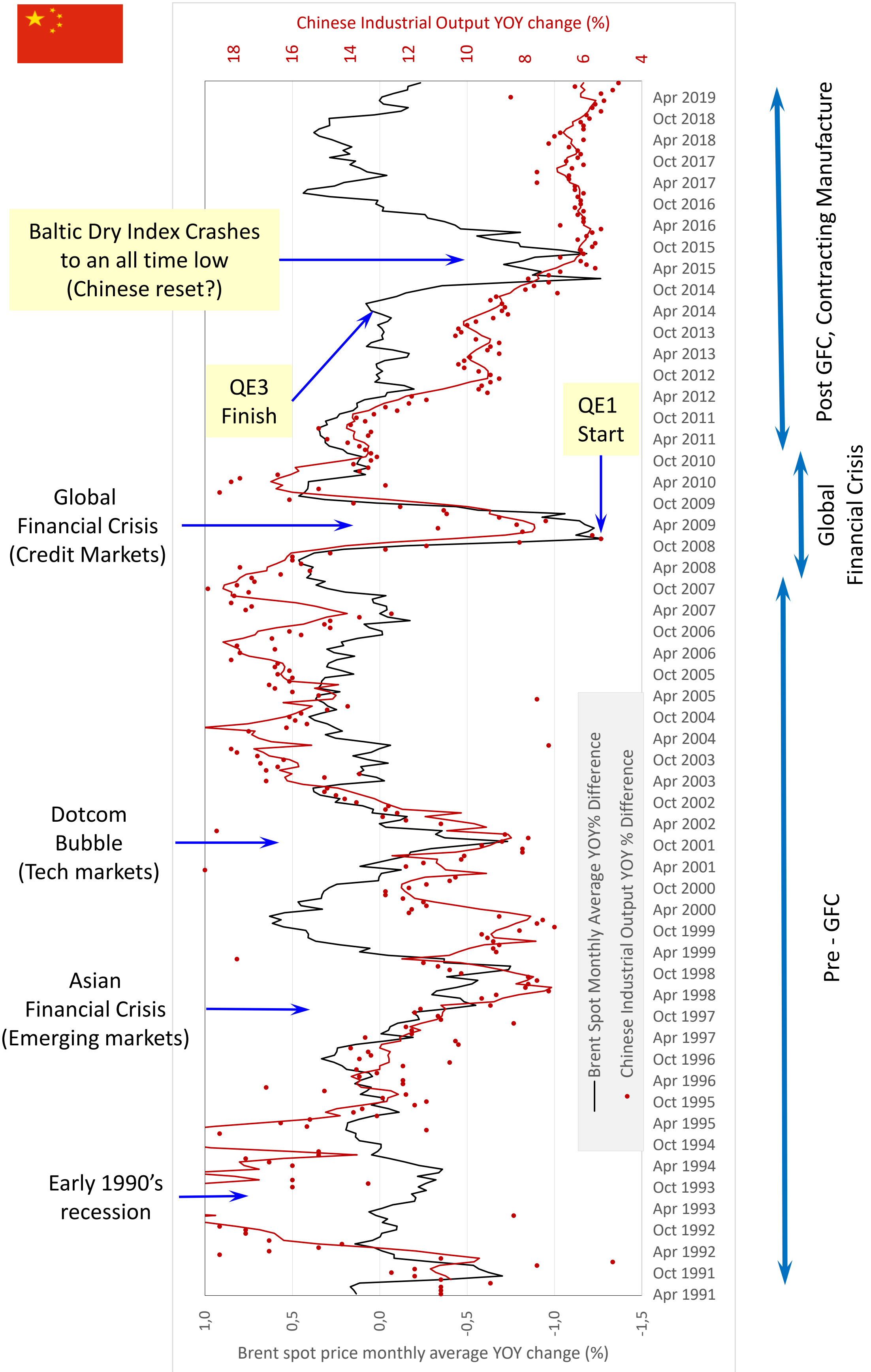


Figure 3.19. Chinese Industrial output and the price of oil, 1991 - 2018
(Source: National Bureau of Statistics of China,
Nasdaq Stock Exchange, https://www.nasdaq.com/markets/crude-oil-brent.aspx)

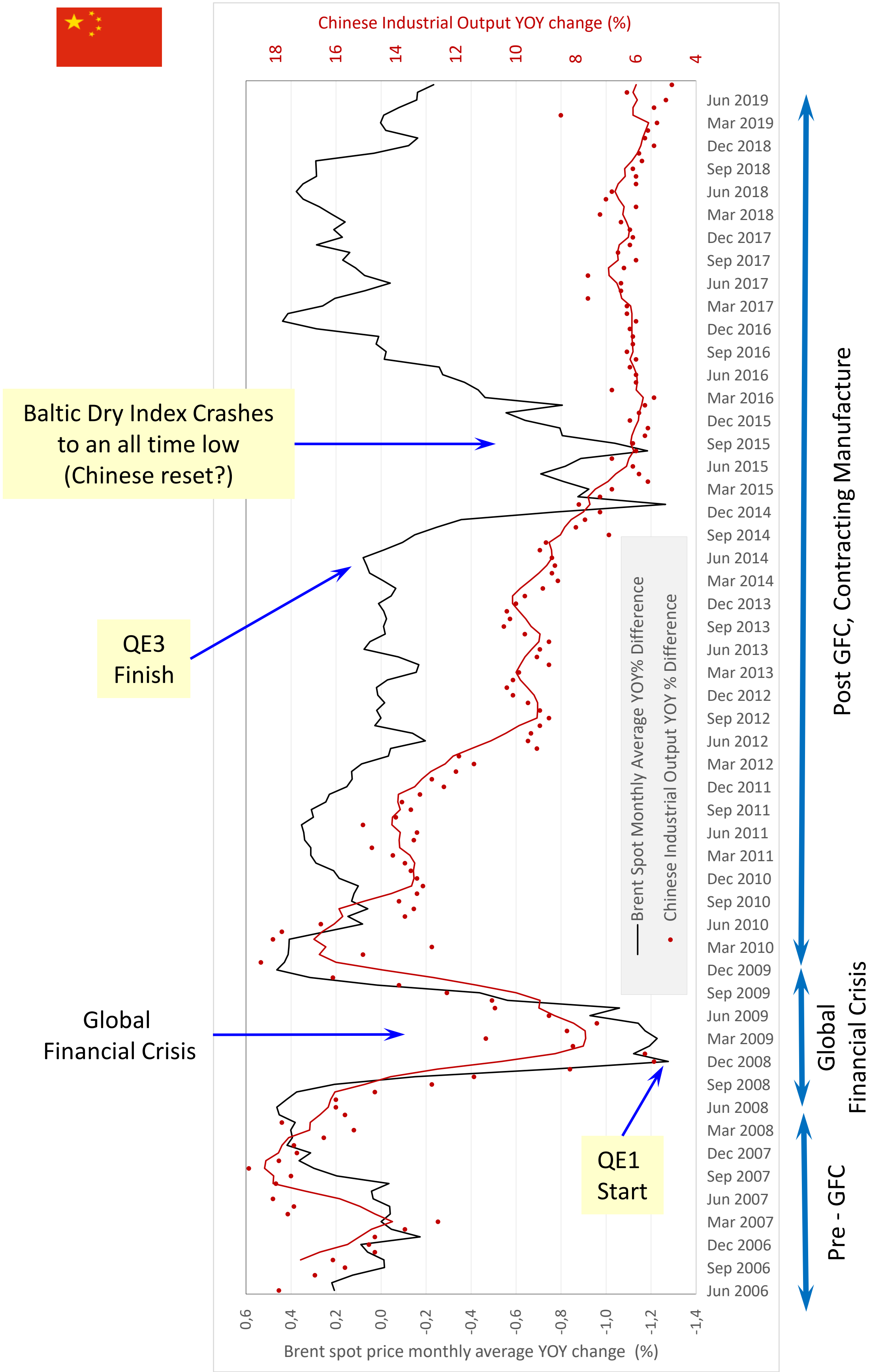


Figure 3.20. Chinese Industrial output and the price of oil, 2006 - 2018
(Source: National Bureau of Statistics of China,
Nasdaq Stock Exchange, https://www.nasdaq.com/markets/crude-oil-brent.aspx)

This is significant as in Figures 3.19 and 3.20, there is a crash in the YOY % change in the average monthly Brent oil spot price in 2015. This crash is of similar size to the Global Financial Crisis (GFC). At a similar time, the industrial Baltic Dry Index (The Baltic Dry Index measures how much it costs to ship "dry" commodities around the world — raw materials like grain and steel) crashed to an all-time low of value of 291 on February 12th, 2016 (Bloomberg BDIY Quote 2019). So Chinese industrial output, the price of oil, and the global maritime trade of dry goods all had a signature in 2015 as significant as the GFC in 2008. This happened just as the U.S. Federal Reserve 3rd Quantitative Easing program (QE3) ended. The Baltic Dry Index has been used as a leading indicator for an economic slowdown (Martin 2016).

This suggests a structural move happened in the global economy in 2015 that significantly affected the real economy (the production of physical goods and services as opposed to financial products like derivatives).

After 2015, Chinese industrial output YOY % change was relatively stable at approximately 6%, while oil price rose significantly, and the two measurements no longer correlate. The world after 2008 is now dependent on Quantitative Easing (Michaux 2019). Also, since 2008, China has been taking action to decouple from the Western World (Michaux 2019).

3.3 The Correlation between Oil Price and Geopolitical Events

In addition to the correlation between industrial output and oil production (energy), there is also a correlation between oil price and geopolitical events. Table 3.1 and Figures 3.21 to 3.22 show the price of oil over a range of time periods. On each chart against the observed market price of oil are notable geopolitical events, market crashes and supply restrictions applied by the OPEC cartel.

Currently, our society, technology, industry, and economy are all supported by and dependent on oil in some form (as shown in Figures 3.13 to 3.20). This high quality energy source became so abundant and inexpensive, that it became the supporting energy source for all aspects of the industrial system in the 1900 to 1970 period of time. While it can be proposed that it is not so cheap and abundant anymore, the modern world certainly does require it to function. Substitution with another energy source will require a high ERoEI, abundant in supply and an inexpensive cost of production.

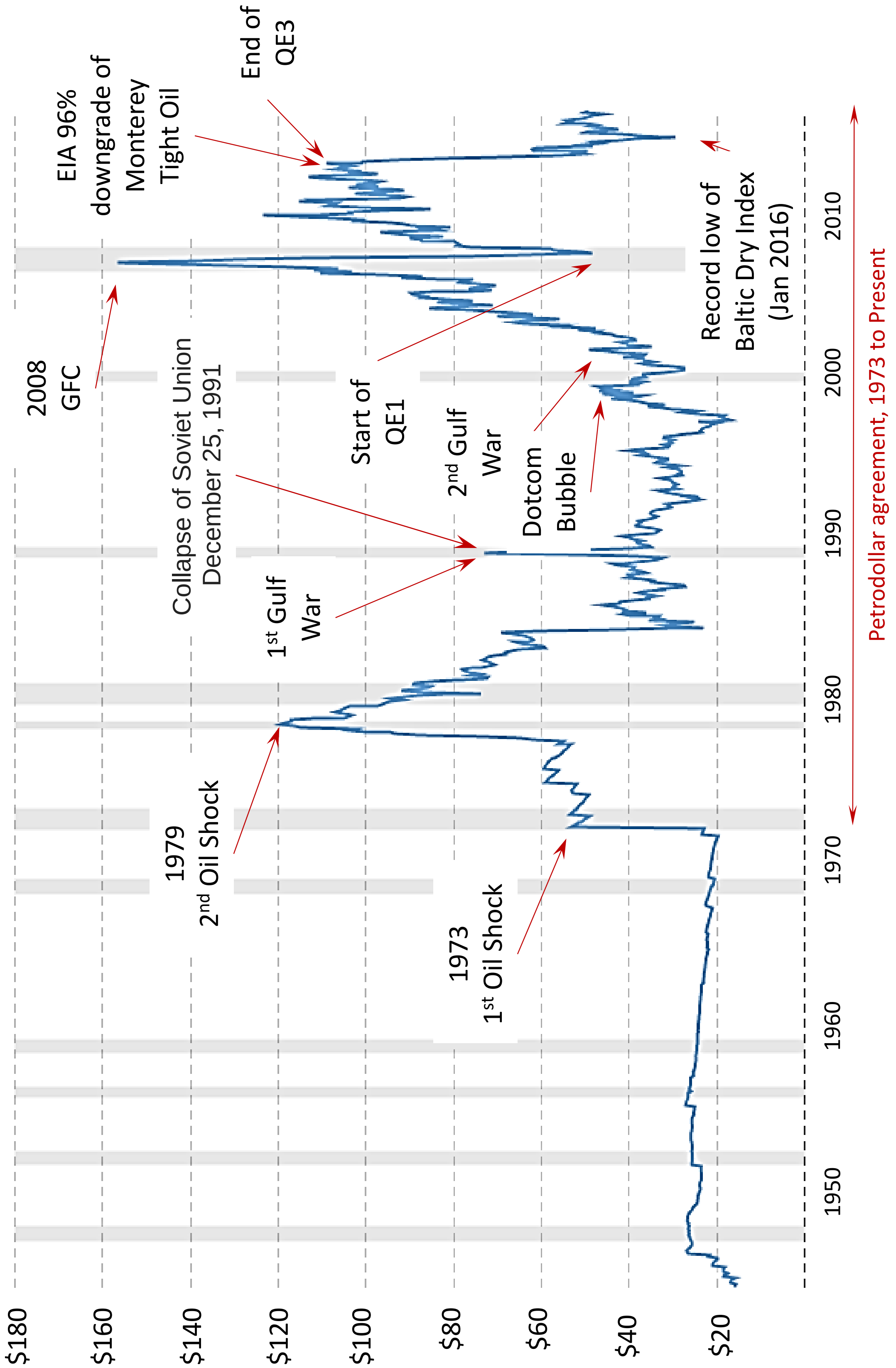


Figure 3.21. Crude Oil Prices - 70 Year Historical Chart 1946 - 2017
(Source: Data from Interactive charts of West Texas Intermediate (WTI or NYMEX) crude oil prices per barrel back to 1946. The price of oil shown is adjusted for inflation using the headline CPI and is shown by default on a logarithmic scale. The current price of WTI crude oil as of August 03, 2017 is $49.20 per barrel.)

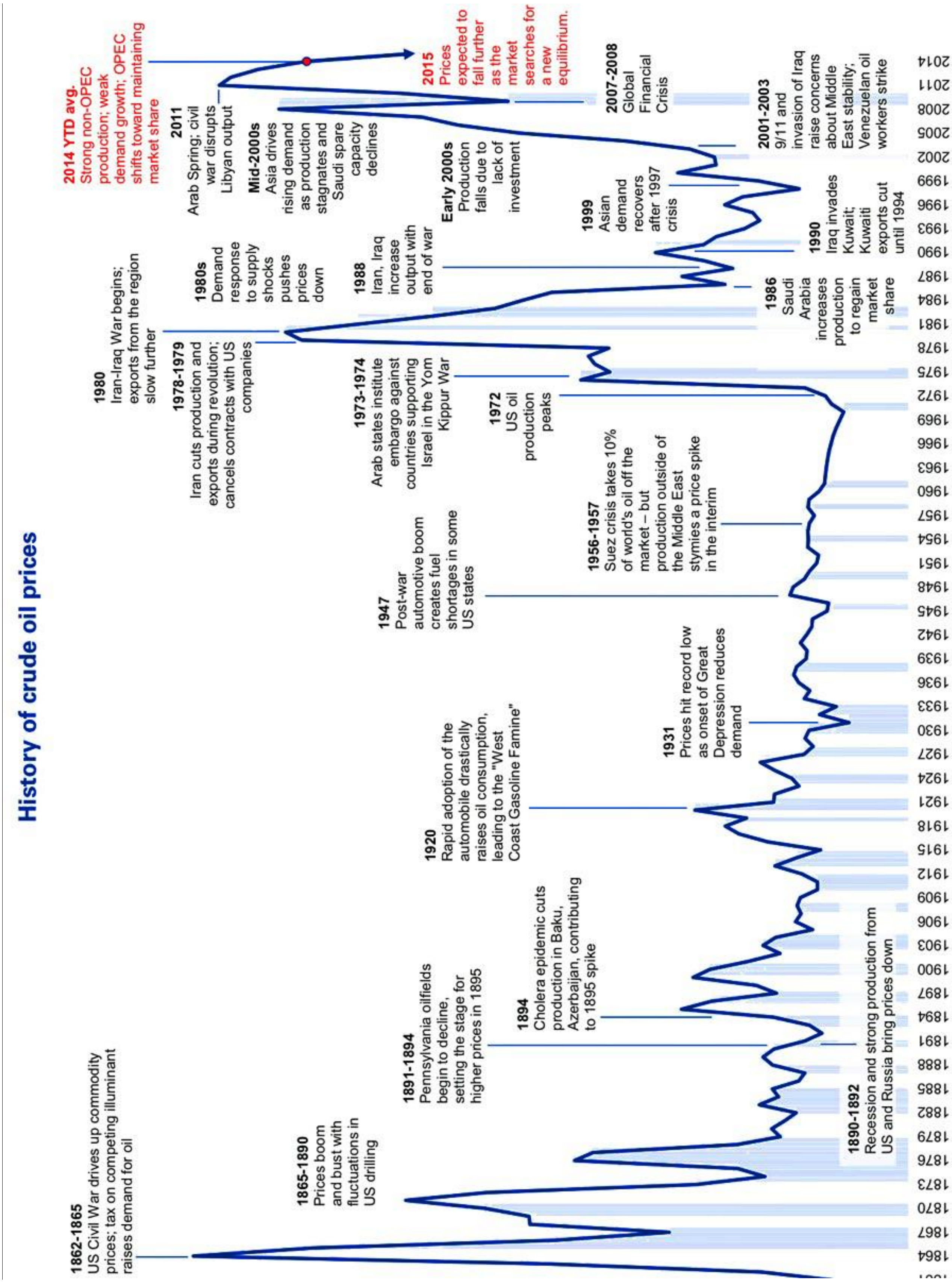


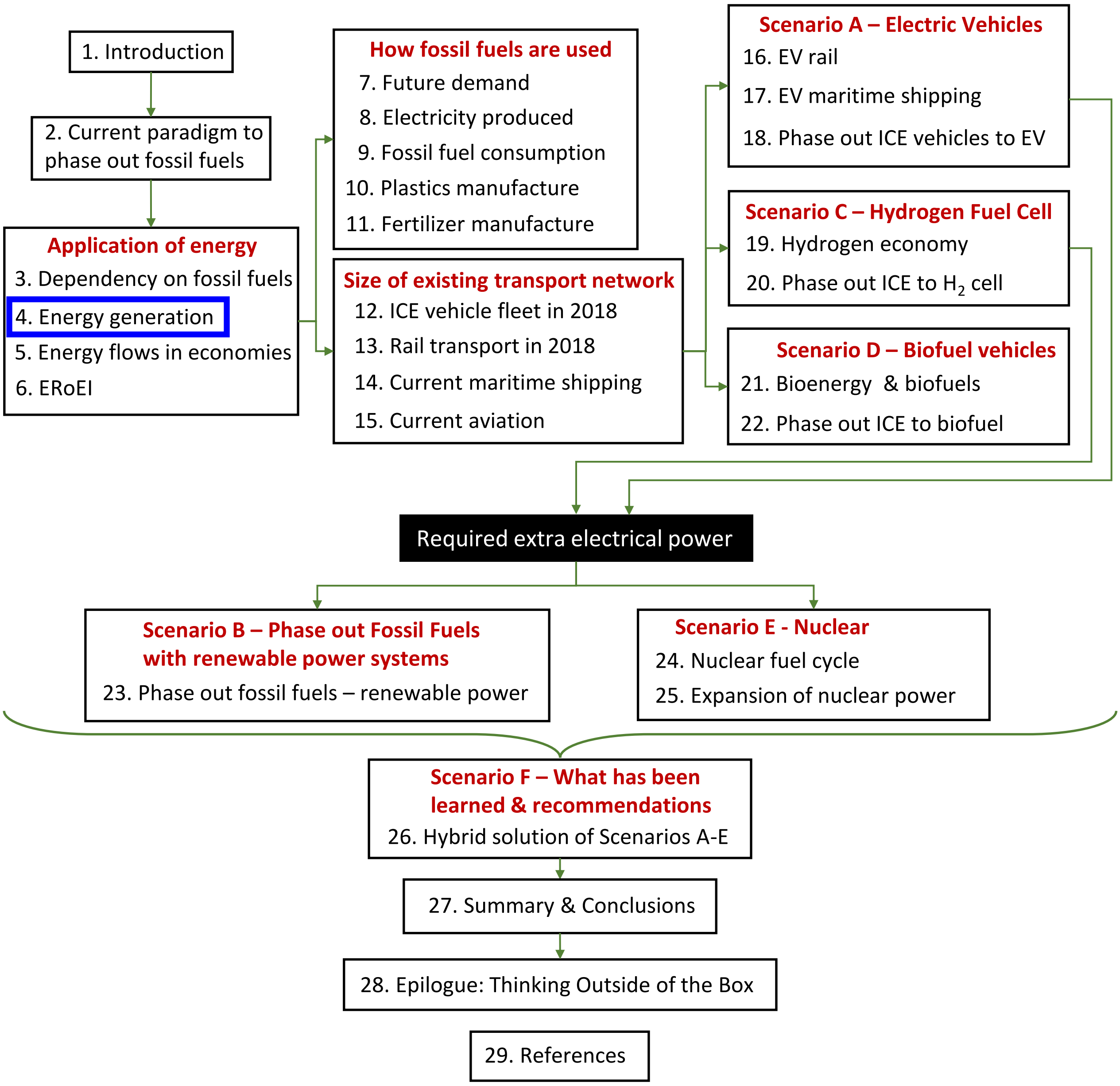
Figure 3.22. Oil market price (West Texas Intermediate WTI or NYMEX) in context geopolitical events, 1863 to 2014 (Source: data from Business Insider, BP Statistics, Goldman Sachs Global Investment Research, Money Morning Staff Research)

Table 3.1. Insights on the causes of key oil-economy events from different research communities (Source: Kallis et al 2016)

Event	Oil economics	Macro economics	Political economy	Ecological economics
Oil and economic crises 1973 & 1979	Growth and rising demand from developed economies (Kilian) vs. supply interruptions from events in Middle East (Hamilton).	Wrong policy response by the Fed which fearing inflation by oil prices precipitated recession by raising interest rates (Bernanke et al). US inflation and depreciation of the dollar to which OPEC responded by restricting production (Frankel).	End of Bretton Woods, US unable to finance Vietnam war un-pegged from gold and became a global importer of surpluses, "recycling" petrodollars (Varoufakis, Spiro). U.S. supported higher prices given dollar devaluation to back up Shah's regime in Iran (Anderson, Engler).	Resource limits to growth.
Low oil prices – low growth 1985–89	Tax reform and low investment in US oil industry (Edelstein & Kilian).	–	U.S. worked with Saudis to increase oil production and damage Soviet Union (Gaidar, Schweizer)	Prices did not reflect real scarcity of oil. (No explanation about low growth)
High oil prices – high growth 2002–2007	Effect of oil prices on expenditures is cumulative and until 2007 hadn't passed the threshold where households change consumption patterns, hence no effect on growth (Hamilton). Prices increased because of economic growth and industrial demand from Asia, which more than compensated for negative effects of high oil prices – the effects of a demand-driven rise of oil price take time to show (Kilian).	Independent monetary authorities responding to core inflation did not repeat mistakes of the 1970s (Blanchard & Gali, Nordhaus). Growth in oil-producing countries and in countries exporting to them overcompensated for negative effects from high oil prices (Rasmusen & Roitman). Asian savings and petrodollars flooding US, pushing interest rates down, keeping growth high and creating housing and commodity asset bubbles (Caballero et al)	Strategic underinvestment by major producers in order to maintain high prices (Smith). Petrodollars channeled from US consumers and developing countries to oil producing nations, and from them back to US Treasury and global banks and corporations (Spiro, Sager).	Resource limitations – major producers could not increase production even if they wanted Over-borrowing and credit/housing bubbles sustained household consumption and growth despite rising oil prices (Martinez-Alier)
Oil shock 2008 – Financial crisis	Rising demand from the East facing. stagnating oil production (Kilian, Hamilton). Reduced expenditures, esp. for cars and houses, from US households tilting economy to recession (Hamilton). Foreclosures in suburbs facing high commuting costs (Cortright, Kaufman et al).	With the subprime mortgage and housing bubble broken, Asian savings and petrodollars shifted to oil. Oil prices appreciated, while the economy collapsed because of the collapse of the housing bubble (Caballero et al).		Peak oil increased oil prices to unsustainable levels causing recession, which in turn led to the collapse of the credit/housing bubbles. (Daly, Martinez-Alier)
Slump of oil prices 2014c, limited recovery	Expectations for a growth slow-down and to a lesser extent higher global oil production (Baumeister & Kilian).	Negative economic effect from low oil prices on domestic US (shale) oil industry (Krugman). Expectations for tightened US interest rates in the near future (Frankel). Appreciation of the dollar (Tokic).	Saudi Arabia increasing production to drive US competitors out of the market.	Low EROI of the new supplies of unconventional oil? (Kerschner and Capellán-Pérez)

4 DIFFERENT KINDS OF ENERGY, HOW THEY ARE GENERATED AND APPLIED

Section 4 will examine the different methods energy generation and how they function. Each method of electricity generation will be examined (coal. How internal combustion engine technology (ICE) functions, and how an electric motor works will also be discussed.



Assessment of the Extra Capacity Required of Alternative Energy Electrical Power Systems to Completely Replace Fossil Fuels

Not all energy systems are equal (Smil 2016a). Each one of them performs different tasks. The purpose of this report is to examine what fossil fuels currently do to support the existing industrial system and what might be required to phase them out. Later in this report, different energy systems are compared, and substitutions are considered. It is appropriate to discuss the difference between the energy resources, what energy really is and how it is generated, and to examine which energy systems are used for transport and which are used for industrial power supply. Also, the heating of buildings needs to be considered as a separate task.

4.1 The Fundamentals of Energy in Industrial Context

Any movement of solid matter in the physical world will also have an energy component. In each action, there would also be a number of different components of energy acting in different ways. For example, a fire burning will have components of heat, light, and sound. The fuel burning (in this case wood) would contain chemical energy stored in it, which is released as it burns. Figure 4.1 shows a simplistic list of the different forms of energy.

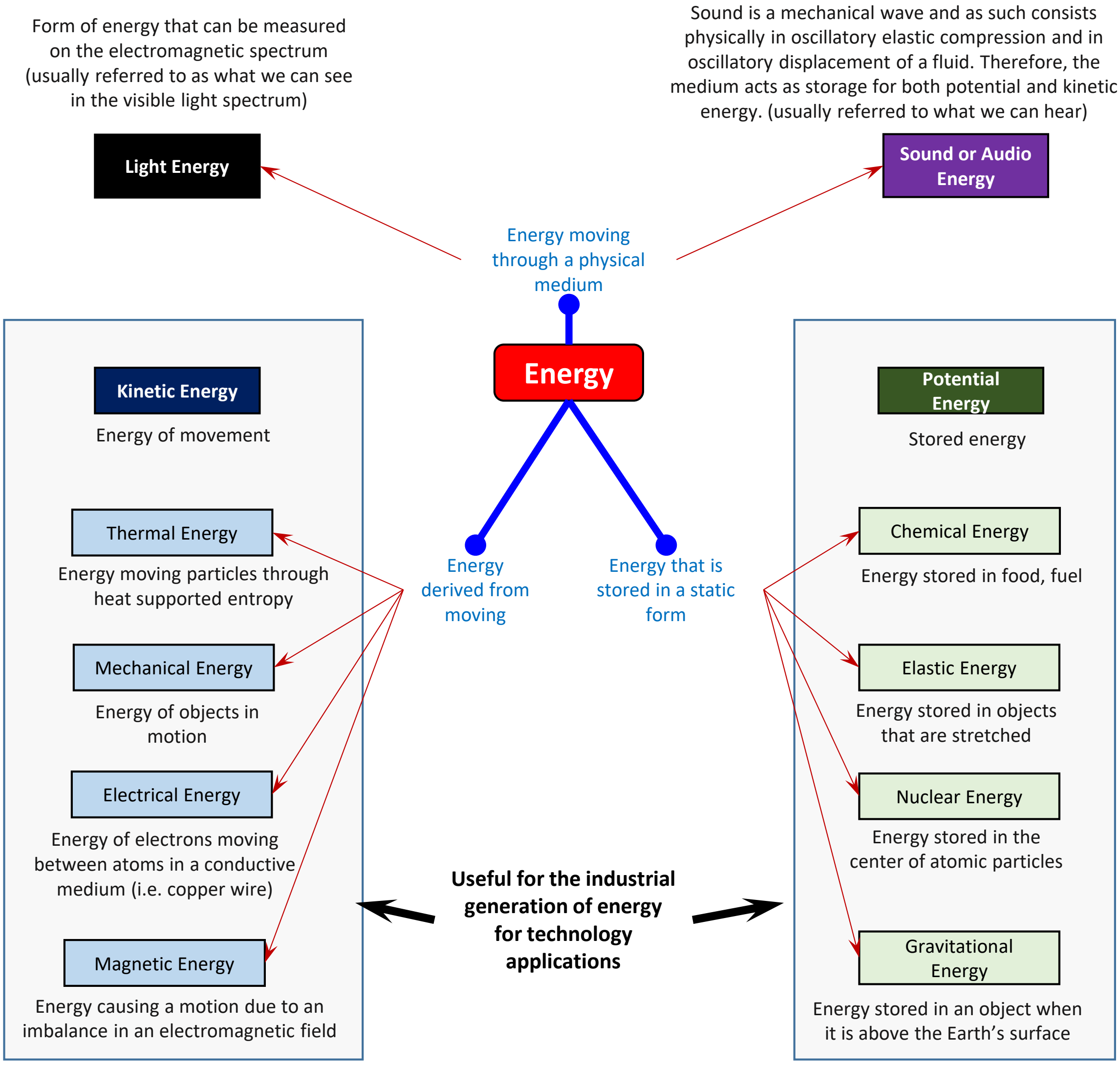


Figure 4.1. The different forms of energy
(Developed from Serway & Jewett 2013)

The current industrial ecosystem is supported with fossil fuel sourced energy generation systems. From a chemical standpoint, Fossil fuels are mostly carbon (C) and hydrogen (H).

- Petroleum is 84 % Carbon and 12 % Hydrogen
- Natural gas is 20 % Carbon and 80 % Hydrogen
- Coal is 84 % Carbon and 5 % Hydrogen

4.2 Energy Generation

Energy generation for industrial purposes has to have a high enough ERoEI to be useful as an energy source. Also, an energy form would have to be exploited in a fit for purpose fashion to perform a task of useful physical work. An energy source like coal for example, is not useful in its natural state. It is required to be converted into some form of useable energy, which is then in turn used for a purpose (Figure 4.2). For example, a furnace fueled with coal (containing chemical energy stored in a static form) is transformed through operation of the furnace, which outputs heat (thermal energy) which can be applied to do physical work (Figure 4.3).

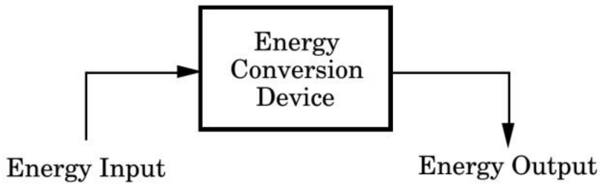


Figure 4.2. An energy conversion device to do physical work

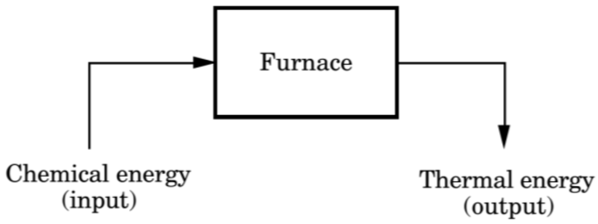


Figure 4.3. A furnace energy conversion unit schematic

Table 4.1 shows examples of energy conversion devices and what they output. Table 4.2 shows the relative efficiencies of these conversion devices. Each of these devices have been engineered to perform a specific task. This has to be quantified if energy sources are to be understood.

Table 4.1. Tasks performed by energy conversion devices (Source: Moran *et al* 2014)

Energy Conversion Device	Energy Input	Useful Energy Output
Electric heater	Electricity	Thermal energy
Hair drier	Electricity	Thermal energy
Electric generator	Mechanical energy	Electricity
Electric motor	Electricity	Mechanical energy
Battery	Chemical energy	Electricity
Steam boiler	Chemical energy	Thermal energy
Furnace	Chemical energy	Thermal energy
Steam turbine	Thermal energy	Mechanical energy
Gas turbine	Chemical energy	Mechanical energy
Automobile engine	Chemical energy	Mechanical energy
Fluorescent lamp	Electricity	Light
Silicon solar cell	Solar energy	Electricity
Steam locomotive	Chemical	Mechanical
Incandescent lamp	Electricity	Light

Table 4.2. Efficiencies of common energy conversion devices (Source: Moran *et al* 2014)

Energy Conversion Device	Energy Conversion	Typical Efficiency, %
Electric heater	Electricity/Thermal	100
Hair drier	Electricity/Thermal	100
Electric generator	Mechanical/Electricity	95
Electric motor (large)	Electricity/Mechanical	90
Battery	Chemical/Electricity	90
Steam boiler (power plant)	Chemical/Thermal	85
Home gas furnace	Chemical/Thermal	85
Home oil furnace	Chemical/Thermal	65
Electric motor (small)	Electricity/Mechanical	65
Home coal furnace	Chemical/Thermal	55
Steam turbine	Thermal/Mechanical	45
Gas turbine (aircraft)	Chemical/Mechanical	35
Gas turbine (industrial)	Chemical/Mechanical	30
Automobile engine	Chemical/Mechanical	25
Fluorescent lamp	Electricity/Light	20
Silicon solar cell	Solar/Electricity	15
Steam locomotive	Chemical/Mechanical	10
Incandescent lamp	Electricity/Light	5

Tables 4.1 and 4.2 show energy conversion devices in application to perform physical work. Figure 4.4 shows the energy conversion steps of an electric power plant that uses a fuel to heat steam, to turn a turbine and generate electric (Figure 4.5).

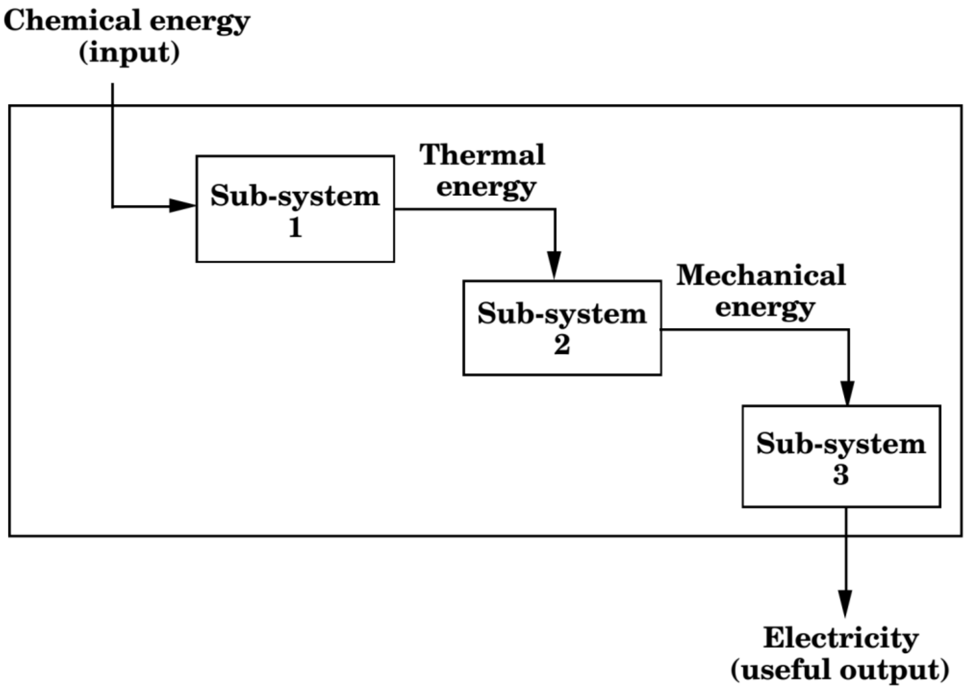


Figure 4.4. Energy conversion in an electric power plant
(Source: Moran *et al* 2014)

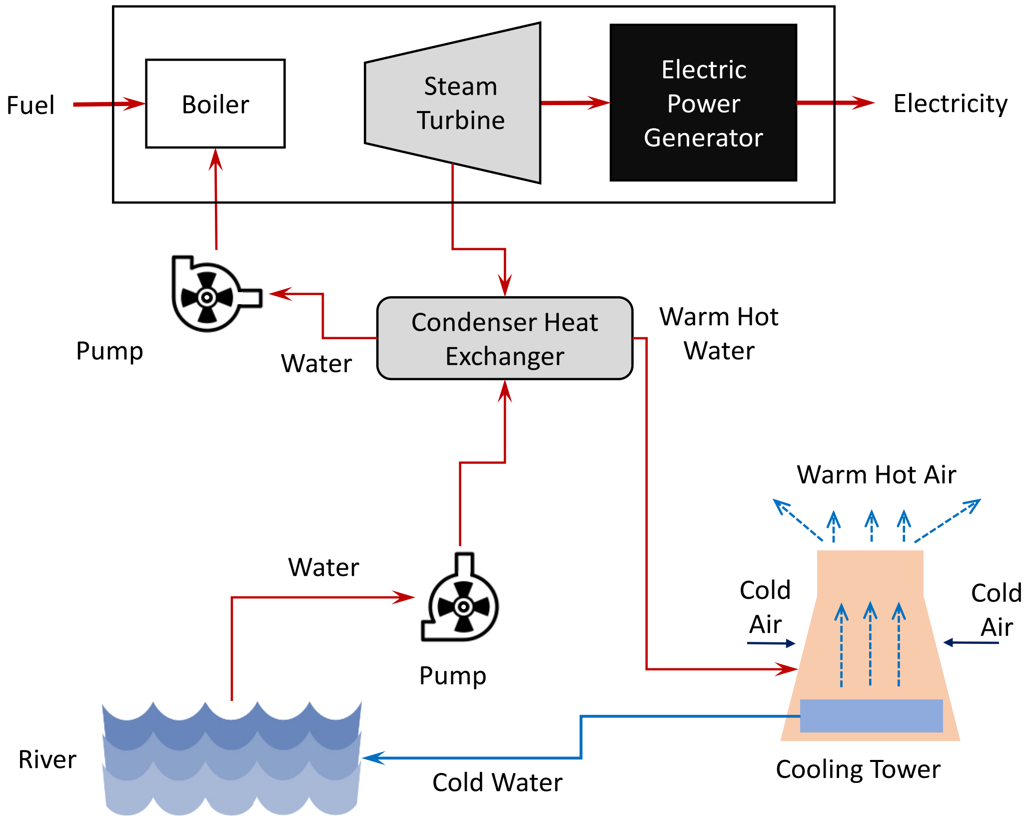


Figure 4.5. Schematic process flowsheet of a fuel based electric power plant
(Image: Simon Michaux, using some copyright free clipart) (Source: concept from Moran *et al* 2014)

The fuel used to feed electric power generation plants is usually something that can be burnt to create thermal heat (coal, gas, charcoal, wood and sometimes oil). Figure 4.6 shows the thermodynamic efficiency profile in the extraction and processing of these fuels into a useable form.

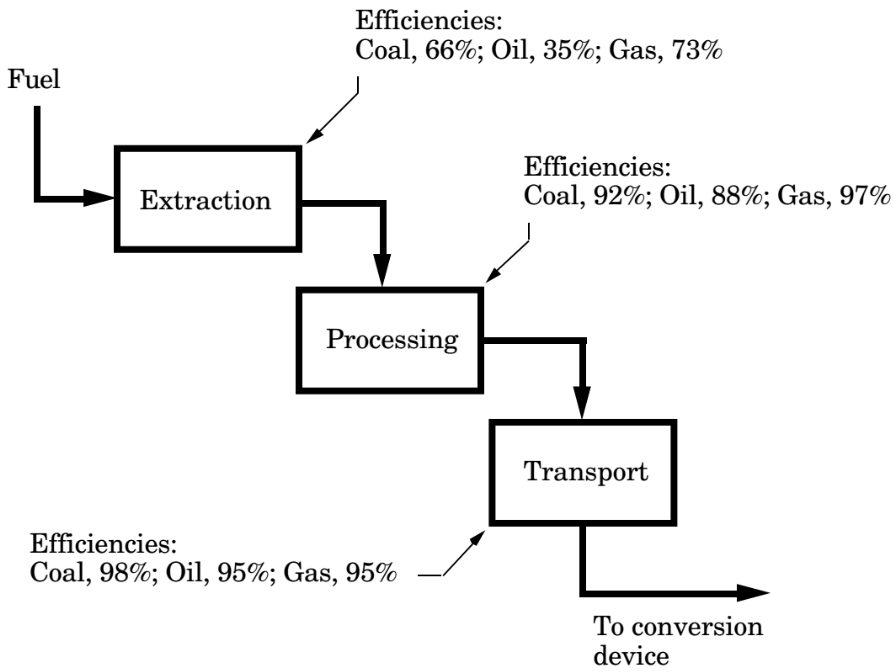


Figure 4.6. Thermodynamic schematic of fuel preparation of final product for use as a fuel in an energy conversion device (Source: redrawn from Moran *et al* 2014)

4.3 Energy Content of Fuels

Energy content or calorific value is the same as the heat of combustion, and can be calculated from thermodynamical values, or can be experimentally measured (Moran *et al* 2014). The combustion process generates water vapor and certain techniques may be used to recover the quantity of heat contained in this water vapor by condensing it.

For the experimental measuring of the energy content in a given fuel, a known quantity of the fuel is burned at constant pressure and under standard conditions (0°C and 1 bar) and the heat released is captured in a known mass of water in a calorimeter. If the initial and final temperatures of the water are measured, the energy released can be calculated using the equation:

$$H = \Delta T \, mC_p \qquad \text{Equation 4.1}$$

where:

H = heat energy absorbed (in J)

ΔT = change in temperature (in °C)

m = mass of water (in g),

Cp = specific heat capacity (4.18 J/g°C for water)

The resulting energy value divided by grams of fuel burned gives the energy content (in J/g). In terms of engineering material characterization, energy sources are differentiated between gross and net heating values:

4.3.1 Gross (or high, upper) Heating Value

The gross or high heating value is the amount of heat produced by the complete combustion of a unit quantity of fuel (Moran *et al* 2014). The gross heating value is obtained when all products of the combustion are cooled down to the initial temperature before combustion and water vapor formed during combustion is condensed. In engineering thermodynamics, the term standard heat of combustion corresponds to Gross heating value.

- Higher Calorific Value (= Gross Calorific Value - GCV = Higher Heating Value - HHV) - the water of combustion is entirely condensed, and the heat contained in the water vapor is recovered

4.3.2 Net (or lower) Heating Value

The net or lower heating value is obtained by subtracting the latent heat of vaporization of the water vapor formed by the combustion from the gross or higher heating value (Moran *et al* 2014).

- Lower Calorific Value (= Net Calorific Value - NCV = Lower Heating Value - LHV) - the products of combustion contain the water vapor and the heat in the water vapor is not recovered

Table 4.3 gives the gross and net heating value of fossil fuels as well as some alternative bio-based fuels. Higher and lower calorific values are also given for some common fuels - coke, oil, wood, hydrogen, and others.

Table 4.3. Higher and Lower Calorific Values of fuels (Source: Redrawn from The Engineering Toolbox https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html)

Fuel	Density at temperature 0°C/32°F, 1 bar		Higher Heating Value (HHV) (Gross Calorific Value - GCV)					Lower Heating Value (LHV) (Net Calorific Value - NCV)				
Gaseous fuels	(kg/m^3)	(g/ft^3)	(kWh/kg)	(MJ/kg)	(Btu/lb)	(MJ/m^3)	(Btu/ft^3)	(kWh/kg)	(MJ/kg)	(Btu/lb)	(MJ/m^3)	(Btu/ft^3)
at tempertaure of 0°C/32°F, and 1 bar of atmospheric pressure												
Acetylene	1.10	31.1	13.9	49.9	21,453	54.7	1,468					
Ammonia				22.5	9,690							
Hydrogen	0.09	2.6	39.4	141.7	60,920	12.7	341	33.3	120.0	51,591.0	10.8	290.0
Methane	0.72	20.3	15.4	55.5	23,874	39.8	1,069	13.9	50.0	21,496.0	35.8	964.0
Natural gas (US market)*	0.78	22.0	14.5	52.2	22,446	40.6	1,090	13.1	47.1	20,262.0	36.6	983.0
Town gas						18	483					
Liquid fuels	(kg/l)	(kg/gal)	(kWh/kg)	(MJ/kg)	(Btu/lb)	(MJ/l)	(Btu/gal)	(kWh/kg)	(MJ/kg)	(Btu/lb)	(MJ/l)	(Btu/gal)
at tempertaure of 15°C/60°F, and 1 bar of atmospheric pressure												
Acetone	0.79	2.98	8.83	31.8	13,671	25	89,792	8.22	29.6	12,726	23.3	83,580
Butane	0.60	3.07	13.64	49.1	21,109	29.5	105,875	12.58	45.3	19,475	27.2	97,681
Butanol	0.81		10.36	37.3	16,036	30.2	108,359	9.56	34.4	14,789	27.9	99,934
Diesel fuel*	0.85	3.20	12.67	45.6	19,604	38.6	138,412	11.83	42.6	18,315	36.0	129,306
Dimethyl ether (DME)	0.67	2.52	8.81	31.7	13,629	21.1	75,655	8.03	28.9	12,425	19.2	68,973
Ethane	0.57	2.17	14.42	51.9	22,313	29.7	106,513	13.28	47.8	20,550	27.3	98,098
Ethanol (100%)	0.79	2.99	8.25	29.7	12,769	23.4	84,076	7.42		11,479	21.1	75,583
Diethyl ether (ether)	0.72	2.71	11.94	43	18,487	30.8	110,464					
Gasoline (petrol)*	0.74	2.79	12.89	46.4	19,948	34.2	122,694	12.06	43.4	18,659	32.0	114,761
Gas oil (heating oil)*	0.84	3.18	11.95	43	18,495	36.1	129,654	11.89	42.8	18,401	36.0	128,991
Glycerin	1.26	4.78	5.28	19	8,169	24	86,098					
Heavy fuel oil*	0.98	3.71	11.61	41.8	17,971	41	146,974	10.83	39.0	16,767	38.2	137,129
Kerosene*	0.82	3.11	12.83	46.2	19,862	37.9	126,663	11.94	43.0	18,487	35.3	126,663
Light fuel oil*	0.96	3.63	12.22	44	18,917	42.2	151,552	11.28	40.6	17,455	39.0	139,841
LNG*	0.43	1.62	15.33	55.2	23,732	23.6	84,810	13.50	48.6	20,894	20.8	74,670
LPG*	0.54	2.03	13.69	49.3	21,195	26.5	94,986	12.64	45.5	19,561	24.4	87,664
Marine gas oil*	0.86	3.24	12.75	45.9	19,733	39.2	140,804	11.89	42.8	18,401	36.6	131,295
Methanol	0.79	2.99	6.39	23	9,888	18.2	65,274	5.54		8,568	15.8	56,562
Methyl ester (biodiesel)	0.89	3.36	11.17	40.2	17,283	35.7	128,062	10.42	37.5	16,122	33.3	119,460
MTBE	0.74	2.81	10.56	38	16,337	41.4	101,244	9.75	35.1	15,090	26.1	93,517
Oils vegetable (biodiesel)*	0.92	3.48	11.25	40.5	17,412	37.3	133,684	10.50	37.8	16,251	34.8	124,772
Paraffin (wax)*	0.90	3.41	12.78	46	19,776	41.4	148,538	11.53	41.5	17,842	37.4	134,007
Pentane	0.63	2.39	13.50	48.6	20,894	30.6	109,854	12.60	45.4	19,497	28.6	102,507
Petroleum naphtha*	0.73	2.75	13.36	48.1	20,679	34.9	125,145	12.47	44.9	19,303	32.6	116,819
Propane	0.50	1.89	13.99	50.4	21,647	25.1	89,963	12.88	46.4	19,927	23.1	82,816
Residual oil*	0.99	3.75				41.8	150,072	10.97	39.5	16,982	39.2	140,470
Tar*			10.00	36	15,477							
Turpentine	0.87	3.27	12.22	44	18,917	38.1	136,555					
Solid fuels*	(kWh/kg)		(kWh/kg)	(MJ/kg)	(Btu/lb)			(kWh/kg)	(MJ/kg)	(Btu/lb)		
Anthracite coal			9.06	32.6	14,015							
Bituminous coal			8.39	30.2	12,984			8.06	29.0	12,468		
Carbon			9.11	32.8	14,101							
Charcoal			8.22	29.6	12,726			7.89	28.4	12,210		
Coke			7.22	26.0	11,178							
Lignite (brown coal)			3.89	14.0	6,019							
Peat			4.72	17.0	7,309							
Petroleum coke			8.69	31.3	13,457			8.19	29.5	12,683		
Semi anthracite			8.19	29.5	12,683							
Sub-Bituminous coal			6.78	24.4	10,490							
Sulfur (s)			2.56	9.2	3,955			2.55	9.2	3,939		
Wood (dry)	0.701		4.50	16.2	6,965			4.28	15.4	6,621		

* Fuels which consist of a mixture of several different compounds may vary in quality between seasons and markets. The given values are for fuels with the given density. The variation in quality may give heating values within a range 5 -10% higher and lower than the given value. Also the solid fuels will have a similar quality variation for the different classes of fuel.

Below is a list of common units used in thermodynamics and conversion formulae between them (Moran *et al* 2014).

- 1 Btu(IT)/lb = 2.3278 MJ/t = 2327.8 J/kg = 0.55598 kcal/kg = 0.000646 kWh/kg
- 1 kcal/kg = 1 cal/g = 4.1868 MJ/t = 4186.8 J/kg = 1.8 Btu(IT)/lb = 0.001162 kWh/kg
- 1 MJ/kg = 1000 J/g = 1 GJ/t = 238.85 kcal/kg = 429.9 Btu(IT)/lb = 0.2778 kWh/kg
- 1 kWh/kg = 1547.7 Btu(IT)/lb = 3.597 GJ/t = 3597.1 kJ/kg = 860.421 kcal/kg
- 1 Btu(IT)/ft^3 = 0.1337 Btu(IT)/gal(US liq) = 0.03531 Btu(IT)/l = 8.89915 kcal/m^3 = 3.7259x10^4 J/m^3
- 1 Btu(IT)/gal(US liq) = 0.2642 Btu(IT)/l = 7.4805 Btu(IT)/ft^3 = 66.6148 kcal/m^3 = 2.7872x10^5 J/m^3
- 1 MJ/m^3 = 26.839 Btu(IT)/ft^3 = 3.5879 Btu(IT)/gal(US liq) = 0.94782 Btu(IT)/l = 239.01 kcal/m^3
- 1 kcal/m^3 = 0.11237 Btu(IT)/ft^3 = 0.01501 Btu(IT)/gal(US liq) = 0.003966 Btu(IT)/l = 4186.8 J/m^3

4.4 The Efficiency of Power Plants of Different Types

Each of the methods used to industrially generate power in the quantities needed all have a range of advantages and disadvantages (Moran *et al* 2014). The fuel used has a range of calorific density values. Then there are the relative efficiencies of generating power.

Table 4.4. Efficiency of electric power generation by fuel source

Power Generation System	Fuel	Global Consumption in 2018 (Appendix C, D, E, F, G, H, I)	Energy Content of Fuel (Table 4.3)	Efficiency of Power Generation from Fuel (Section 8.6)	Installed Global Capacity (Section 8.6 & Global Energy Observatory)	Global Electricity Production in 2018 (Appendix B, G, H, I & Agora Energiewende and Sandbag 2019)
Coal	Coal	3772.1 Mtoe	30.2 MJ/kg	32-42%	1237.7 GW	10100.5 TWh
Gas	Gas	3309.4 Mtoe	40.6 MJ/m^3	32-38%	1207.5 GW	6182.8 TWh
Nuclear	Enriched Uranium	611.3 Mtoe	2000 MJ/Kg	0.27%	431.8 GW	2701.4 TWh
Hydroelectric	Moving water	948.8 Mtoe	-	85-90%	712.9 GW	4193.1 TWh
Wind	Moving air	-	-	35-45%	597 GW	1303.8 TWh
Solar PV	Sunlight	-	-	15-20%	580.14 GW	579.1 TWh
Solar Thermal	Sunlight	-	-	20%	5.5 GW	5.5 TWh
Geothermal	Geological heat	-	-	10-35%	14.6 GW	93 TWh
Biowaste to energy	Biowaste	-	12-35 MJ/kg	13%	55 GW	60 TWh
Fuel Oil Diesel	Crude Oil	4662.1 Mtoe	45.6 MJ/kg	38%	225.8 GW	802.8 TWh

4.4.1 *Steam turbine used to generate electricity*

The development of the Watt steam engine in the late eighteenth century spurs a wave of mechanization in Europe and the United States known as the Industrial Revolution. Coal is the main energy source driving the revolution in its beginning years. The Industrial Revolution marks a major turning point in history; almost every aspect of daily life was influenced in some way. In particular, average income and population began to exhibit unprecedented sustained growth.

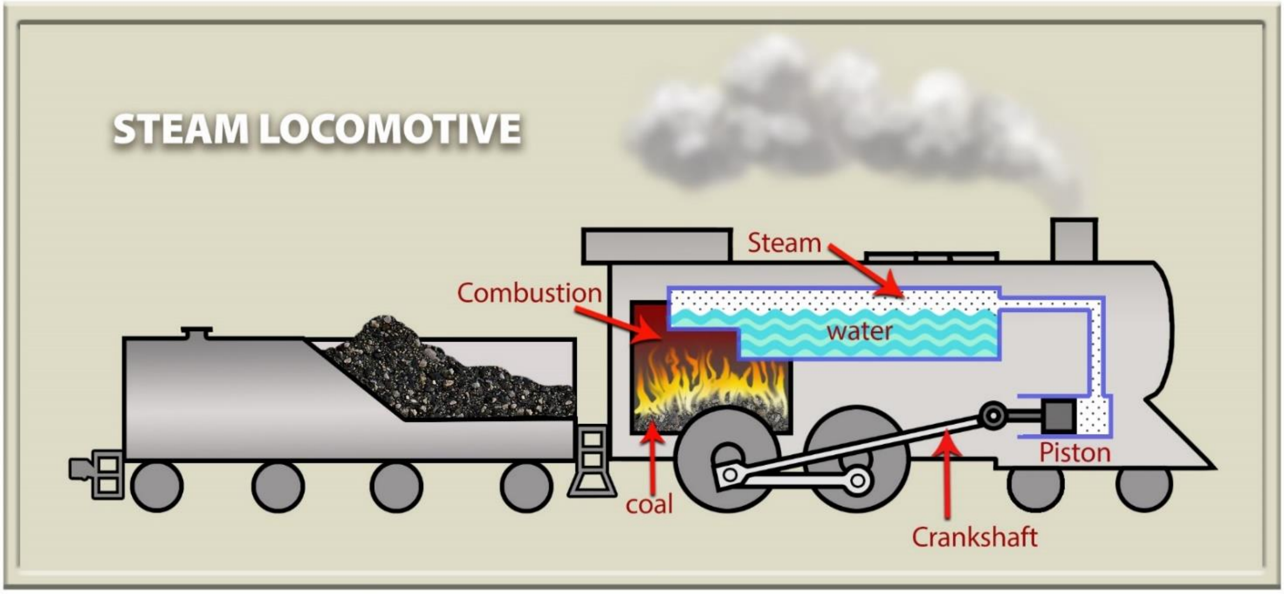


Figure 9.27. Working principle of a steam locomotive using fuel gas
(Source: Figure draw based on similar in Moran *et al* 2014) (Image: Tania Michaux)

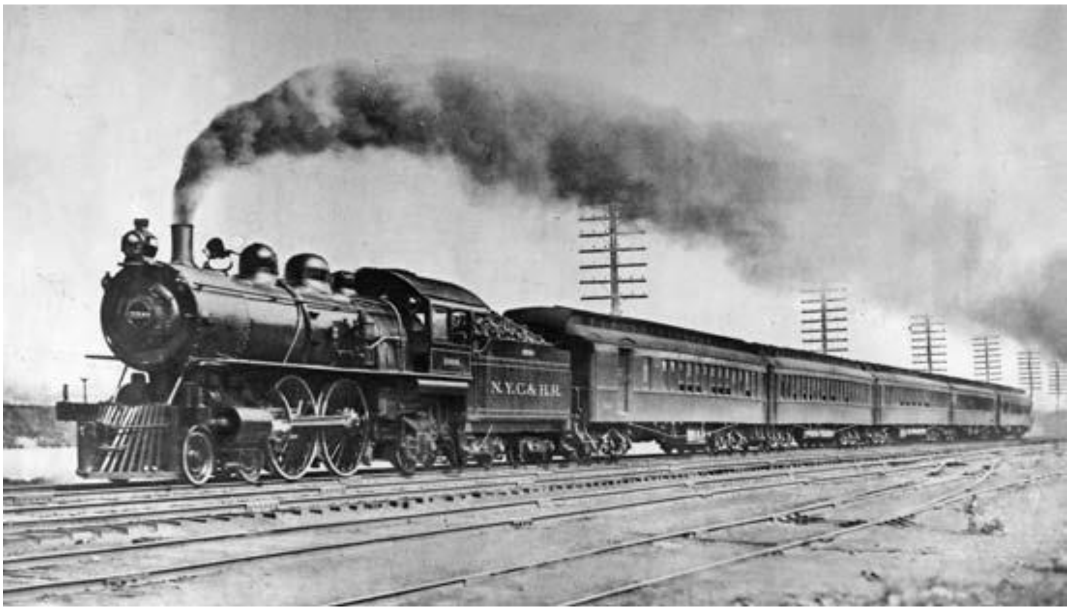


Figure 9.28. Coal burning steam locomotive (Source: Lake Shore and Michigan Southern Railway in 1873)

Steam locomotives were about 4–8% efficient on average, which means that 92–96% of the energy in the wood or coal was a heat loss in the boiler (Ayres *et al* 2003, Heck 2011). After the internal combustion engine powered with petroleum made the coal fired steam obsolete, coal use was continued for electrical power generation in coal fired power stations.

Electrical power stations use large steam turbines driving electric generators to produce most (about 80%) of the world's electricity (EIA 2017). The advent of large steam turbines made central-station electricity generation practical, since reciprocating steam engines of large rating became very bulky and operated at slow speeds (Smil 2018). Most central stations are fossil fuel power plants and nuclear power plants; some installations use geothermal steam or use concentrated solar power (CSP) to create the steam. Steam turbines can also be used directly to drive large centrifugal pumps, such as feedwater pumps at a thermal power plant.

The turbines used for electric power generation are most often directly coupled to their generators. As the generators must rotate at constant synchronous speeds according to the frequency of the electric power system, the most common speeds are 3 000 RPM for 50 Hz systems, and 3 600 RPM for 60 Hz systems. Since nuclear reactors have lower temperature limits than fossil-fired plants, with lower steam quality, the turbine generator sets may be arranged to operate at half these speeds, but with four-pole generators, to reduce erosion of turbine blades.

Most of the energy generation methods use a steam turbine to turn an electric generator, which generates electricity. A steam turbine is a device that extracts thermal energy from pressurized steam and uses it to do mechanical work on a rotating output shaft. Its modern manifestation was invented by Charles Parsons in 1884 (Moran *et al* 2014).

Figure 4.7. The rotor of a modern steam turbine used in a power plant
(Source: Siemens Pressebild, http://www.siemens.com - Photo taken from with the permission of Siemens Germany by Christian Kuhna)
(Copyright license: https://en.wikipedia.org/wiki/Steam_turbine#/media/File:Dampfturbine_Laeufer01.jpg)

The steam turbine is a form of heat engine that derives much of its improvement in thermodynamic efficiency from the use of multiple stages in the expansion of the steam, which results in a closer approach to the ideal reversible expansion process. Because the turbine generates rotary motion, it is particularly suited to be used to drive an electrical generator.

Usually the steam is heated by various methods (varies from generation type to type). The steam is forced through a turbine with thermal expansion. The steam turbine operates on basic principles of thermodynamics using the part 3-4 of the Rankine cycle shown in Figure 4.8. Superheated steam (or dry saturated steam, depending on application) leaves the boiler at high temperature and high pressure. At entry to the turbine, the steam gains kinetic energy by passing through a nozzle (a fixed nozzle in an impulse type turbine or the fixed blades in a reaction type turbine). When the steam leaves the nozzle, it is moving at high velocity towards the blades of the turbine rotor. A force is created on the blades due to the pressure of the vapor on the blades causing them to move.

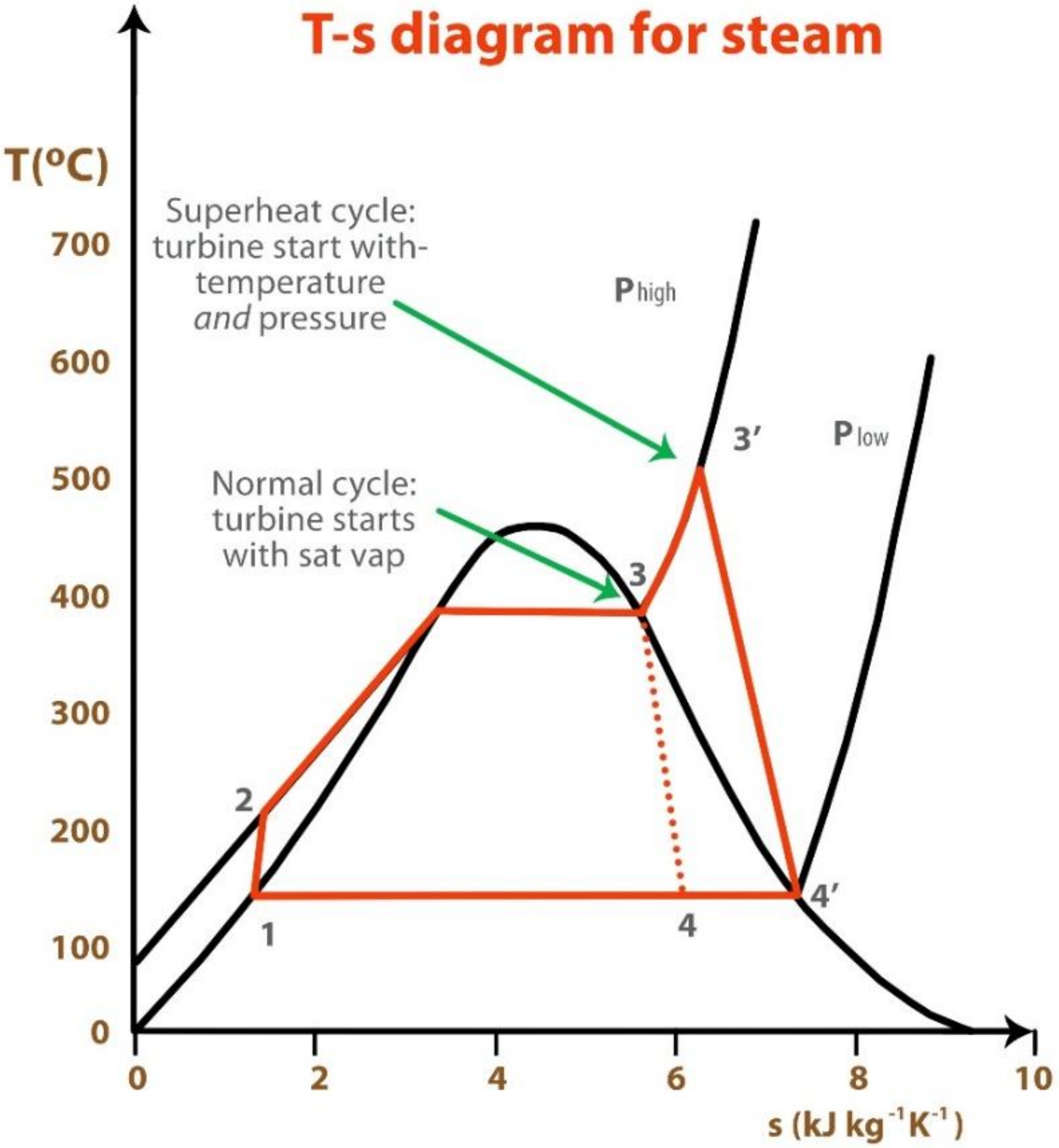


Figure 4.8. T-s diagram of a superheated Rankine cycle
(Image: Tania Michaux)

The steam turbine is then in turn used to turn an electric generator. In electricity generation, a generator is a device that converts motive power (mechanical energy) into electrical power for use in an external circuit (Thomas 1991 and Gottlieb 1997). Generators provide nearly all of the power for electric power grids (Smil 2018). The reverse conversion of electrical energy into mechanical energy is done by an electric motor, and motors and generators have many similarities.

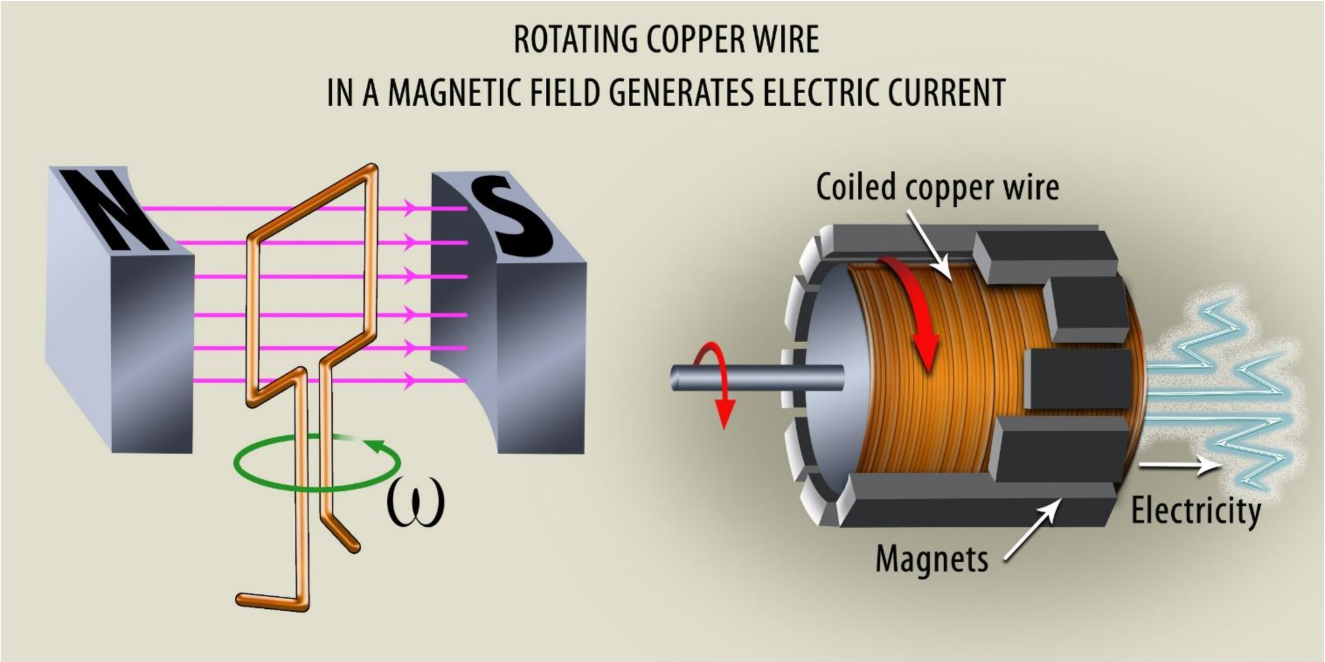


Figure 4.9. Electric current generation by mechanically rotating a copper wire in a magnetic field (Source: Drawn from concepts in Gottlieb 1997 and Serway 2013) (Image: Tania Michaux)

A coil of wire rotating in a magnetic field produces a current which changes direction with each 180° rotation, an alternating current (AC) (Thomas 1991 and Gottlieb 1997). Charges in the wires of the loop experience the magnetic force because they are moving in a magnetic field. Thus, when a wire loop is rotated mechanically (by the steam turbine) in a magnetic field (between two permanent magnets), electrical current flows through the wires (Grigsby 2006). This current can be used to charge a battery, or to be used directly in an application.

The dynamo was the first electrical generator capable of delivering power for industry. However, many early uses of electricity required direct current (DC). In the first practical electric generators, called dynamos, the AC was converted into DC with a commutator, a set of rotating switch contacts on the armature shaft (Gottlieb 1997). The commutator reversed the connection of the armature winding to the circuit every 180° rotation of the shaft, creating a pulsing DC current.

Figure 4.10 shows a schematic diagram of a steam turbine and electric generator in one unit.

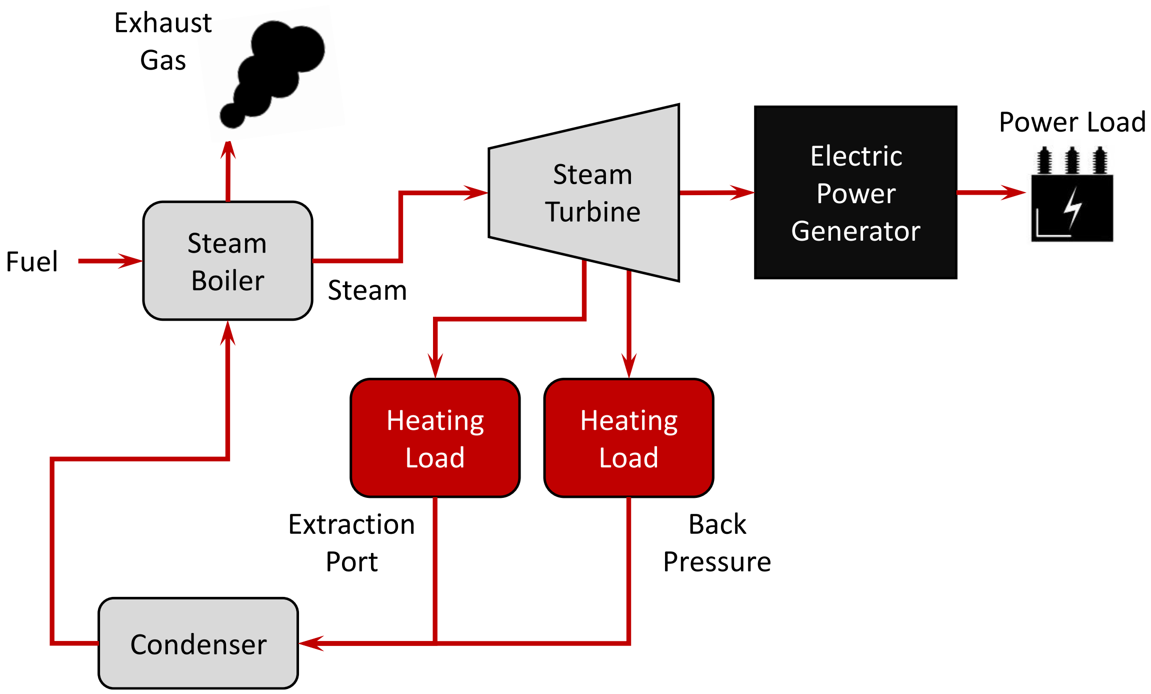


Figure 4.10. Steam turbine schematic
(Image by Simon Michaux, using some copyright free clipart)

Since the 1980s, steam turbines have been replaced by gas turbines on fast ships and by diesel engines on other ships; exceptions are nuclear-powered ships and submarines and LNG carriers (Ship Technology 2012).

4.4.2 Coal Fired Power Plants Efficiency

Coal based power accounts for approximately 40% of the world's electricity generation (BP Statistics 2019). Coal has an energy content of 30.2 MJ/kg, but also is the most polluting fossil fuel in context of the generation of CO^2 in terms of a kg/kg basis.

Coal fired power plants operate on the modified Rankine thermodynamic cycle. The efficiency is dictated by the parameters of this thermodynamic cycle. The overall coal plant efficiency ranges from 32% to 42% (Kiameh 2013). This is mainly dictated by the Superheat and Reheat steam temperatures and Superheat pressures. Most of the large power plants operate at steam pressures of 170 bar and 570 °C Superheat, and 570 ° C reheat temperatures. The efficiencies of these plants range from 35% to 38%. Super critical power plants operating at 220 bar and 600/600 °C can achieve efficiencies of 42%. Ultra-super critical pressure power plants at 300 bar and 600/600 °C can achieve efficiencies in the range of 45% to 48% efficiency.

As of July 2018, global coal installed power generation capacity was 1237.7 GW (Global Energy Observatory 2018). Installed power generation capacity is related to the number and size of physical power stations that are operating and supplying electricity to the grid. In the year 2018, 10 100.5 TWh of electricity (or 38% of the 2018 total) was generated with coal fired power stations (Table 7).

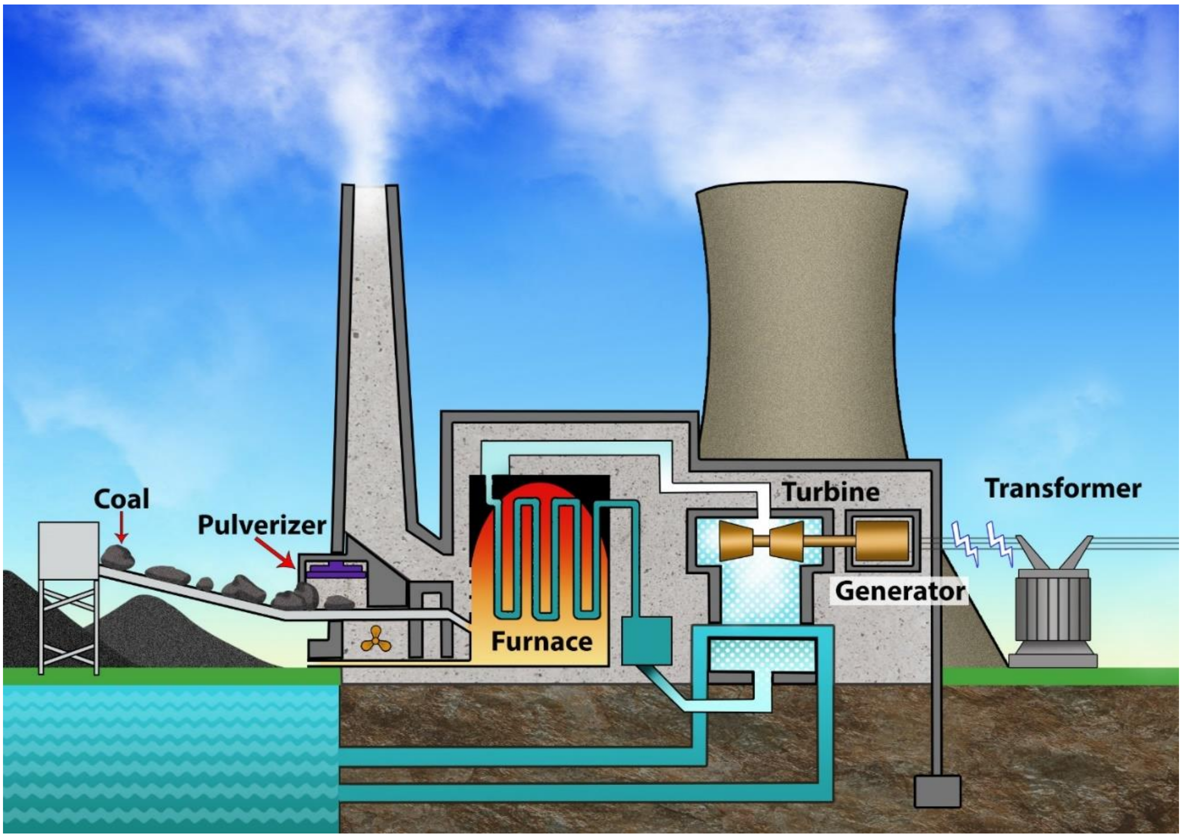


Figure 4.11. Coal fired power plant schematic
(Source: Figure drawn on concepts based on similar to Moran et al 2014) (Image: Tania Michaux)

Figure 4.12. Coal fired power plant
(Image by Benita Welter from Pixabay)

4.4.3 Natural Gas Fired Power Plants Efficiency

Natural Gas fired (including LNG fired) power plants account for approximately 20 % of the world's electricity generation and has an energy content of 40.6 MJ/m^3 (Kiameh 2013).

Gas fueled power plants use gas turbines or a gas turbine based combined cycles. Gas turbines in the simple cycle mode, with only gas turbines running, have an efficiency of 32% to 38%. The most important parameter that dictates the efficiency is the maximum gas combustion temperature possible. This accounts for most current gas power plants.

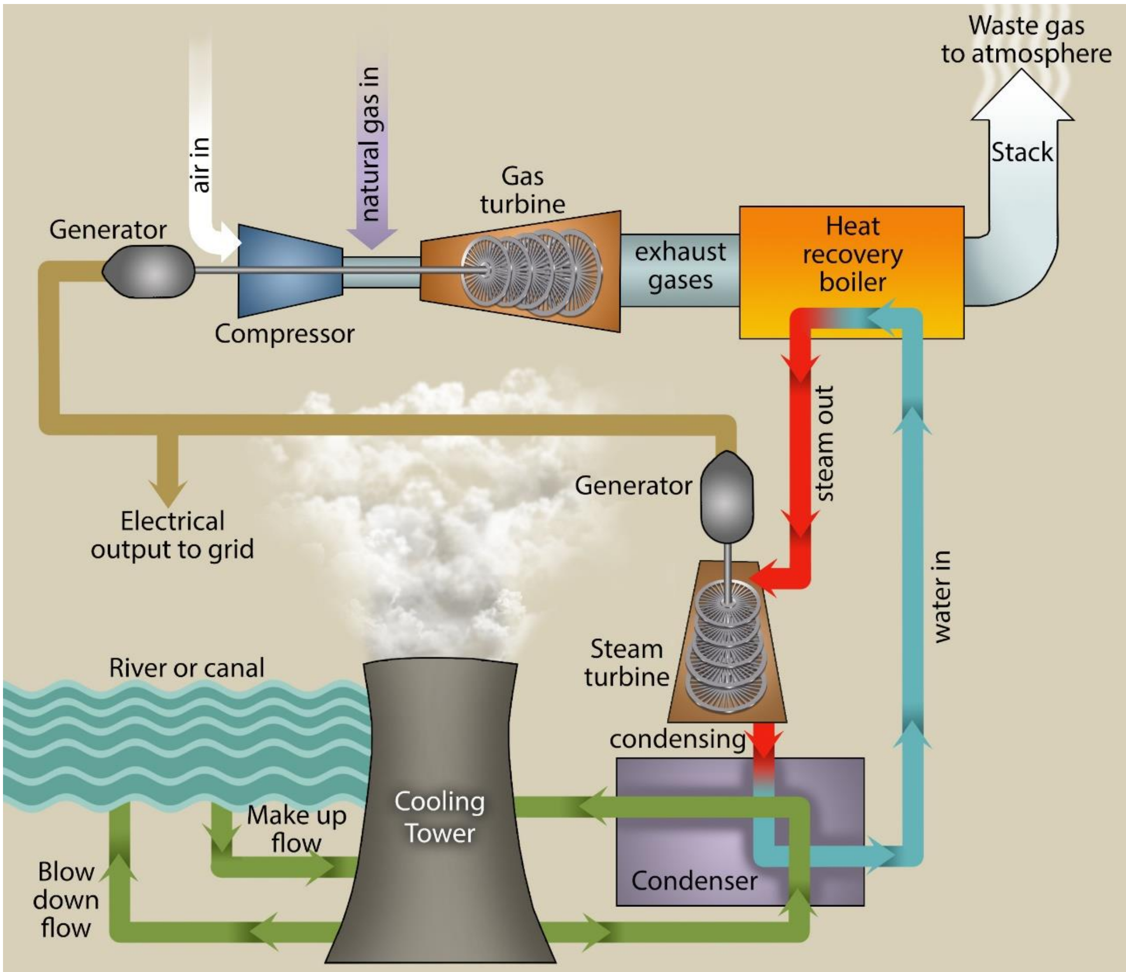


Figure 4.13. Gas power generation conceptual process flow sheet
(Image: Tania Michaux)

The latest generation of gas turbines with technological advances in materials and aerodynamics has efficiencies up to 38%. In the combined cycle mode, the new "H class" gas turbines with a triple pressure HRSG and steam turbine can run at 60% efficiency at ISO conditions. This is by far the highest efficiency in the thermal power field. These new H Class units are not very widespread yet and account for a relatively small proportion of the whole gas electricity power generation fleet.

As of July 2018, global gas installed power generation capacity was 1207.5 GW (Global Energy Observatory 2018). Installed power generation capacity is related to the number and size of physical power stations that are operating and supplying electricity to the grid. In the year 2018, 6 182.2 TWh of electricity (or 23.2% of the 2018 total) was generated with gas fired power stations (Table 8.1).

4.4.4 Hydroelectricity Power Generation Efficiency

Hydro turbines have the highest efficient of all power conversion process. The potential head of water is available right next to the turbine, so there are no energy conversion losses, only the mechanical and copper losses in the turbine and generator and the tail end loss. The efficiency is in the range of 85 to 90% (Abu-Rub *et al* 2014).

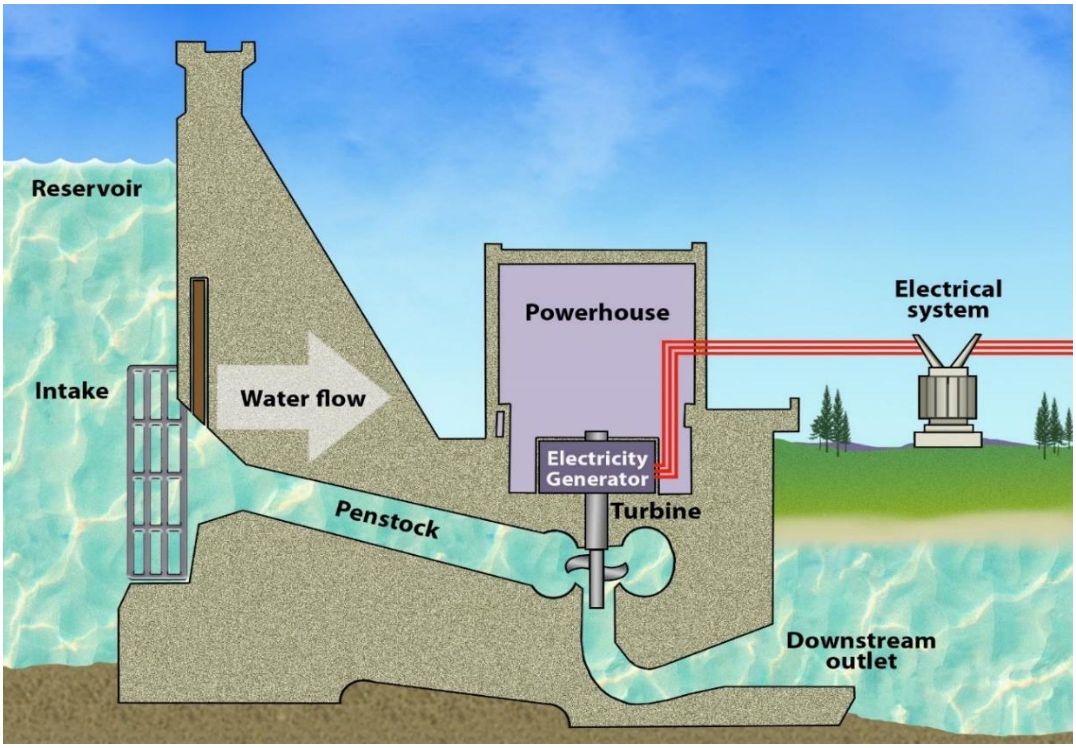
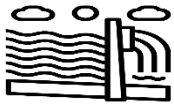


Figure 4.14. Simplified layout of a hydroelectricity power plant
(Image: Tania Michaux)

The best gains for hydroelectricity as a useful system will be power generated in an optimized context by embedding hydro system in amongst another system. An example of this could be Pumped storage hydroelectricity. Pumped-storage hydroelectricity (PSH), or pumped hydroelectric energy storage (PHES), is a type of hydroelectric energy storage used by electric power systems for load balancing. The method stores energy in the form of gravitational potential energy of water, pumped from a lower elevation reservoir to a higher elevation. Low-cost surplus off-peak electric power is typically used to run the pumps. During periods of high electrical demand, the stored water is released through turbines to produce electric power. Although the losses of the pumping process make the plant a net consumer of energy overall, the system increases revenue by selling more electricity during periods of peak demand, when electricity prices are highest.



The use of pumped-storage hydroelectricity allows energy from intermittent sources (such as solar, wind) and other renewables, or excess electricity from continuous base-load sources (such as coal or nuclear) to be saved for periods of higher demand (Al-Hadhrami *et al* 2015). The reservoirs used with pumped storage are quite small when compared to conventional hydroelectric dams of similar power capacity, and generating periods are often less than half a day. This could be quite useful as the real challenge for the viability of many renewable systems is their intermittent supply characteristics.

As of July 2018, global hydroelectric installed power generation capacity was 712.9 GW (Global Energy Observatory 2018). Installed power generation capacity is related to the number and size of physical power stations that are operating and supplying electricity to the grid. In the year 2018, 4 193.1 TWh of electricity (or 15.8% of the 2018 total) was generated with hydro power stations (Tables 8.1 and 8.4 in Section 8).

4.4.5 Tidal power generation

Tidal power or tidal energy is a form of hydropower that converts the energy obtained from tides into useful forms of power, mainly electricity. Although not yet widely used, tidal energy has potential for future electricity generation. Tides are more predictable than the wind and the sun. Among sources of renewable energy, tidal energy has traditionally suffered from relatively high cost and limited availability of sites with sufficiently high tidal ranges or flow velocities, thus constricting its total availability. However, many recent technological developments and improvements, both in design (e.g. dynamic tidal power, tidal lagoons) and turbine technology (e.g. new axial turbines, cross flow turbines), indicate that the total availability of tidal power may be much higher than previously assumed, and that economic and environmental costs may be brought down to competitive levels (Abu-Rub *et al* 2014).

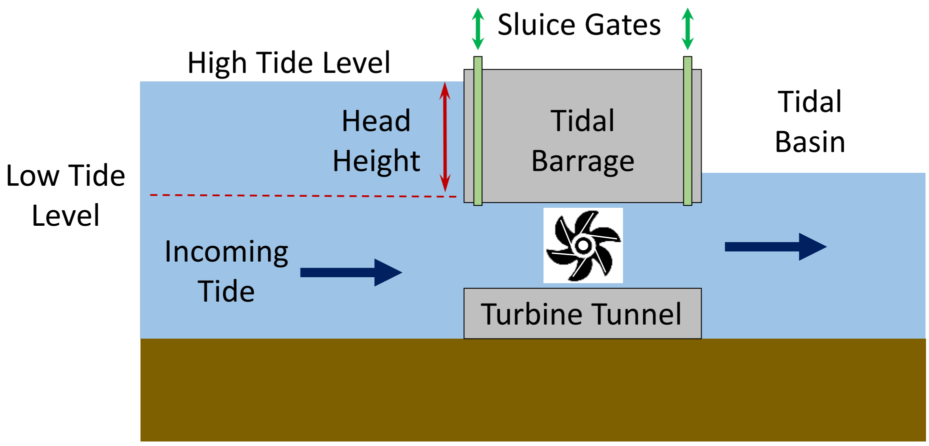


Figure 4.15. Tidal power generation schematic simplified diagram
(Image by Simon Michaux using some copyright free clipart)

The potential of tidal power has led to proposals of a barrage (a dam that lets water flow in and out) across the entrance of a bay that has a large range of height between low and high tides. It would generate power by releasing water trapped behind the barrage at high tide through turbines similar to a hydro-power facility. Or this could be done with in-stream turbines similar to the way that wind turbines work.

Tidal power has not been applied in large numbers of operating sites. This could be due to the engineering and logistical limitations. Corrosion, biofouling, and metal fatigue in the vigorous turbulence typically associated with strong tidal flows, are only some of the challenges to overcome.

Tidal energy requires a large catchment area to generate a reasonable quantity of electricity. A tidal amplitude of 1 meter would require over 285 km^2 costal catchment area to produce 100 MW (using data from Abu-Rub *et al* 2014). This is why tidal power stations are limited to regions with very large tides, which tend to be in the northern latitudes, far from most cities that could/would use the power (not always the case, but a generalization).

To put this in context, a 100 MW tidal power station in an area with a tidal current speed of 3 m/s (a volumetric flow of nearly 40 000 m^3/s), would require an array of 120 turbines, each having a cross-sectional area of 100 m^2, or 24 turbines of 25 m diameter. Many more turbines would be needed for more typical, smaller currents. Power is reduced if there's more than 1 channel, which also tends to divert flow to other channels (Abu-Rub *et al* 2014).

There are challenges in finding a suitable site for a tidal power turbine array. Some of the locations with the highest tidal energy density are also estuaries having ports with heavy commercial shipping traffic. It is likely that there will be limitations to the number and size of turbines and the depth at which they can be deployed so as not to interfere with established shipping lanes (Friedemann 2020).

4.4.6 Wave power generation

Wave power generation is the transport of energy by wind waves, and the capture of that energy to do useful work – for example, electricity generation, water desalination, or the pumping of water (into reservoirs). Extracting energy from waves is achieved with floating cylinders which are hinged together using special hinges which are connected to hydraulic generators inside the cylinders. An example of this type of system is shown in the picture above. These cylinders float on the water surface and move relative to each other in response to the wave motion. The relative motion of the cylinders causes the hinges to "flex" which drives the hydraulic generators which then produce electricity as a result.

A machine able to exploit wave power is generally known as a wave energy converter (WEC) (Mishra *et al* 2016). Wave power is distinct from the diurnal flux of tidal power and the steady gyre of ocean currents. Wave-power generation is not currently a widely employed commercial technology, although there have been attempts to use it since at least 1890. In 2008, the first experimental wave farm was opened in Portugal, at the Aguçadoura Wave Park.

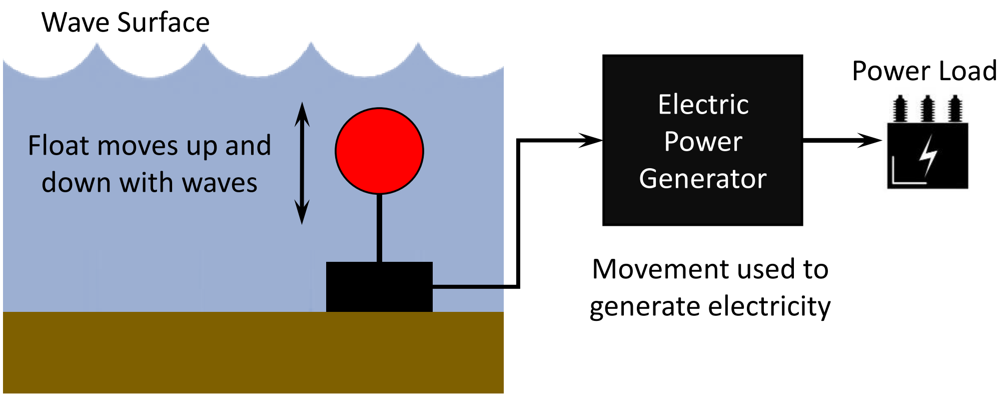


Figure 4.16. Wave power generation concept 1
(Image by Simon Michaux, using some copyright free clipart)

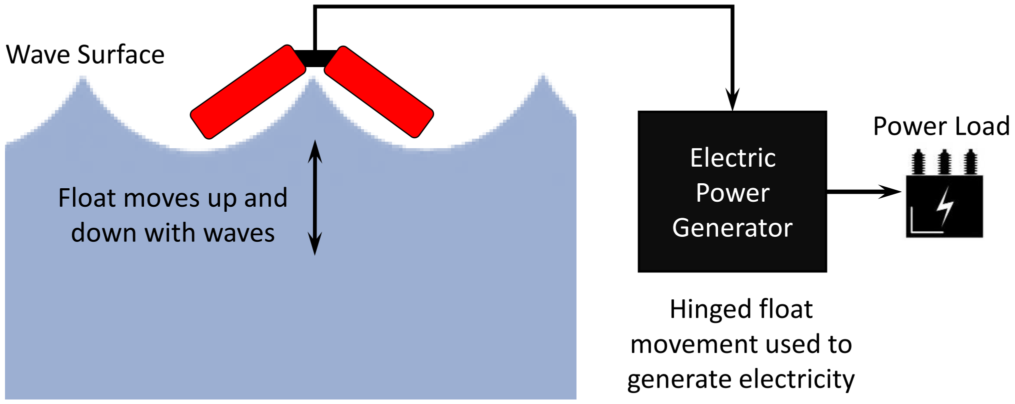


Figure 4.17. Wave power generation concept 2
(Image by Simon Michaux, using some copyright free clipart)

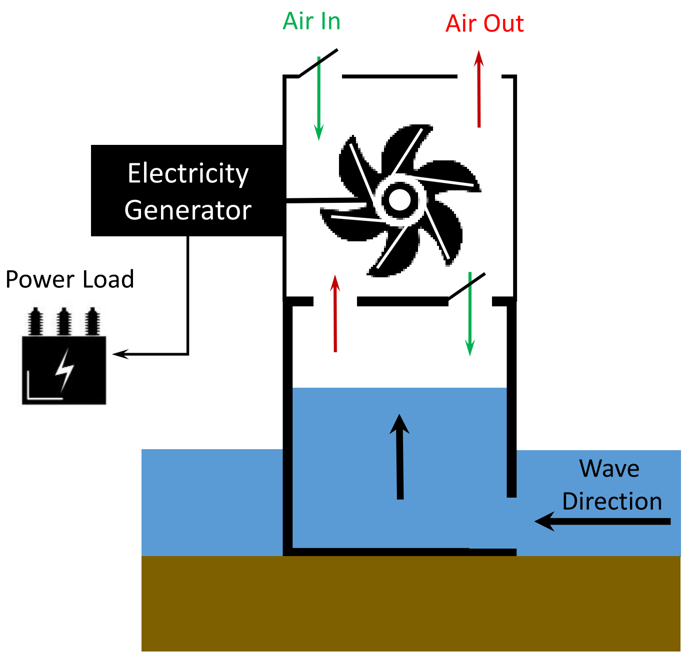


Figure 4.18. Wave power air compression power generation schematic simplified diagram
(Image by Simon Michaux, using some copyright free clipart)

4.4.7 Wind Power Generation Efficiency

Wind power or wind energy is the use of air flow through wind turbines to provide the mechanical power to turn electric generators and traditionally to do other work, like milling or pumping. Wind power is a sustainable and renewable alternative to burning fossil fuels and has a much smaller impact on the environment (Abu-Rub *et al* 2014).

Wind farms consist of many individual wind turbines, which are connected to the electric power transmission network. Onshore wind is an inexpensive source of electric power, competitive with or in many places cheaper than coal or gas plants. Offshore wind is steadier and stronger than on land and offshore farms have less visual impact, but construction and maintenance costs are considerably higher (Deisadze 2013). Small onshore wind farms can feed some energy into the grid or provide electric power to isolated off-grid locations.

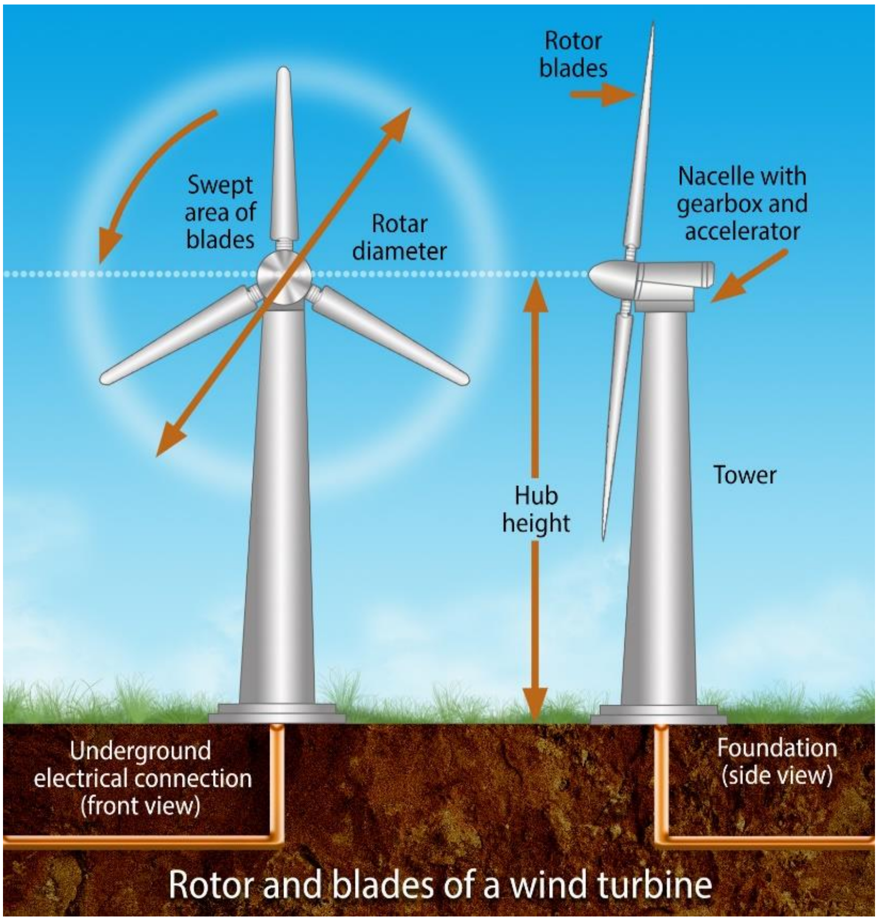


Figure 4.19. Wind power turbine setup
(Image: Tania Michaux)

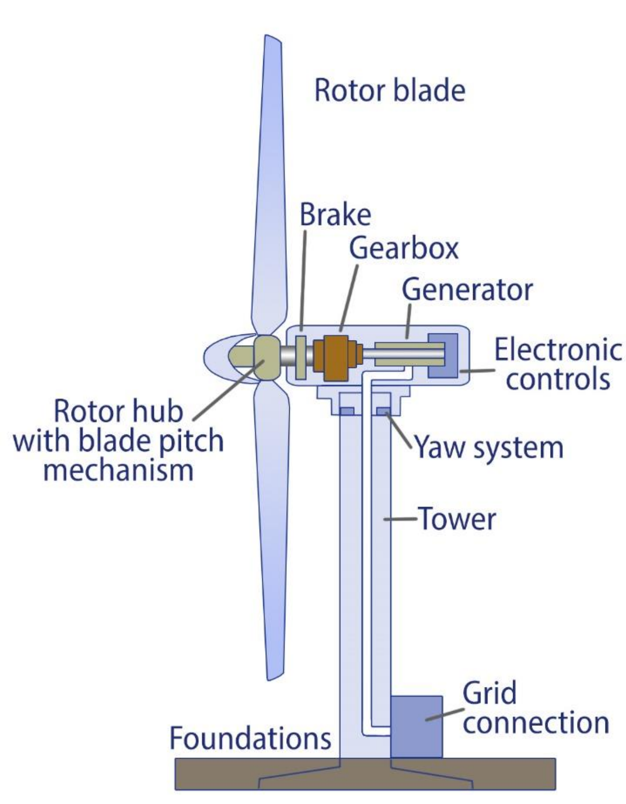


Figure 4.20. Wind power turbine schematic
(Image: Tania Michaux)

Figure 4.21. Wind power turbine
(Image by TeeFarm from Pixabay)

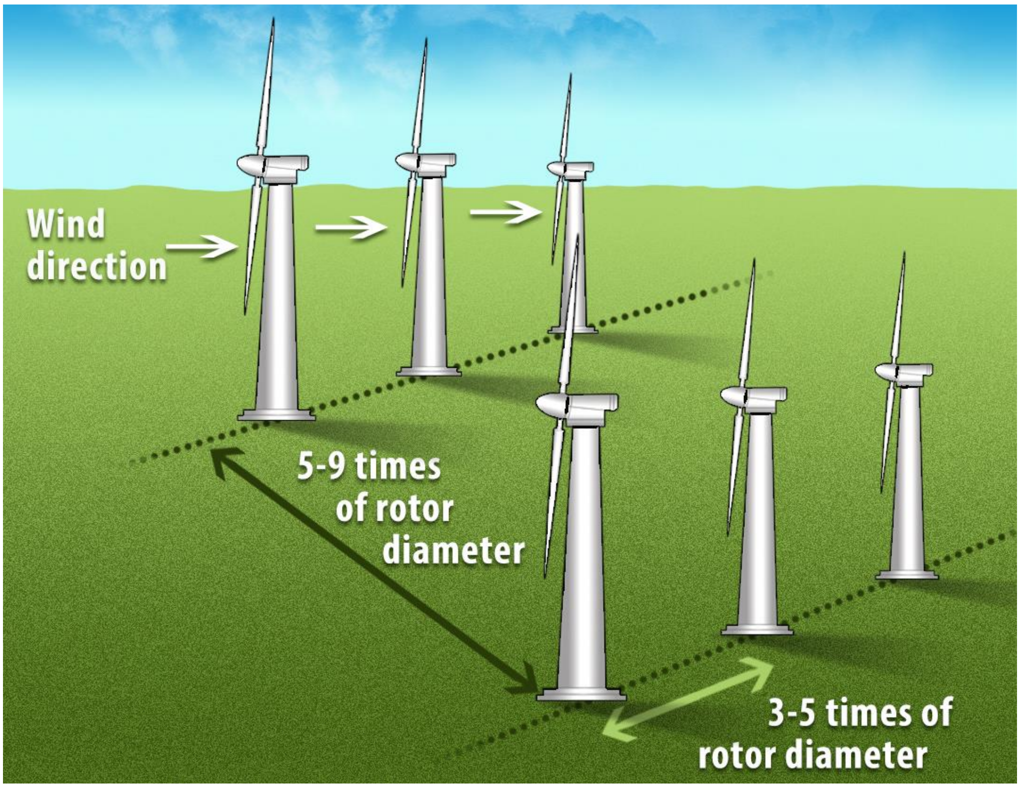


Figure 4.22. Wind turbine spacing in an array
(Image: Tania Michaux)

Figure 4.23. Wind power turbine array
(Image by PublicDomainImages from Pixabay)

Figure 4.24. Offshore wind power turbine array
(Image by Anette Bjerg from Pixabay)

Wind turbines have an overall conversion efficiency of 30% to 45% (Abu-Rub *et al* 2014). The size and effectiveness of wind turbines has evolved considerably even in the last few years. In 2018, a state of the art wind turbine was able to generate 8MW, with the swept area twice the size of a football field (Rohrig 2019).

In the year 2018, 1 270 TWh of electricity (or 4.9% of the 2018 total) was generated with wind power array stations (8.4 in Section 8).

Commissioning a wind turbine is getting more logically complicated, as the turbines get larger. Individual blades can be 80 tonnes in weight and more than 50m in length (Siciliano 2017). This creates a difficult logistical problem in transporting the turbine parts from the factory to the site of operation.

Wind power has shown to be highly intermittent (Fares 2015 and EIA 2015). Power is generated when the wind blows, and also changes with the force the wind speed applies to the turbine. Wind power is considered highly intermittent and non-dispatchable because it is a variable power source, meaning that its electrical output depends on many factors, such as wind speed, air density, turbine characteristics, and more. All of these factors also change depending on location of the site. Wind speed must also be in a certain range (depending on the turbine), above 3.5 m/s in order to generate electricity, and below 25 m/s to avoid damage to the turbine (Huang *et al* 2014). When taking multiple wind farm's intermittency into consideration, it would make sense that the reliability would somewhat increase, but this actually doesn't appear to be the case. For example, between October 2006 and February 2007 there were 17 days when the output from Britain's 1632 windmills was less than 10% of their capacity. During that period there were five days when output was less than 5% and one day when it was only 2% (McKay 2008).

The difficulty associated with integrating variable sources of electricity stems from the fact that the current power grid was generally designed around the concept of large, controllable, steady supply electric generators (J.M.K.C. *et al* 2017). In current industrial practice, the grid operator uses a three-phase planning process to ensure power plants produce the required amount of electricity at the appropriate time to meet electric demand consistently and reliably. Because most grids in 2019 have very little storage capacity, the balance between electricity supply and demand must be maintained at all times to avoid a blackout or other cascading problem.

Intermittent renewables are challenging because they disrupt the conventional methods for planning the daily operation of the electric grid. Their power fluctuates over multiple time horizons, forcing the grid operator to adjust its day-ahead, hour-ahead, and real-time operating procedures.

Wind power is by far the primary energy source that most need high quality energy storage options. Thus, for this power source to be viable, a large battery bank will also need to be built as part of the up front development costs. As of July 2018, global wind installed power generation capacity was 597 GW (WWEA 2019 and Global Energy Observatory 2018). Installed power generation capacity is related to the number and size of physical power stations that are operating and supplying electricity to the grid.

4.4.8 Solar Power Generation Efficiency

Solar power is the conversion of energy from sunlight into electricity, either directly using photovoltaics (PV), indirectly using concentrated solar power, or a combination. Concentrated solar (thermal solar) power systems use lenses or mirrors and tracking systems to focus a large area of sunlight into a small beam. Photovoltaic cells convert light into an electric current using the photovoltaic effect.

The moving path of the sun and the weather conditions drastically alter the incident solar radiation. Figure 4.25 shows the annual variation in daily solar radiation in Germany (Wesselak & Voswinckel 2016). Amount of solar radiation has a direct influence on the efficiency and effectiveness for solar photovoltaic panels to generate electricity. This also makes solar power highly intermittent in supply. This problem is more extreme closer to the geographical poles as compared to the planetary equator.

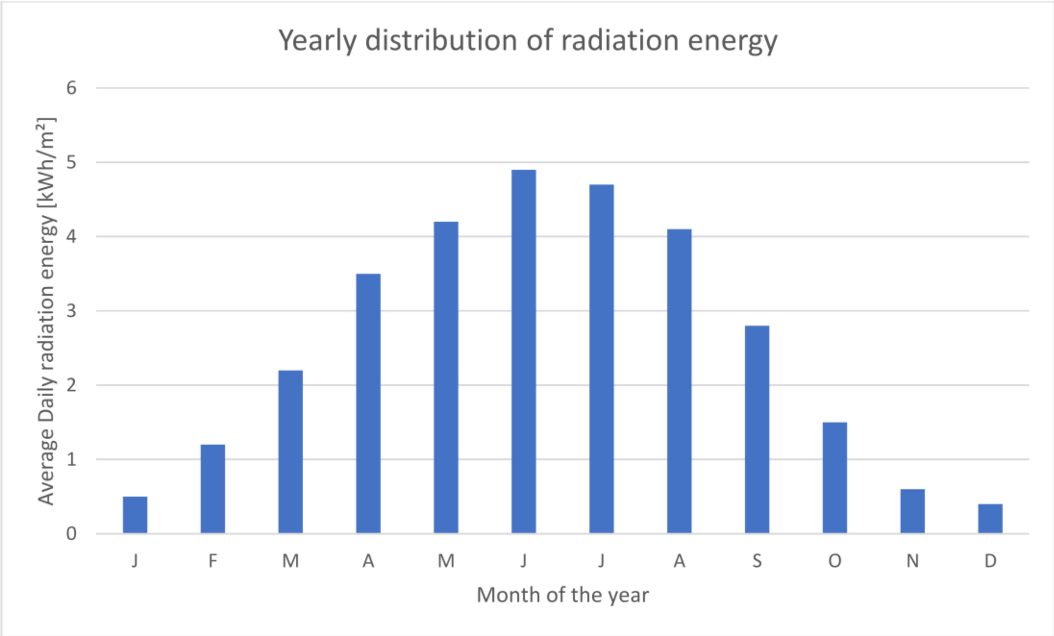


Figure 4.25. Distribution of the sun's radiation energy over the year in Germany (Wesselak & Voswinckel 2016)

For industry to operate, regular power supply of consistent quality (sinusoidal wave), a large power buffer (a battery bank, or spinning flywheel or pumped storage) is required to act as a buffer (Droste-Franke 2015). A common method used to express economic costs is to calculate a price per delivered kilowatt-hour (kWh). The solar cell efficiency in combination with the available irradiation has a major influence on the costs. The efficiency on an annual basis, is approximately 12% as a general average, is considerably less than on a daily basis according to weather conditions.

Of course, solar PV systems do not function after sunset and cannot generate power at night.

4.4.8.1 Solar Photovoltaic (PV)

PV cell efficiencies vary from 6% for amorphous silicon-based solar cells to 44.0% with multiple-junction production cells. Solar cell energy conversion efficiencies for commercially available multi-crystalline silicon solar cells are around 14-19%. The highest efficiency cells have not always been the most economical — for example a 30% efficient multifunction cell based on exotic materials such as gallium arsenide or indium selenide produced at low volume might well cost one hundred times as much as an 8% efficient amorphous silicon cell in mass production, while delivering only about four times the output (Abu-Rub *et al* 2014). These were the top five best solar panel manufacturers in 2019 ranked based on the highest efficiency solar panel the 2019 market has to offer (Energysage 2019):

- SunPower (22.8%)
- LG (21.7%)
- REC Solar (21.7%)
- Panasonic (20.3%)
- Silfab (20.0%)

Figure 4.26. Photovoltaic solar panel array power generation
(Image by David Mark from Pixabay)

The most efficient solar panels on the market today have efficiency ratings as high as 22.8%, whereas the majority of panels range from 15% to 17% efficiency rating (Abu-Rub *et al* 2014).

Such systems are dependent on a battery bank to act as a buffer between generation and application. This is often not included in energy efficiency calculations. Solar PV is rapidly becoming an inexpensive, low-carbon technology to harness renewable energy from the Sun (Solar Power Europe 2018). The current largest photovoltaic power station in the world is the 850 MW Longyangxia Dam Solar Park, in Qinghai, China. In 2017, global installed solar PV capacity was 580.14 GW (Solar Power Europe 2018). Installed power generation capacity is related to the number and size of physical power stations that are operating and supplying electricity to the grid.

In the year 2018, 579.1 TWh of electricity (or 2.18% of the 2018 total) was generated with solar PV power stations (Table 8.4 in Section 8, Solar PV and Solar Thermal are combined).

4.4.8.2 Solar thermal

Systems can achieve efficiency up to 20% (EIA 2019 and Abu-Rub *et al* 2014). Solar thermal power plants are electricity generation plants that utilize energy from the Sun to heat a fluid to a high temperature. This fluid then transfers its heat to water, which then becomes superheated steam. This steam is then used to turn turbines in a power plant, and this mechanical energy is converted into electricity by a generator. This type of generation is essentially the same as electricity generation that uses fossil fuels, but instead heats steam using sunlight instead of combustion of fossil fuels. These systems use solar collectors to concentrate the Sun's rays on one point to achieve appropriately high temperatures.

The principle of the solar tower is the same as that of the solar trough: focus sunlight onto a solar receiver where a heat transfer fluid can be heated, and the heat carried away to generate electricity. With the solar tower the linear receiver is replaced with a single-point receiver mounted at the top of the central tower (Breeze 2016). This receiver must be able to capture all the heat energy from a large number of heliostats mounted at ground level around it. The type of receiver used in commercial solar tower power plants is called an external tube receiver. The solar heat directly hits the outside of tubes that carry the heat transfer fluid, and the heat is conducted through the tube material to the fluid inside.

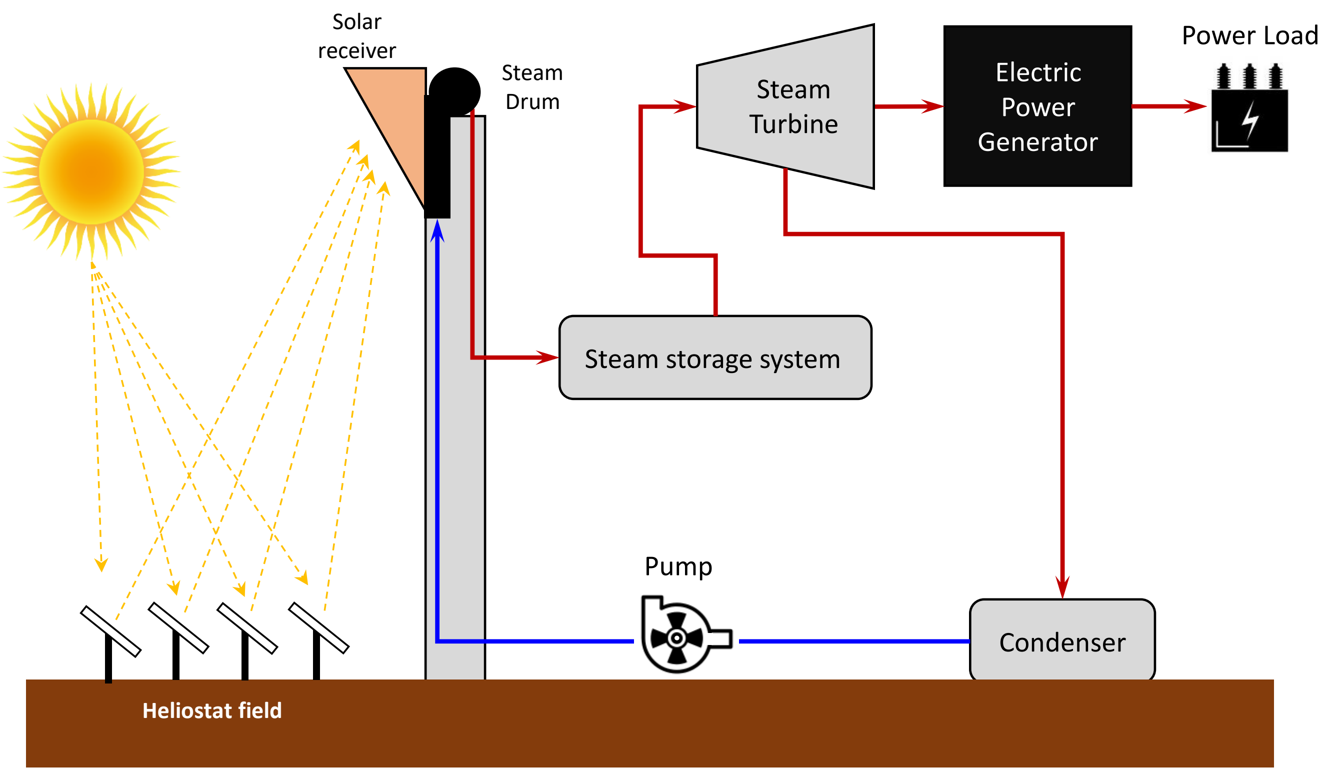


Figure 4.27. Thermal solar tower power plant schematic
(Image by Simon Michaux, using some copyright free clipart)

Another system is the parabolic-trough solar concentrating systems, where there are parabolic-shaped collectors made of reflecting materials (Breeze 2016). The collectors reflect the incident solar radiation onto its focal line toward a receiver that absorbs the concentrated solar energy to raise the temperature of the fluid inside it.

Parabolic trough systems use curved, parabola-shaped reflectors that use mirror coating to concentrate sunlight on a tube filled with liquid (Breeze 2016). This tube, frequently called a Dewar tube, is usually filled with oil, and carries the heated fluid to an engine similar to a traditional power plant.

To reach its maximum thermal efficiency of 60–80%, parabolic reflectors are mounted on tracking systems to follow the sun. The intensity of the concentrated solar rays heats the liquid medium to approximately 400°C.

There are two types of systems to collect solar radiation and store it: passive systems and active systems. Solar thermal power plants are considered active systems. These plants are designed to operate using only solar energy, but most plants can use fossil fuel combustion to supplement output when needed.

At the end of 2018, global thermal solar installed power generation capacity was 5.5GW, after an increase of 11% over the year 2018 (Global Energy Observatory 2018 and Reve 2019). In the year 2018, 5.5 TWh of electricity (or 0.02% of the 2018 total) was generated with solar thermal power stations (Table 8.4 in Section 8, Solar PV and Solar Thermal are combined).

4.4.9 Geothermal Power Generation Efficiency

Geothermal power stations are similar to other steam turbine thermal power stations in that heat from a fuel source (in geothermal's case, the Earth's core) is used to heat water or another working fluid. The working fluid is then used to turn a turbine of a generator, thereby producing electricity. The fluid is then cooled and returned to the heat source. Geothermal systems also use the Rankine cycle with steam temperatures at saturation point. Since there is no other conversion loss, this plant can achieve efficiencies in the range of 35% but can be as low as 10% (Kiameh 2013 and Abu-Rub *et al* 2014). As of July 2018, global geothermal installed power generation capacity was 14.6 GW (IEA 2018a, Wang 2018 and Global Energy Observatory 2018). In the year 2018, 93 TWh of electricity (or 0.35% of the 2018 total) was generated with geothermal power stations (BP Statistical Review of World Energy 2019).

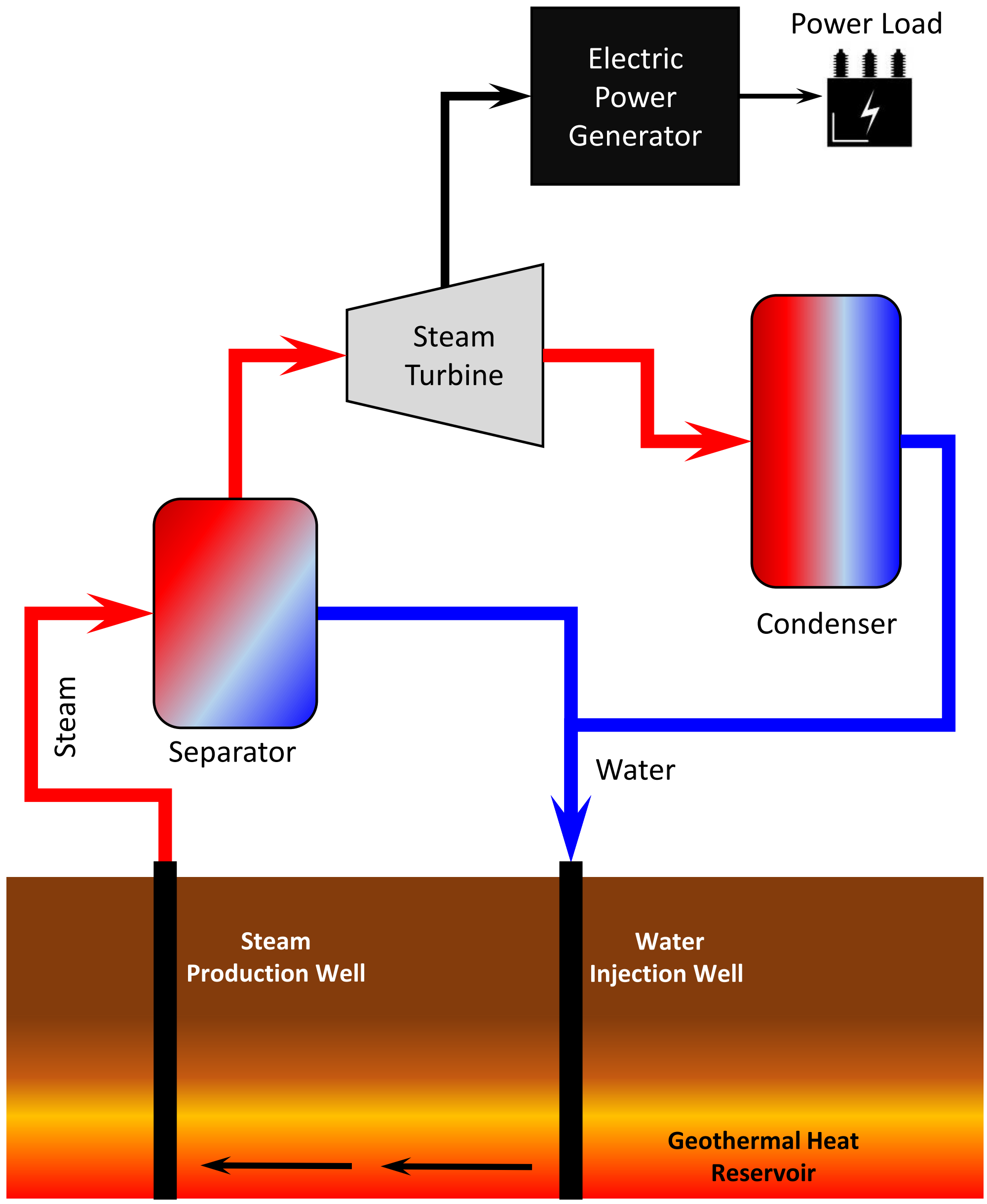


Figure 4.28. Geothermal power plant general schematic
(Image: Simon Michaux, using some copyright free clipart)

4.4.9.1 Dry steam power stations

Dry steam stations are the simplest and oldest design. This type of power station is not found very often, because it requires a resource that produces dry steam. In these sites, there may be liquid water present in the reservoir, but no water is produced to the surface, only steam. Dry Steam Power directly uses geothermal steam of 150 °C or greater to turn turbines. As the turbine rotates it powers a generator which then produces electricity and adds to the power field. Then, the steam is emitted to a condenser. Here the steam turns back into a liquid which then cools the water. After the water is cooled it flows down a pipe that conducts the condensate back into deep wells, where it can be reheated and produced again.

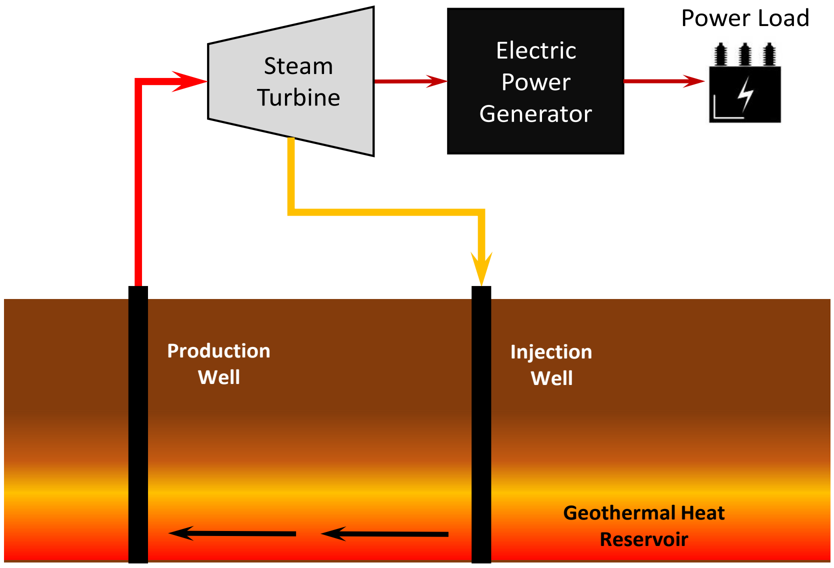


Figure 4.29. Geothermal dry steam power plant schematic
(Image: Simon Michaux, using some copyright free clipart)

4.4.9.2 Flash steam power stations

Flash steam stations pull deep, high-pressure hot water into lower-pressure tanks and use the resulting flashed steam to drive turbines. They require fluid temperatures of at least 180°C, sometimes more. This is the most common type of station in operation today. Flash steam plants use geothermal reservoirs of water with temperatures greater than 182°C. The hot water flows up through wells in the ground under its own pressure. As it flows upward, the pressure decreases and some of the hot water boils into steam. The steam is then separated from the water and used to power a turbine/generator. Any leftover water and condensed steam may be injected back into the reservoir, making this a potentially sustainable resource.

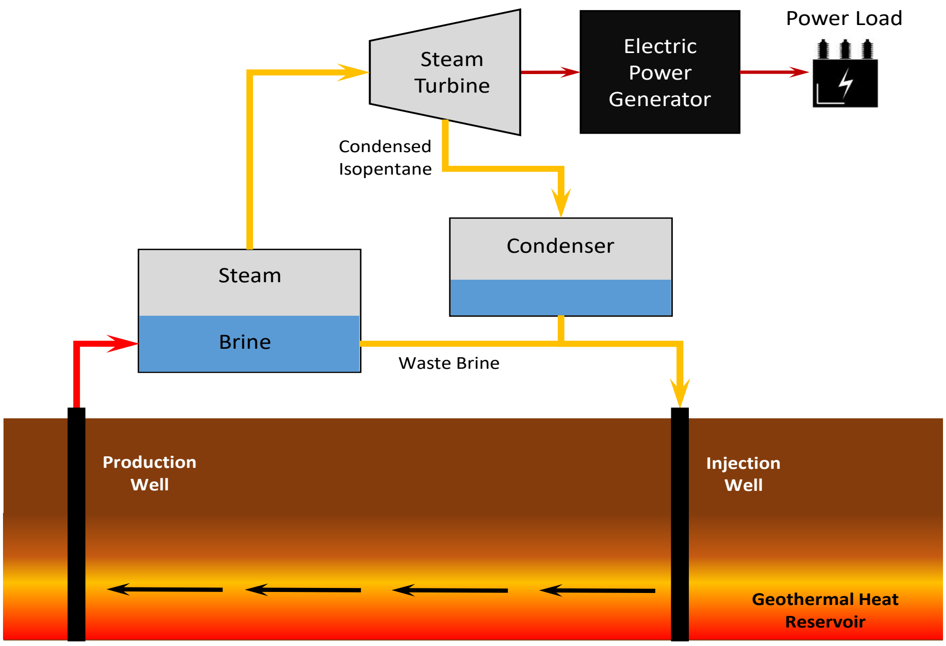


Figure 4.30. Geothermal power flash steam power plant schematic
(Image: Simon Michaux, using some copyright free clipart)

4.4.9.3 Binary cycle power stations

Binary cycle power stations are the most recent development, and can accept fluid temperatures as low as 57°C. The moderately hot geothermal water is passed by a secondary fluid with a much lower boiling point than water. This causes the secondary fluid to flash vaporize, which then drives the turbines. This is the most common type of geothermal electricity station being constructed today. Both Organic Rankine and Kalina cycles are used. The thermal efficiency of this type of station is typically about 10–13%.

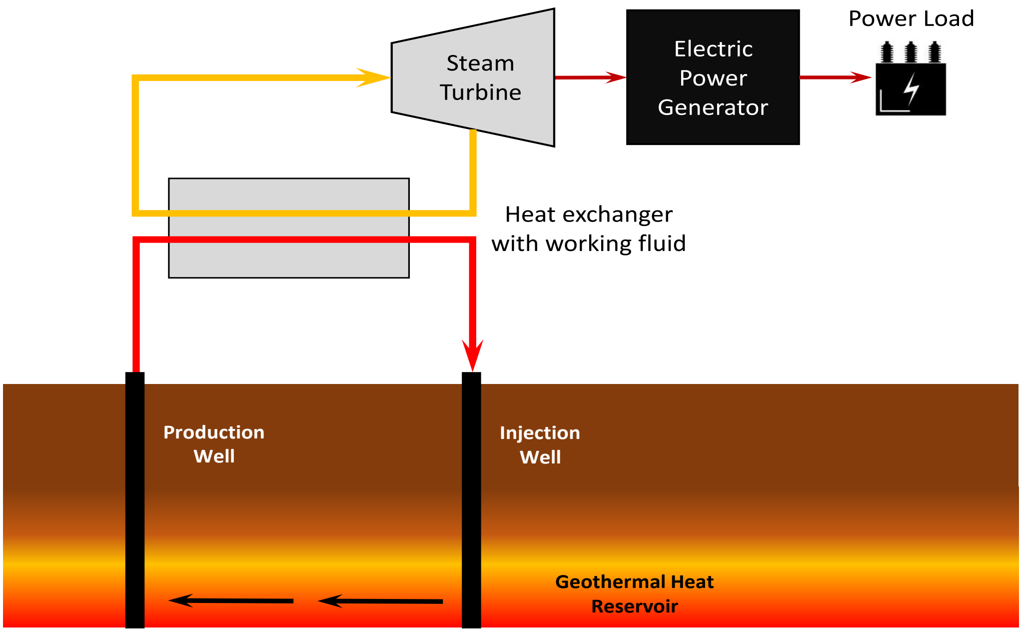


Figure 4.31. Geothermal binary cycle power plant schematic
(Image: Simon Michaux, using some copyright free clipart)

4.4.9.4 Low-enthalpy geothermal 'passive' power

Low-enthalpy geothermal energy can be generated from groundwater in gravels infilling buried valleys formed during the Pleistocene glaciation, when the sea level was significantly lower than at present (Allen & Milenic 2003). Where buried valleys underlie floodplains of present-day rivers, flowing through major cities, a 'heat island' effect can generate slightly enhanced temperatures in shallow groundwater. This groundwater can be utilized for space heating buildings by passing it through a heat pump, and the chilled water then used as a heat exchanger to satisfy cooling requirements of the building.

For flow rates of 20 liters/ s, and a temperature reduction of 8 °C in the heat pump, a 672 kW heating resource can be generated, sufficient to heat buildings of 11 000 m^2 floor area. A cooling resource of 336 kW is also available. Potentially, this geothermal resource could be utilized without the 'heat island' effect. Cost of the development is minimal and long-term economic benefits are significant (Allen & Milenic 2003).

4.4.10 Oil Fueled Electrical Power Generation

Before natural gas power plants became widespread, oil fueled electric generation power plants were used on a small scale. Power plants that burn petroleum liquids (such as distillate or residual fuel oils) are generally used for short periods during times of peak electricity demand. Most oil-fired generators are either turbines or internal combustion engines used to supply power only at times of peak electric power demand or when natural gas prices rise due to local natural gas demand (EIA 2017).

Currently, petroleum-fired power plants operate mostly at low capacity factors because of the high price of petroleum relative to other fuels, air pollution restrictions, and lower efficiencies of their aging generating technology. Roughly 70% of petroleum-fired electric generating capacity that still exists today was constructed prior to 1980 (EIA 2017).

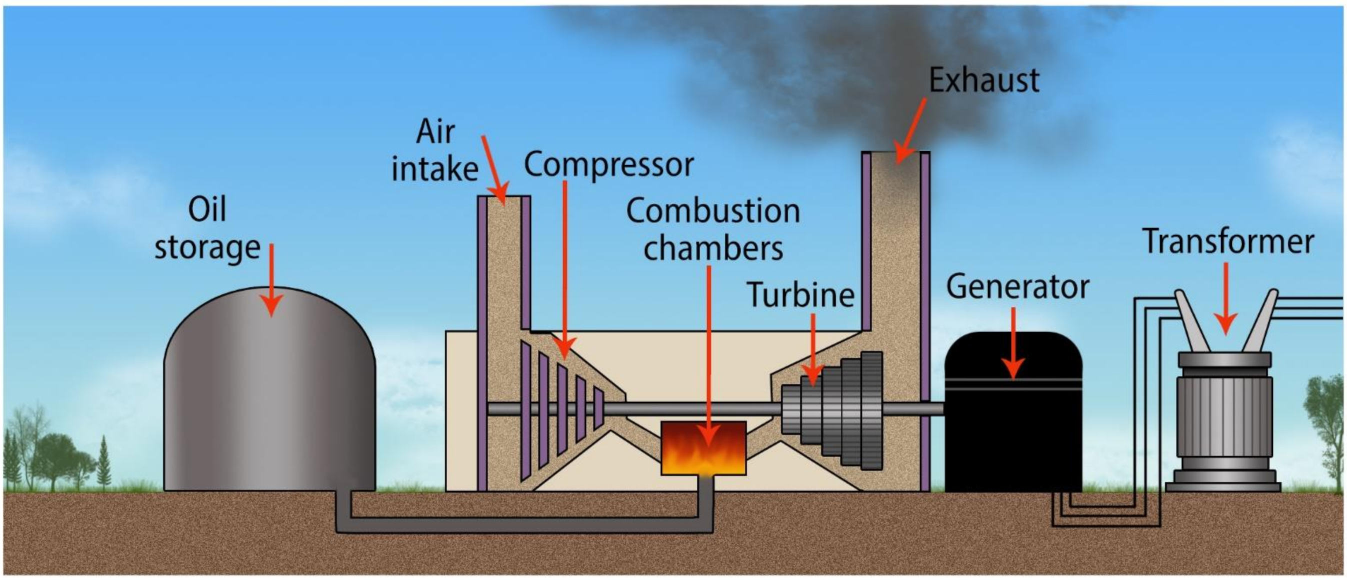


Figure 4.32. Oil electrical power generation
(Image: Tania Michaux)

4.4.11 Diesel Engines Efficiency

The diesel engine (also known as a compression-ignition or CI engine), named after Rudolf Diesel, is an internal combustion engine (ICE) in which ignition of the fuel, which is injected into the combustion chamber, is caused by the elevated temperature of the air in the cylinder due to the mechanical compression (adiabatic compression) (Kiameh 2013).

Diesel engines work by compressing only the air. This increases the air temperature inside the cylinder to such a high degree that atomized diesel fuel injected into the combustion chamber ignites spontaneously. With the fuel being injected into the air just before combustion, the dispersion of the fuel is uneven; this is called a heterogeneous air-fuel mixture.

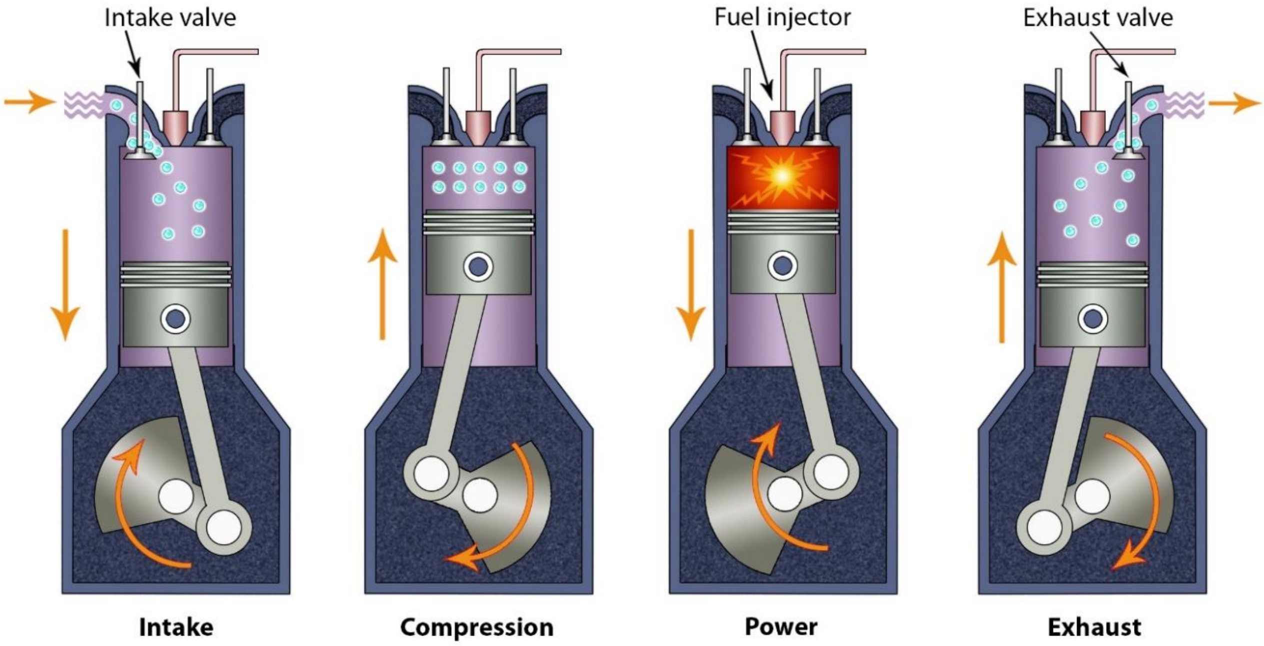


Figure 4.33. Four-stroke diesel engine typical sequence of compression cycle events
(Image by Tania Michaux)

The diesel engine has the highest thermal efficiency (engine efficiency) of any practical internal or external combustion engine due to its very high expansion ratio and inherent lean burn which enables heat dissipation by the excess air. Diesel engines, large capacity industrial engines, deliver efficiencies in the range of 35 – 42 % (Kiameh 2013).

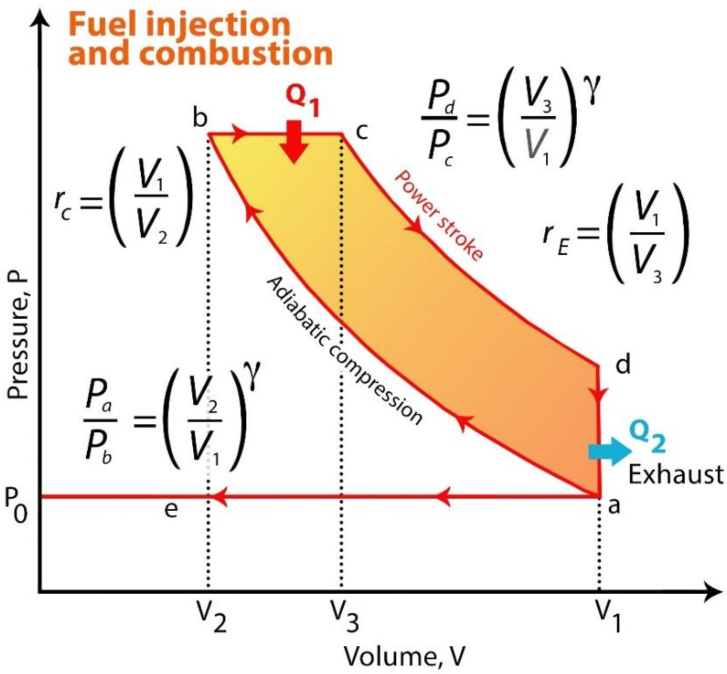


Figure 4.34. The diesel compression cycle
(Image: Tania Michaux)

Diesel engines are used in heavy load applications. Most diesel engines are used to power trucks and commercial vehicles (Figure 4.35).

Figure 4.35. A Class 8 semi-trailer long haul truck
(Image by RENE RAUSCHENBERGER from Pixabay)

Another application is a diesel powered stationary engine (an engine whose framework does not move). They are used to drive immobile equipment, such as pumps, generators, mills, or factory machinery. The term usually refers to large immobile reciprocating engines, principally stationary steam engines and, to some extent, stationary internal combustion engines. An example is shown in Figure 4.36, where two stationary engines are used to power a U-boat submarine (same configuration of a maritime ship).

Figure 4.36. Engine room of a U-boat submarine
(Image by Achim Scholty from Pixabay)

While diesel fuel is mainly used for transport applications, a small portion of it is used for electric power generation. As of July 2018, global fuel oil power generation capacity was 255.8 GW (Global Energy Observatory 2018). In the year 2018, 802.8 TWh of electricity (or 3.02% of the 2018 total) was generated with oil fueled power stations (Table 8.4 in Section 8).

Liquefied coal to substitute diesel fuel

Coal liquefaction is a process of converting coal into liquid hydrocarbons: liquid fuels and petrochemicals. Höök *et al* 2014 assessed this energy extraction method and estimated that at best, 54 million barrels of fuel per day (Mb/day) of liquefied coal (CTL) (Friedemann 2021). To put this in context, in 2019, global oil consumption was 95.2 million barrels (BP Statistical review of World Energy 2020). The thermal efficiency of the CTL process is approximately 50 – 60 % (Höök et al 2010). This will have direct implications on the ERoEI ratio for CTL as a viable fuel. As this is a fossil fuel and not very efficient, this was not considered.

4.4.12 Petrol Engines Efficiency

A petrol engine (known as a gasoline engine) is an internal combustion engine (ICE) with spark-ignition, designed to run on petrol (gasoline) and similar volatile fuels. Petrol engines are used mostly in passenger cars and motorcycles, due to superior performance compared to diesel engines. Petrol engines run at higher rotation speeds than diesels, partially due to their lighter pistons, connecting rods and crankshaft (a design efficiency made possible by lower compression ratios) and due to petrol burning more quickly than diesel.

Because of the difference in burn rates between the two different fuels, petrol engines are mechanically designed with different timing than diesels, so to auto-ignite a petrol engine causes the expansion of gas inside the cylinder to reach its greatest point before the cylinder has reached the "top dead center" (T.D.C) position.


Figure 4.37. The Internal Combustion Engine ICE
(LHS Image by MikesPhotos from Pixabay, RHS Image by Paul Brennan from Pixabay)

Most modern automobile petrol engines generally have a compression ratio of 10.0:1 to 13.5:1. In most petrol engines, the fuel and air are usually mixed after compression (although some modern petrol engines now use cylinder-direct petrol injection). The pre-mixing was formerly done in a carburetor, but now it is done by electronically controlled fuel injection, except in small engines where the cost/complication of electronics does not justify the added engine efficiency (Kiameh 2013). Modern gasoline engines have a maximum thermal efficiency of about 25% to 50% when used to power a car.

4.4.13 Jet Fuel Turbine Engine Efficiency

A jet engine is a type of reaction engine discharging a fast-moving jet that generates thrust by jet propulsion. This broad definition includes airbreathing jet engines (turbojets, turbofans, ramjets, and pulse jets). In general, jet engines are combustion engines. The term "jet engine" is commonly used only for air breathing jet engines. These typically feature a rotating air compressor powered by a turbine, with the leftover power providing thrust through the propelling nozzle – this process is known as the Brayton thermodynamic cycle (Kiameh 2013). Jet aircraft use such engines for long-distance travel.

Figure 4.38. A cut away of a jet turbine
(Image by PublicDomainPictures from Pixabay)

Figure 4.39. LHS - A jet engine (Image by WikimediaImages from Pixabay), RHS – An A380 Airbus Passenger aircraft
(Image by Rudi Nockewel from Pixabay)

Jet engines use a number of rows of fan blades to compress air which then enters a combustor where it is mixed with fuel (typically JP fuel) and then ignited. The burning of the fuel raises the temperature of the air which is then exhausted out of the engine creating thrust. A modern turbofan engine can operate at as high as a range of 36 - 48% efficiency (Griggs *et al* 2014).

4.4.14 Hydrogen Fuel Cell

See Section 16

4.4.15 Biowaste to energy

See Section 21.

4.4.16 Biofuel

See Section 21.

4.4.17 Nuclear Power Generation Efficiency

See Section 24.

4.5 Energy use in manufacturing

Manufacturing consumes 54 % of primary energy supply in the global industrial ecosystem (EIA 2019b). Moreover, manufacturing requires large quantities of energy in concentrated in individual industrial sites. This energy is also often required to be consistently and reliably supplied, often over a continuous time period measured in years. Industrial annual consumption of energy in the global market by raw material in 2018 was (EIA 2019b):

- 73% of coal
- 37% of natural gas
- 7.2% of oil
- 42% of electricity generated

The use of energy in industrial applications is very process requirement specific. That being stated, there are patterns. Heat is often required, where the steady temperature consistently maintained is critical to the manufacturing process. Industrial sites will draw large quantities of electric off the power grid, but the majority of the energy is generated directly with the combustion of fossil fuels (coal, gas, and oil) in furnaces, boilers, or kilns. Sometimes thermal heat is used directly, sometimes it is used to generate electricity on site, and sometimes it is used to make steam, which drives turbines. Examples of this are steel and cement production. In the United States, 75% of industrial energy use is to generate heat, with 83% generated from fossil fuels (Friedemann 2021, U.S. DoE 2014).

Fossil fuels has been the most efficient and effective method of generating large quantities of thermal heat that can be used industrially (Friedemann 2021). It has been the industrial application of thermal that has allowed the mass production of materials like steel or concrete (cement). It has been the underlying parameter that has allowed such high purity materials to be produced in any quantity (especially metals with very high melting temperatures), for which current engineering standards depend upon. Many renewable power technologies require high heat capability. For example, Solar panels require 1 500 – 2 000 °C of heat to transform silicon dioxide into metallurgical grade silicon metal (Honsberg & Bowden 2019, Friedemann 2021). Thermal heat has been required to manufacture products such as fertilizers, glass, plastics, rubber, ceramics, computers, chemicals, and tools (Table 4.5).

Table 4.5 Manufacturing temperatures, energy proportion, operations and applications
(Source: U.S. DoE 2015, Friedemann 2021, Sandalow *et al* 2019, McMillan *et al* 2016)

Temperature (^{0}C)	Proportion of total US manufacturing energy consumption (%)	Manufacturing Operation	Application Examples
932 - 1 649	3.7	Nonmetal melting	Plastics, rubber, food prepartion, softening
721 - 1 649	17.8	Ore smelting and metal melting	Steelmaking and other metal production, glass, ceramics
621 - 1 449	7.3	Cement	Calcining 900 ^{0}C, Sintering 1 449 ^{0}C
721 - 1 649	3.7	Metal heat treating and reheating	Hardening; annealing; tempering; forging; rolling
377 - 1 099	1.7	Coking	Ironmaking and other metal production
160 -549	21.6	Drying	Water and organic compound removal
138 -649	2.0	Curing and forming	Coating; polymers; enameling; moulding; extrusion
110 - 460	29.3	Fluid heating	Food preparation: chemicals; ditsillation; cracking
850	-	Combustion gases/primary steam reforming	Nitrogenous fertilizer manufacturing
99 - 1 649	12.8	Other	Incineration; preheating; catalysis

To date, most of the tasks shown in Table 4.5 have been met with the use of fossil fuels (coal, gas and oil). To replace fossil fuels, non-fossil fuel power sources are required that are capable of consistently and reliably producing quantities of heat over 1 200 ^{0}C, for sustained time periods.

Most iron and steel are made in large scale blast furnaces that take time to be brought to a stable temperature high enough to produce metal products. Some of these industrial sites optimally run continuously for up to 20 years, without shutting down. Unexpected power outages or disruptions of fuel supply can damage the brickwork lining. Complex fabrication assembly lines like those that produce computer chip need to run continuously for weeks to accomplish the thousands of steps needed to make microchips. Even a short disruption can be very costly. For example, a half-hour power outage at Samsung's Pyeongtaek chip plant caused losses of over $43 million dollars (Reuters 2019).

For some products, it may be possible to run in batches as opposed to a continuous process. If this were possible, it would be less energy efficient (otherwise it would be done now), cost more, and produce less product (Heinberg and Fridley 2016). Complex electronics (e.g. microchips), some chemicals, and other products might not be possible to produce in batch mode.

Unexpected outages can leave materials cooling in tanks and pipes, causing them to crystallize or harden, clogging the pipes (Friedemann 2021). Many processes need an exact continuous temperature and pressure because variations can cause metal fatigue and wear and tear. Even facilities that do not run continuously need to be up 60–95% of the time to repay their high capital investment (Friedemann 2021).

Currently, there are no means to store hours of high heat (Friedemann 2021). As many industrial processes need continuous heat a high temperature, either manufacturing plants are required to relocate to a continuous heat source like a nuclear power plant, or a completely new kind renewable power source has to be developed. Solar applications can only produce heat for a few hours at a time, then the sun sets. Wind is highly intermittent, as previously discussed, and is not suitable. For renewable power sources to truly substitute fossil fuels they must not only deliver enough electricity to replace fossil fuel applications in transport, but also must reach a “thermal parity” by powering industrial manufacturing processes that use high levels of heat in excess of 1 500 ^{0}C (Friedemann 2021). Table 4.6 shows non-fossil fuel heat sources.

Table 4.6. Maximum heat generated by non-fossil energy sources
(Source: U.S. DoE 2015, Friedemann 2021, Sandalow *et al* 2019)

Heat Source	Maximum Temperature Generated (^{0}C)	Comment	Feasible heat supply for smelting, metal forming & cement manfucature applications?
Biomass (Fuel)	2204	Biodiesel, ethanol	**Yes**
Hydrogen (H_2 gas)	2093	Made from natural gas or electrolysis	**Yes**
Electric: Resistance	1802	Indirect heat	**Yes**
Solar: Parabolic dish	1204	Small surface area heated, only for a few hours at a time	No
Biomass: Charcoal	1099	From forests, agriculture, waste	No
Concentrated Solar Power (CSP)	982	Small surface area heated, only for a few hours at a time	No
CSP oven	982	Small surface area heated, only for a few hours at a time, not commerical	No
Nuclear: Advanced	850	Not commercial	No
Biomass: Birch wood	950	Depends on the tree, i.e., rewood is 364 ^{0}C	No
Molten Salt	560	Thermal energy storage	No
Solar: Parabolic trough	400	Small surface area heated, only for a few hours at a time	No
Nuclear: Conventional	300	Gneration III+ reactors	No
Geothermal	193		No
Electric: Microwave direct heat		Temperature depends on material	

Due to the size and operational footprint of each industrial asset, the manufacturing sector is global in nature. The feedstocks for one industrial plant are often sourced from a very geographically different region. This means that manufacturing is intimately linked with global transport logistics. The United States is a remarkable case study, where much of the needed logistics exist inside just one national economy. For the last century, it has been the dominant economy, and holds the international reserve currency. Historically, the United States has an unusual signature in that it is very large, has a large consumer base, is a globally significant supplier of raw materials, and has globally significant industrial capacity. China may well be evolving into this profile. The United States manufactures 18% of the world goods (West & Lansang 2018), which makes it an excellent case study to quantify how industrialization consumes energy. Figure 4.40 and 4.41 compilation of the energy consumption requirements for the United States manufacturing sector. These flowsheets were released by the U.S. Department of Energy in 2014 (U.S. Department of Energy 2014). Figure 4.40 provides a high-level view of supply and end use (primary energy use). Figure 4.41 shows details of how energy is distributed to onsite industrial end uses. Appendix R shows a version of Figures 4.40 and 4.41 for each of the industrial products made in the US economy.

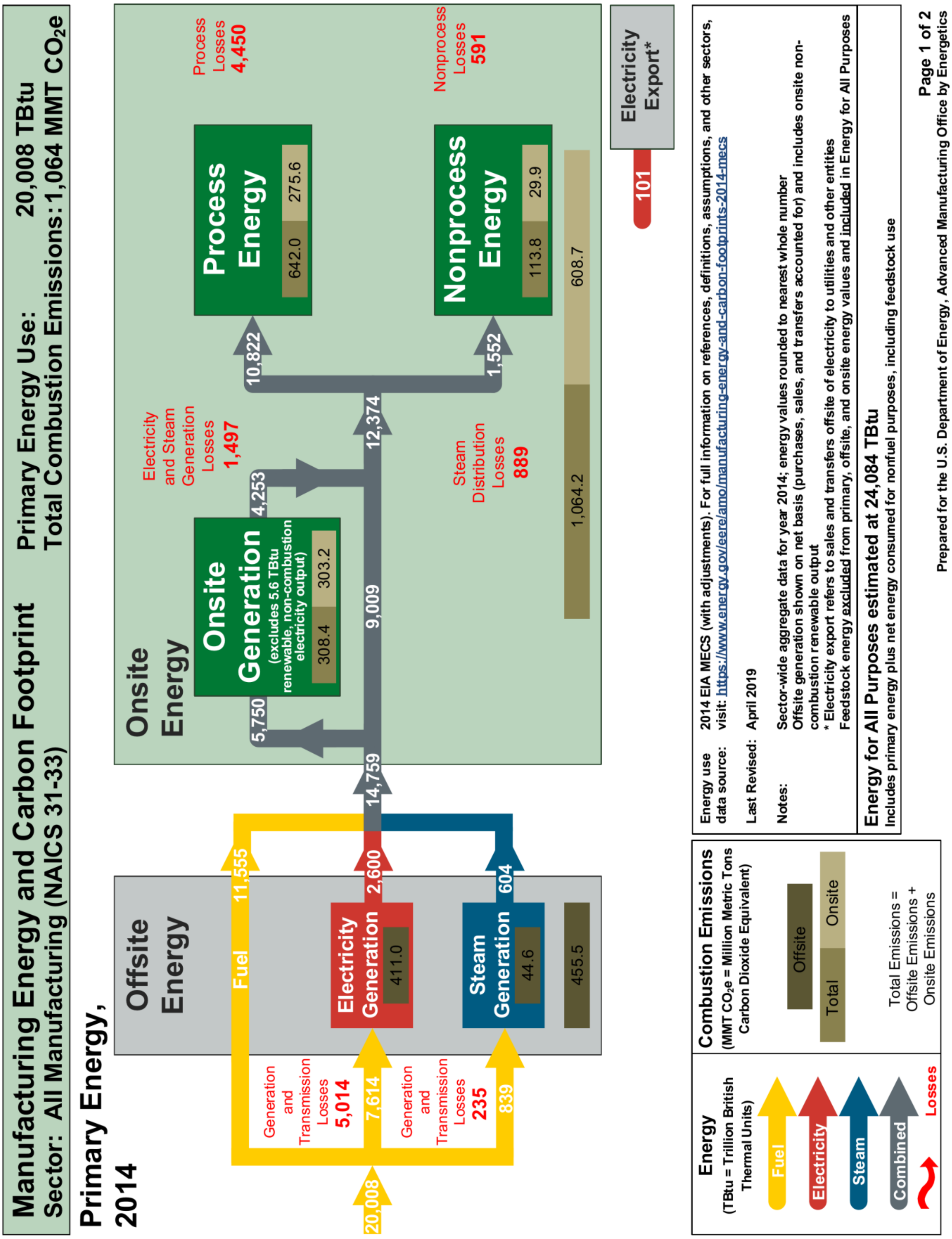


Figure 4.40. Manufacturing energy Onsite energy use of all manufacturing in the US, combines the footprints of 94% of manufacturing energy used for: Alumina and aluminum, cement, chemicals, computers, electronics, electrical equipment, fabricated metals, food and beverage, forest products, foundries, glass, iron and steel, machinery, petroleum refining, plastics, textiles, transportation equipment. Part 1 (US DoE 2014) (Copyright License: https://www.energy.gov/about-us/web-policies)

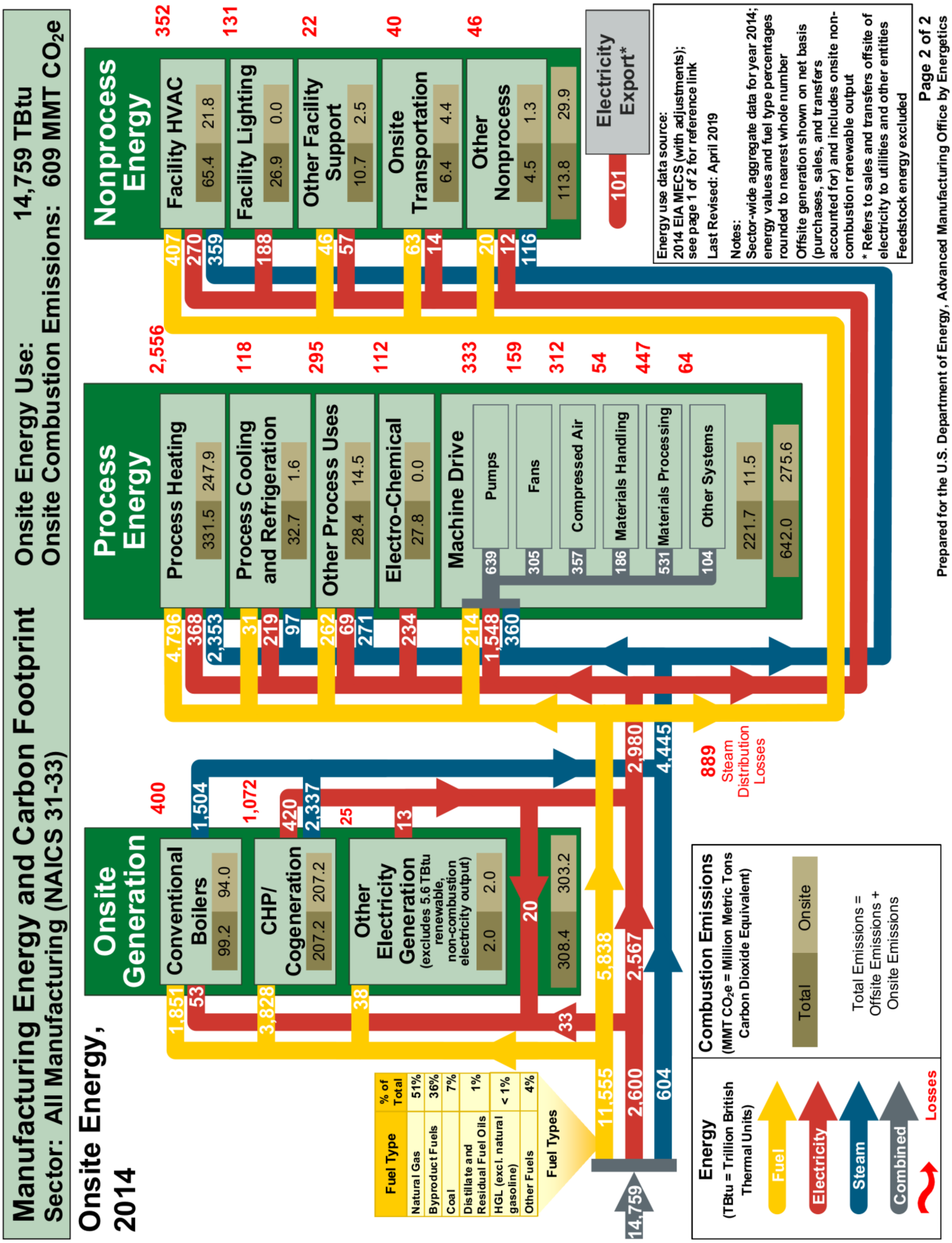


Figure 4.41. Manufacturing energy Onsite energy use of all manufacturing in the US, combines the footprints of 94% of manufacturing energy used for: Alumina and aluminum, cement, chemicals, computers, electronics, electrical equipment, fabricated metals, food and beverage, forest products, foundries, glass, iron and steel, machinery, petroleum refining, plastics, textiles, transportation equipment. Part 2 (US DoE 2014) (Copyright License: https://www.energy.gov/about-us/web-policies)

Figures 4.40 and 4.41 represents a summary of all United States manufacturing (in 2014). Energy losses and inefficiencies are visible in these flow charts. Before fossil fuel energy is delivered to an industrial site, 27 % is lost in processes offsite (off site energy input of 20 008 TBtu into the energy generation system with an actual delivery of 14,759 TBtu to site) (Figure 4.40) (Friedemann 2021). A further 50 % of energy is lost in internal industrial site processes like electricity generation and steam production (7427/14,759) (14 759 TBtu delivered to site and 2 980 TBtu electricity and 4 445 TBtu of steam directly applied to engineering processes, with a net loss of 7 334 TBtu of energy in process) (Figure 4.41) (Friedemann 2021). The mechanics of these flowsheets are discussed in Brueske *et al* (2012). With 77 % of energy losses, only 23% of that energy is converted into usable work.

The manufacturing sector is the industrial grouping for the production of:

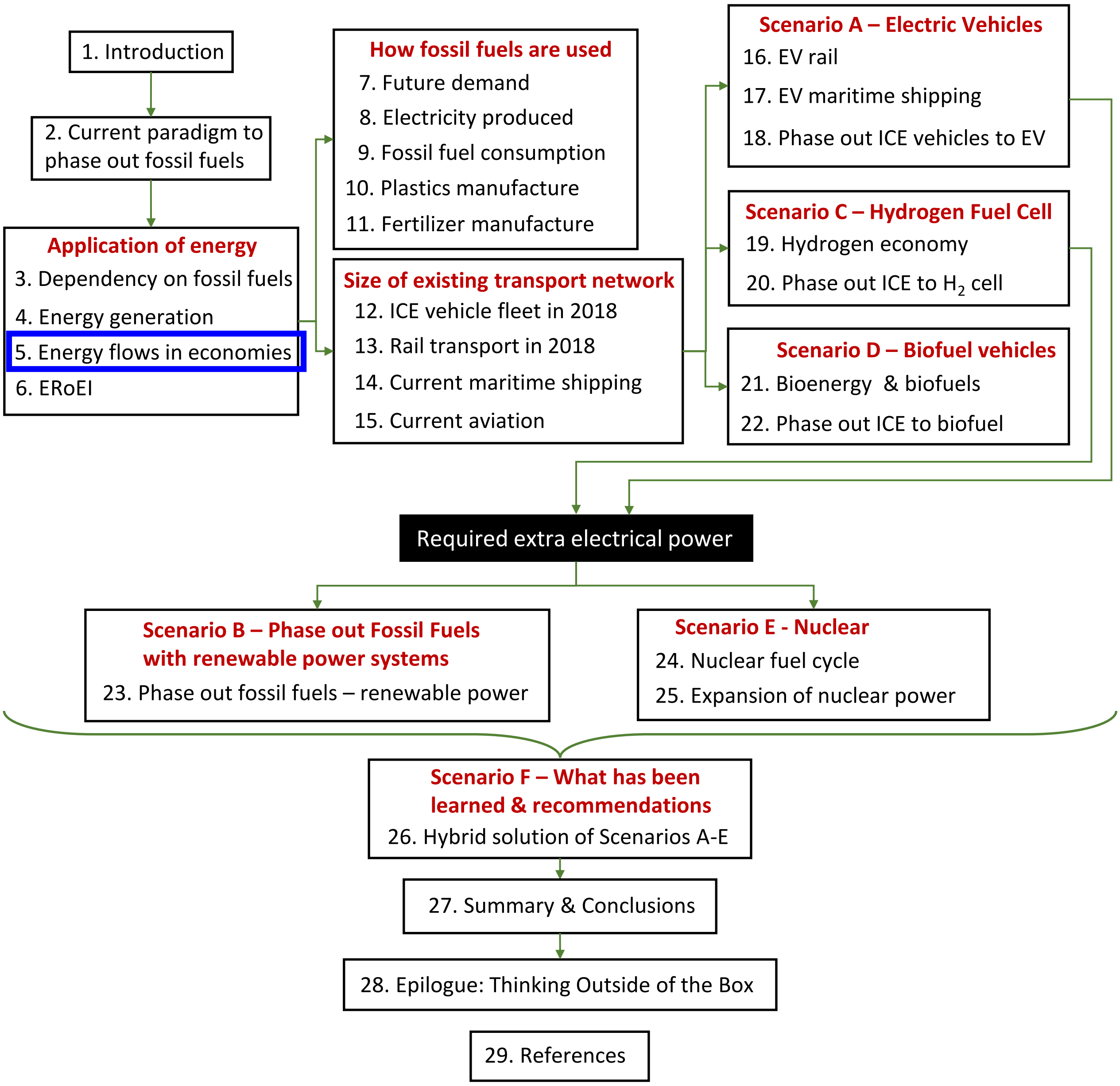
- Alumina and Aluminum
- Cement
- Chemicals
- Computers, Electronics and Electrical Equipment
- Fabricated Metals
- Food and Beverage
- Forest Products
- Foundries
- Glass
- Iron and Steel
- Machinery
- Petroleum Refining
- Plastics
- Textiles
- Transportation Equipment

To manufacture these products requires industrial conditions like stable high volume supply of electrical power, fuels, and feedstocks. Most products have no known way of being made with electricity or renewables (Friedemann 2021). Most of the manufacturing value chain will have to be re-designed and re-tooled. Possibly new equipment and processes need to be developed to replace fossil fuel supported systems, for nearly all kinds of industry (Malico *et al* 2019; Sandalow *et al* 2019).

This requirement to completely reinvent the manufacturing sector also impacts the current capability to produce engineering units for non-fossil fuel energy generation systems. Consider for example, what is required to construct a wind turbine array with 30 turbines connected to the electric power grid, or even a single solar panel. Most past developments of engineering have evolved with the assumption of easy access to concentrated electrical power, and concentrated thermal heat, both of which are consistently delivered for long periods of time. Rebuilding the manufacturing value chain to meet sustainable requirements of zero carbon emissions will be a challenge.

5 ENERGY FLOWS INSIDE MAJOR ECONOMIES

Section 5 will examine the energy mix for each major economy. Each economy will be examined in context what kind of energy source is used and for what basic application. A series of Sankey diagrams have been assembled to show the structure of how energy flows through each economy, with estimates of sources of energy waste.



Assessment of the Extra Capacity Required of Alternative Energy Electrical Power Systems to Completely Replace Fossil Fuels

The purpose of this report is to examine what purpose fossil fuels serve for the current industrial society and will examine what would be required of alternative power systems if fossil fuels are phased out immediately. To do this, the energy flows through several of the larger economies needs to be understood from an industrial ecology context. What energy resources were inputted into each economic entity, and how were these resources used in what tasks?

Industrial Ecology (IE) is the study of material and energy flows through industrial systems. The global industrial economy can be modelled as a network of industrial processes that extract resources from the Earth and transform those resources into commodities which can be bought and sold to meet the needs of humanity. Industrial ecology seeks to quantify the material flows and document the industrial processes that make modern society function. In industrial environments, the main goal of energy management is reliable, high quality and efficient use of energy in the light of sustainable development of companies.

Naturally, global factors should be considered as well as local specificities as the energy-supply value chain is international and concentrated in a relatively small number of foreign owned (in context of the EU) operators.

Figures 5.2 to 5.28 are Sankey diagrams developed mostly by the Lawrence Livermore National Laboratory (A more complete listing of energy Sankey diagrams is shown in Appendix L.). The energy flow diagram shows, on the left side, the fuels (primary energy) as sources. Streams lead to energy generation (power plants) or directly to the consuming sectors on the right (industry, commercial, residential, transportation). 'Rejected energy' (losses) are shown in grey color and contrasted with 'Energy services' (useful energy). These are energy lost through technical inefficacies of physical actions

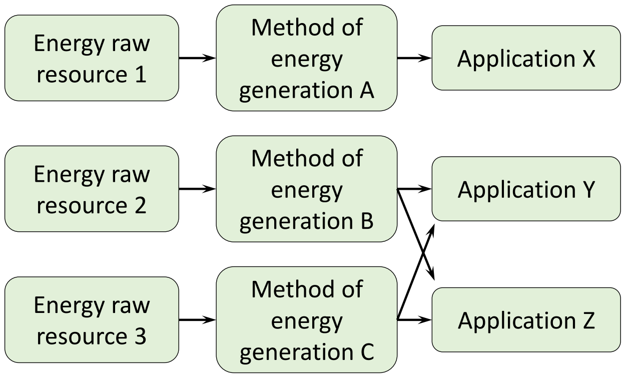


Figure 5.1. Relationship between energy resources and their application

What is clear in examining these diagrams is that energy is a support function for all activities, and that fossil fuels accounts for most of that energy supply in one form or another.

The modern industrial ecosystem is global in form. A relatively small number of nation states also dominate the industrial system and the international energy market, both in raw material supply and in consumption.

There are seven kinds of economies to consider:

1. **Nation States that Produce Energy Raw Materials**

The current energy system is heavily dependent on fossil fuels oil, gas, and coal. These are the producing nations.

2. **Nation States that Produce Raw Materials**

These nation states produce mineral resources and agricultural products. They are a vital part of the industrial ecosystem. This includes Congo, as it has more than half of the world's cobalt reserves, which will be needed to resource the perceived EV battery revolution.

3. **Industrial Production States**

These nation states produce the majority of the goods and services or have the potential to do so. If our industrial grid was to transform to renewable power only, these economies would have to transition while continuing to produce industrial products. China is the dominant economy in this context.

4. **Developed Nation States that are Consumers**

These nation states are fully developed and complex 'first world' economic systems. They generally do not produce raw materials in large enough quantities to be considered a major global producer. These economies are the globally largest consumer of finished products and manufactured goods. There is often some industrial capacity. These nations drive consumption, and therefore market patterns.

5. **Emerging Economies**

These economies are developing into 'first world' complexity. A case can be made that when these economies do this, an unprecedented strain on natural resources will result. Nation states like China, Poland and Hungary can also be placed in this classification but each of those nations are also classed as industrial production states.

6. **United States**

The United States is in a class of its own (for now). Since World War II, it was the largest economy, the largest consumer of energy, the largest producer of energy raw materials (up until 1970) and the largest supplier of industrial goods. It also has the current world reserve currency, the dollar. It is simultaneously a developed nation, the largest consumer, a world class energy producer, and an industrial manufacturer. It is predicted that China will soon have this profile.

7. **Nation States around Finland**

The implications of this reports and others like it suggest that structure of the industrial ecosystem will change in the next 5 to 50 years. The future ecosystem architecture may well be a series of alliances between industrial clusters. These clusters will almost certainly be geographically close. This report was written for the Finnish ecosystem and its neighbors.

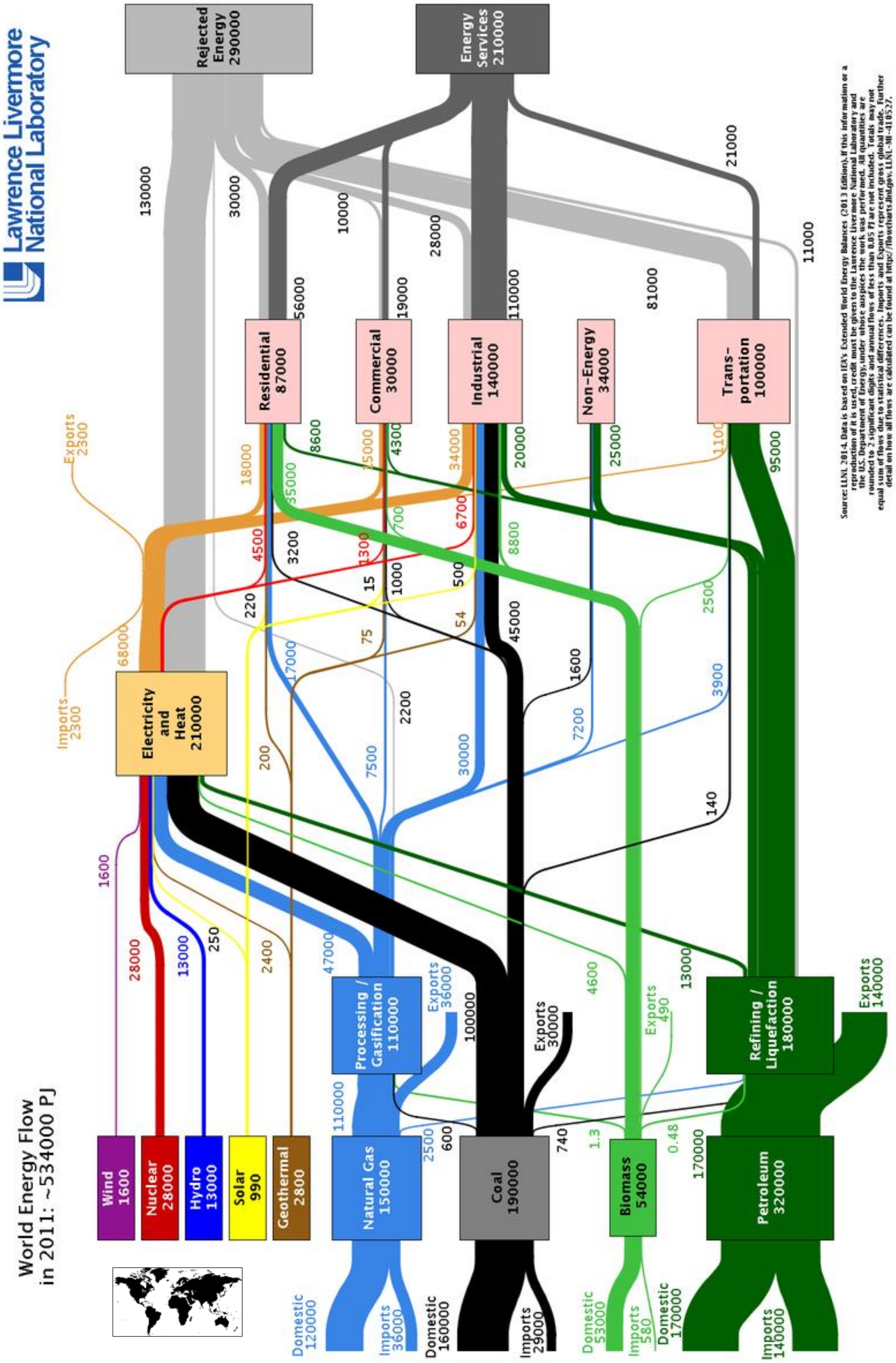


Figure 5.2. Global energy flow between energy source and application
(Source: Lawrence Livermore National Laboratory Energy Flow Charts)

(World Map Image by Clker-Free-Vector-Images from Pixabay)

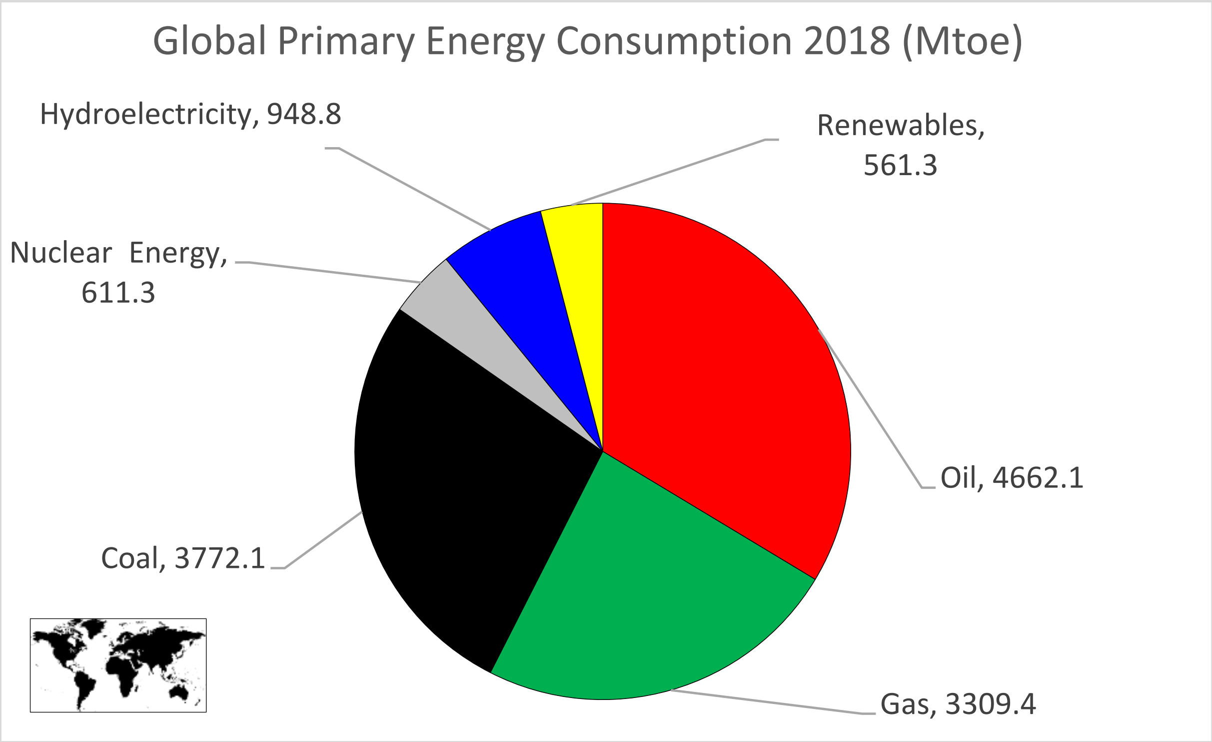


Figure 5.3. Global primary energy consumption by raw material source
(Source: BP Statistical Review of World Energy 2019 & Appendix A)
(World Map Image by Clker-Free-Vector-Images from Pixabay)

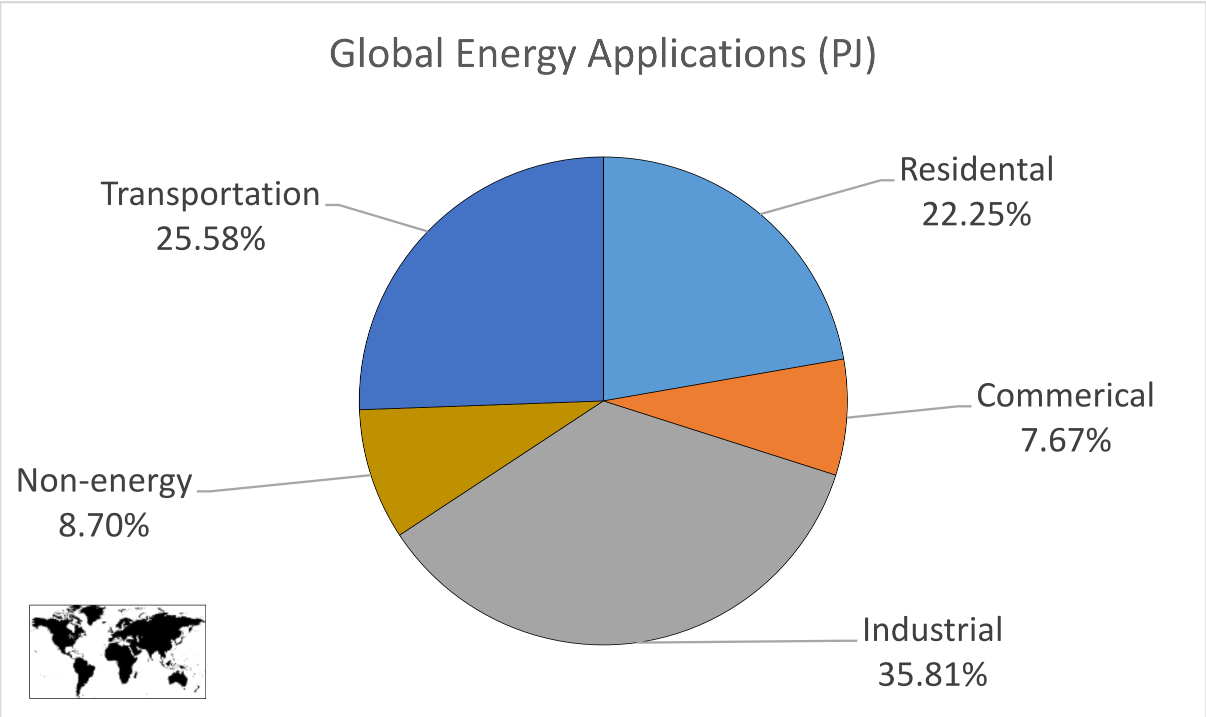


Figure 5.4. Global energy applications
(Source: Lawrence Livermore National Laboratory 2017, EIA 2017)
(World Map Image by Clker-Free-Vector-Images from Pixabay)

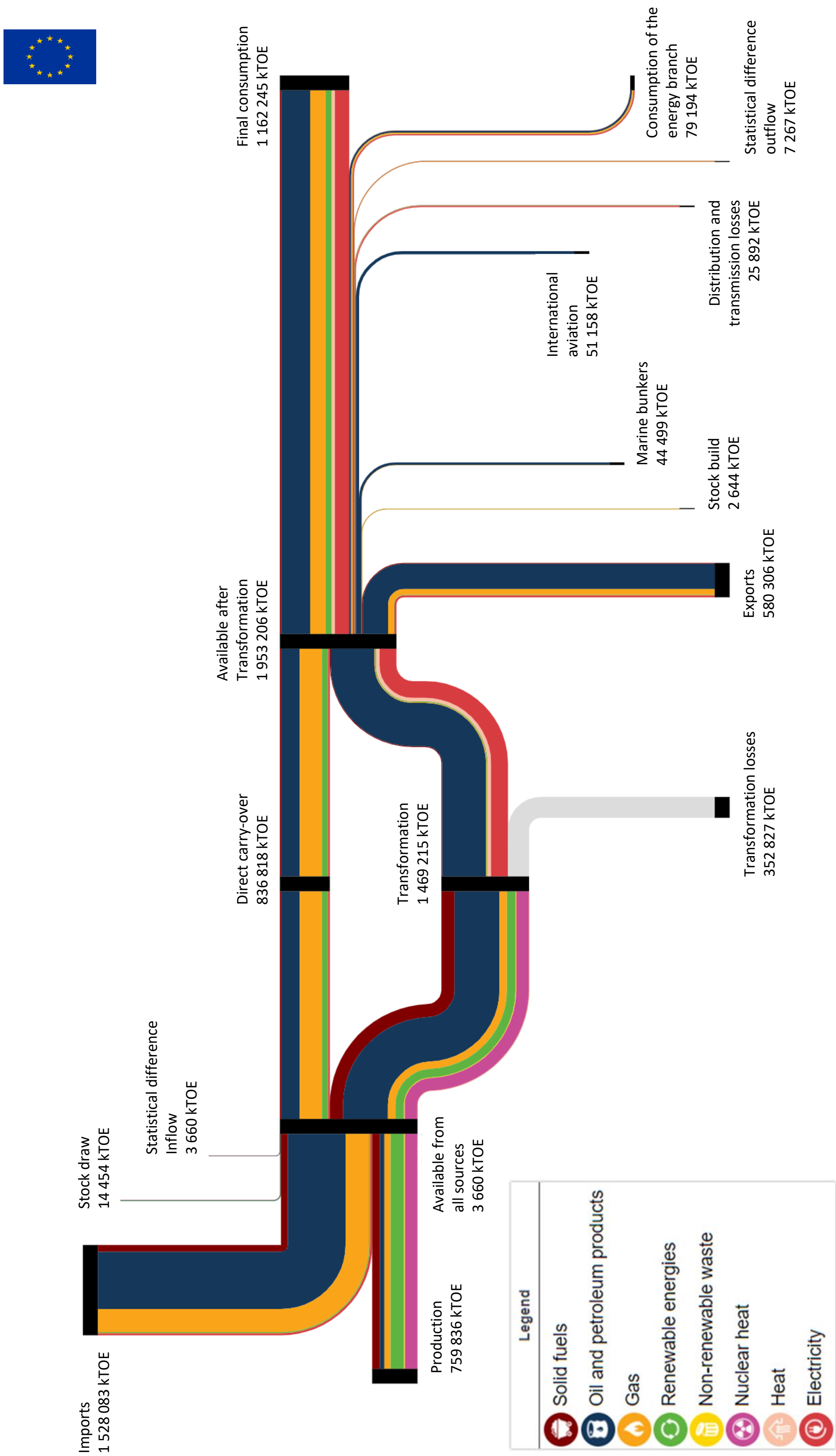


Figure 5.5: Energy balance flow for European Union EU-28 in 2017
(Source: European Commission Eurostat)
(https://ec.europa.eu/eurostat/web/products-eurostat-news/-/WDN-20190329-1)

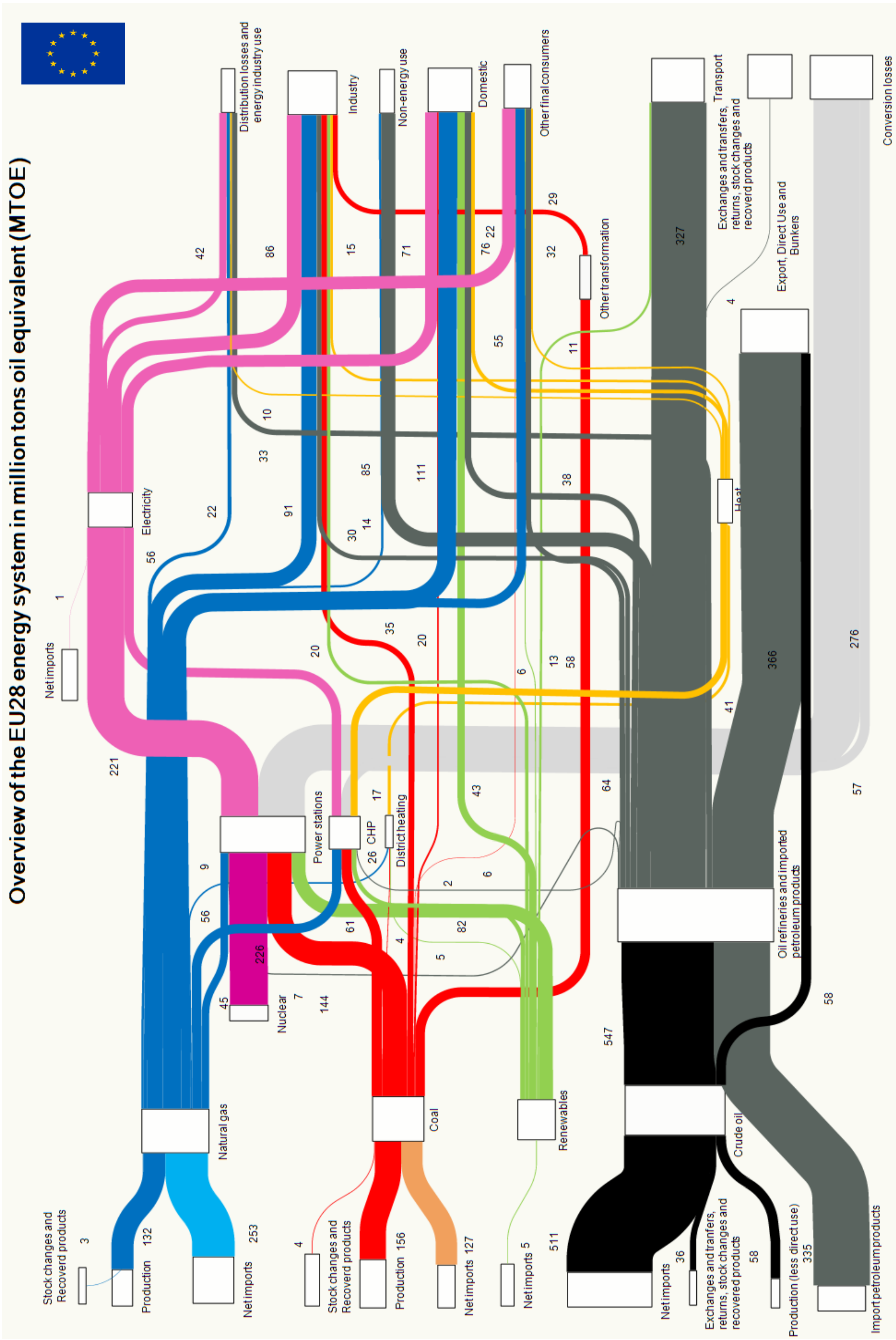


Figure 5.6: Composition of the primary energy entering the energy system of the EU-28 in 2013
(Source: European Environmental Agency, https://www.eea.europa.eu/)
(Copyright License: https://creativecommons.org/licenses/by-nc-sa/4.0/)

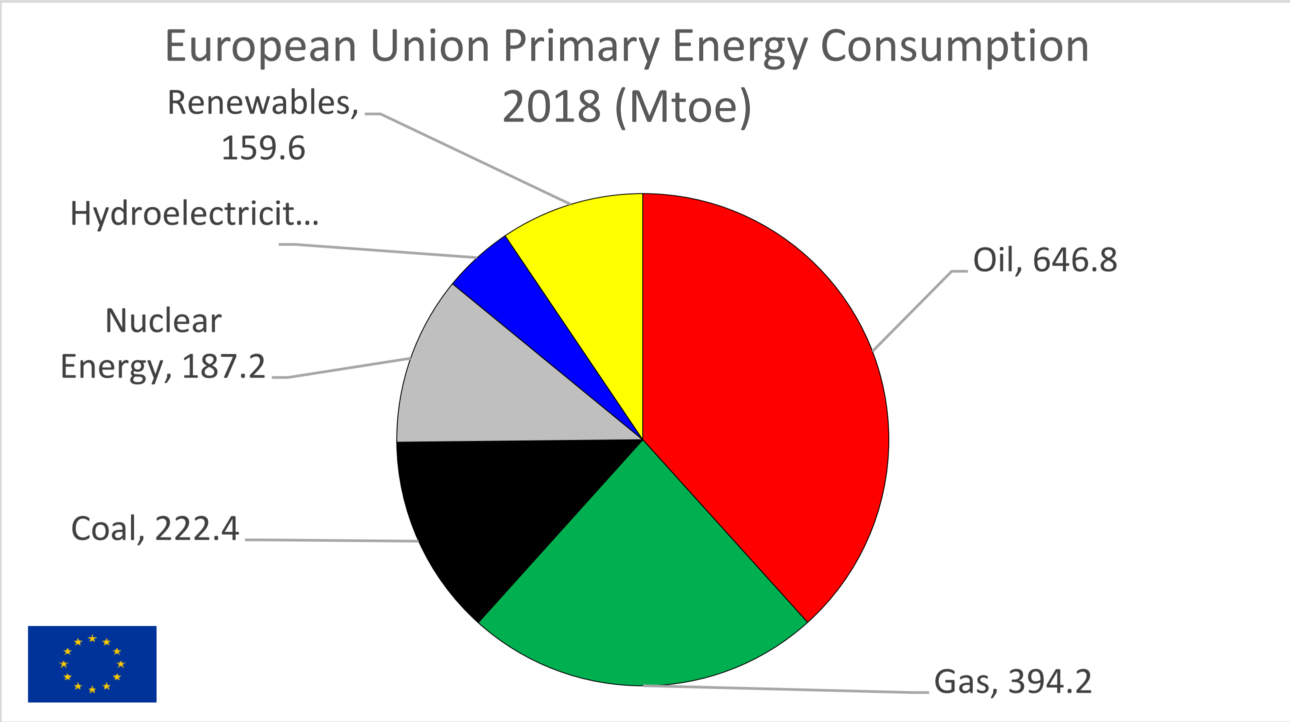


Figure 5.7. European EU-28 primary energy consumption by raw material source
(Source: BP Statistical Review of World Energy 2019 & Appendix A)

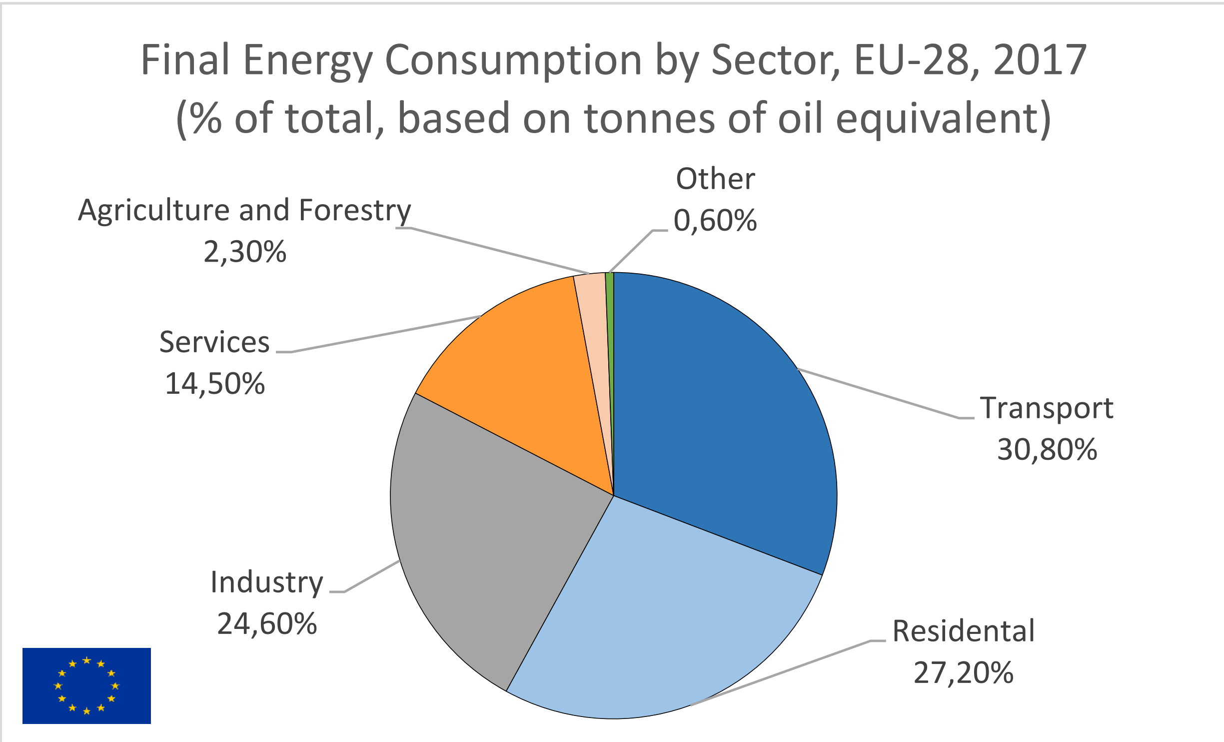


Figure 5.8. Final energy consumption by sector, EU-28, 2017
(% of total, based on tonnes of oil equivalent)
Source: Eurostat (nrg_bal_s)

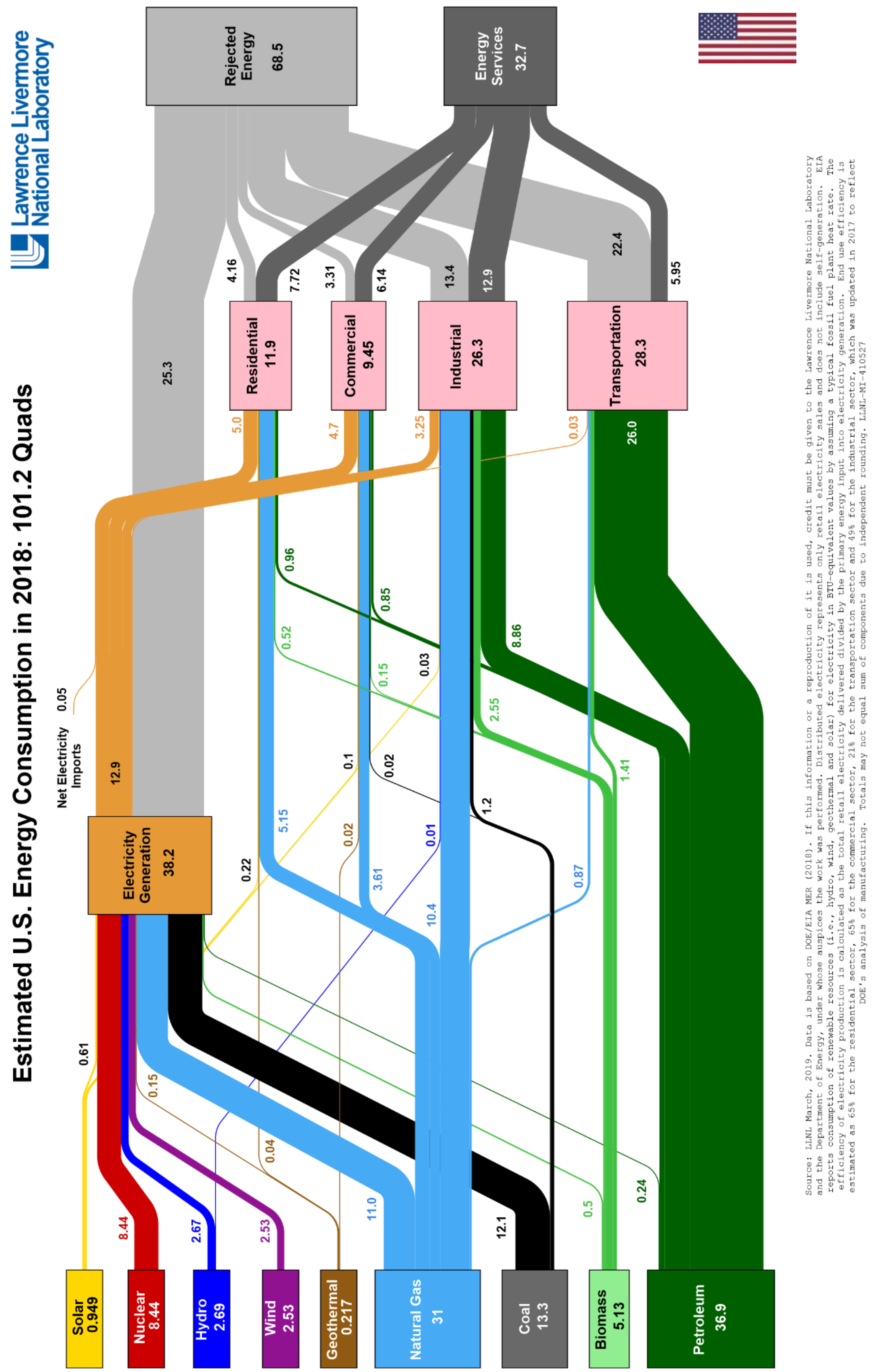


Figure 5.9. United States energy flow between energy source and application (Source: Lawrence Livermore National Laboratory 2019, EIA 2019) (Copyright License: https://creativecommons.org/licenses/by-nc-sa/4.0/)

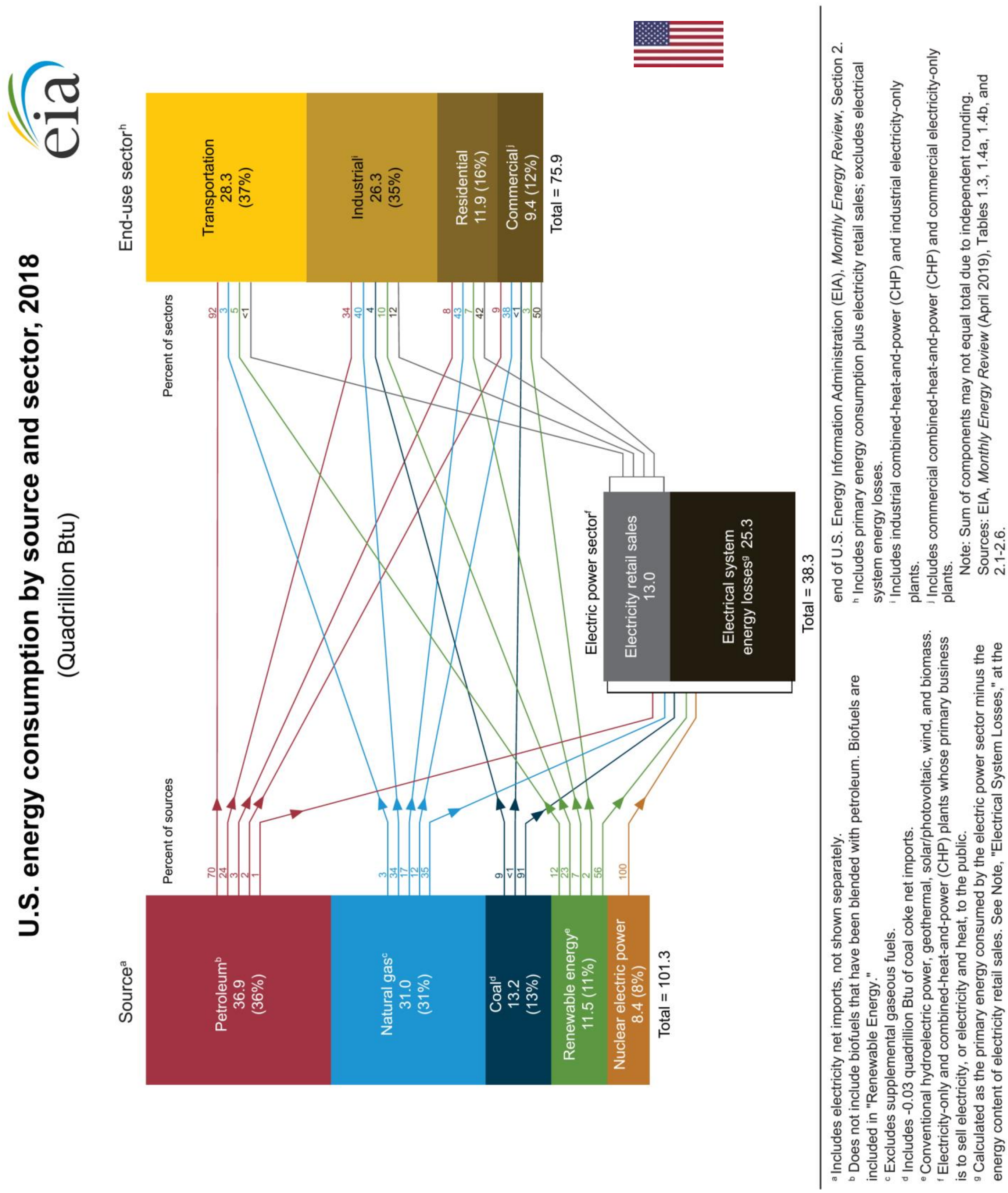


Figure 5.10. United States energy consumption
(Source: EIA 2019)

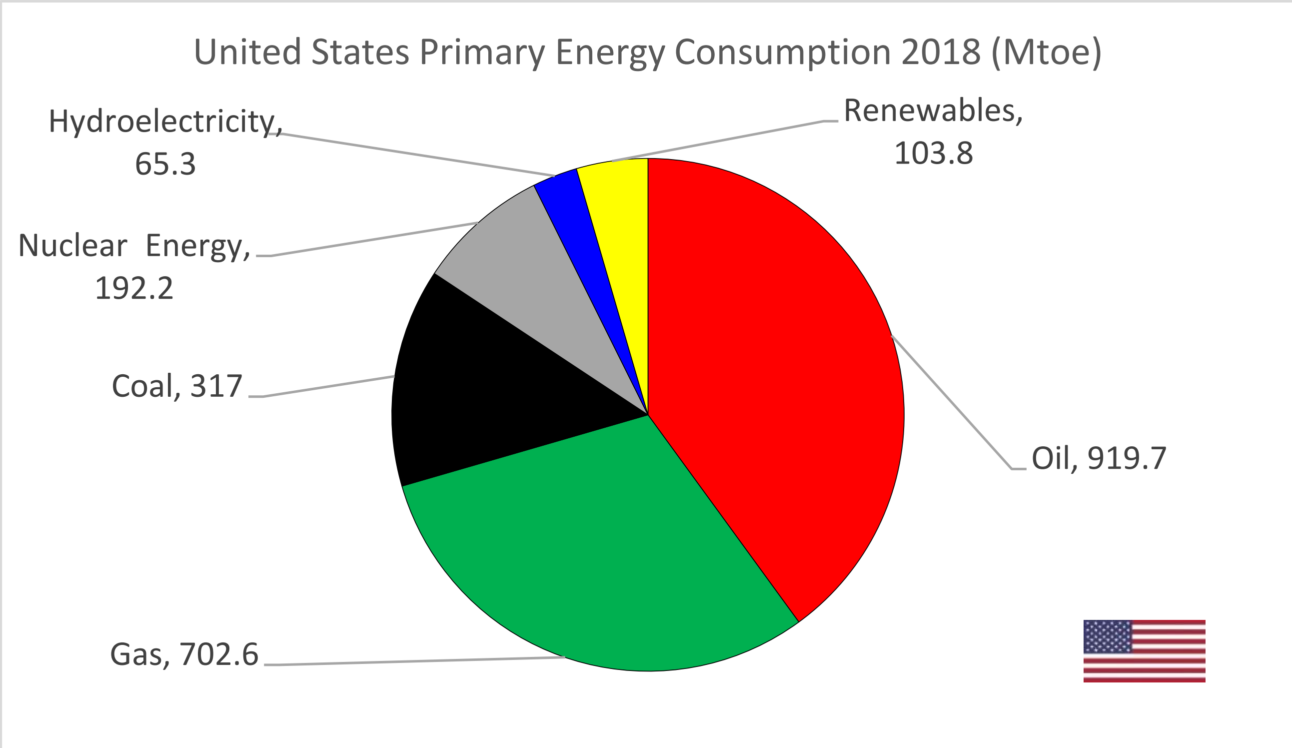


Figure 5.11. United States primary energy consumption by raw material source
(Source: BP Statistical Review of World Energy 2019 & Appendix A)

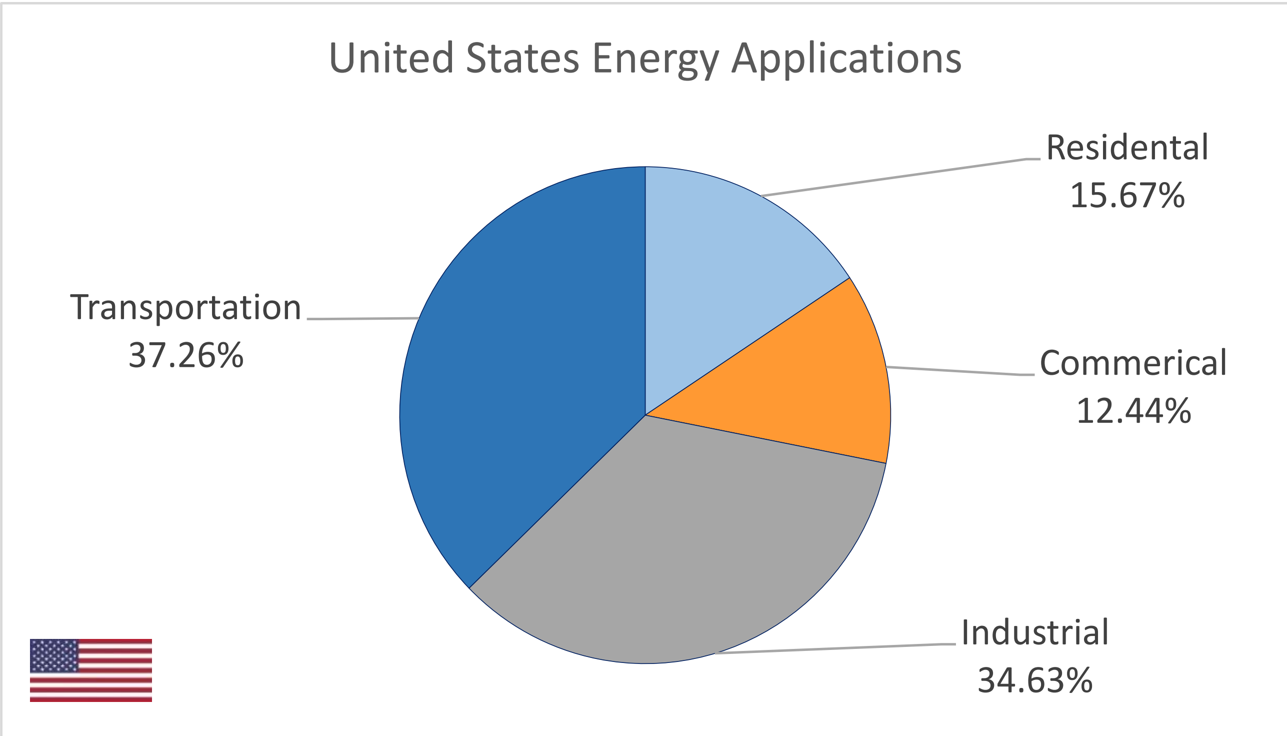


Figure 5.12. United States energy applications
(Source: Lawrence Livermore National Laboratory 2017, EIA 2017)

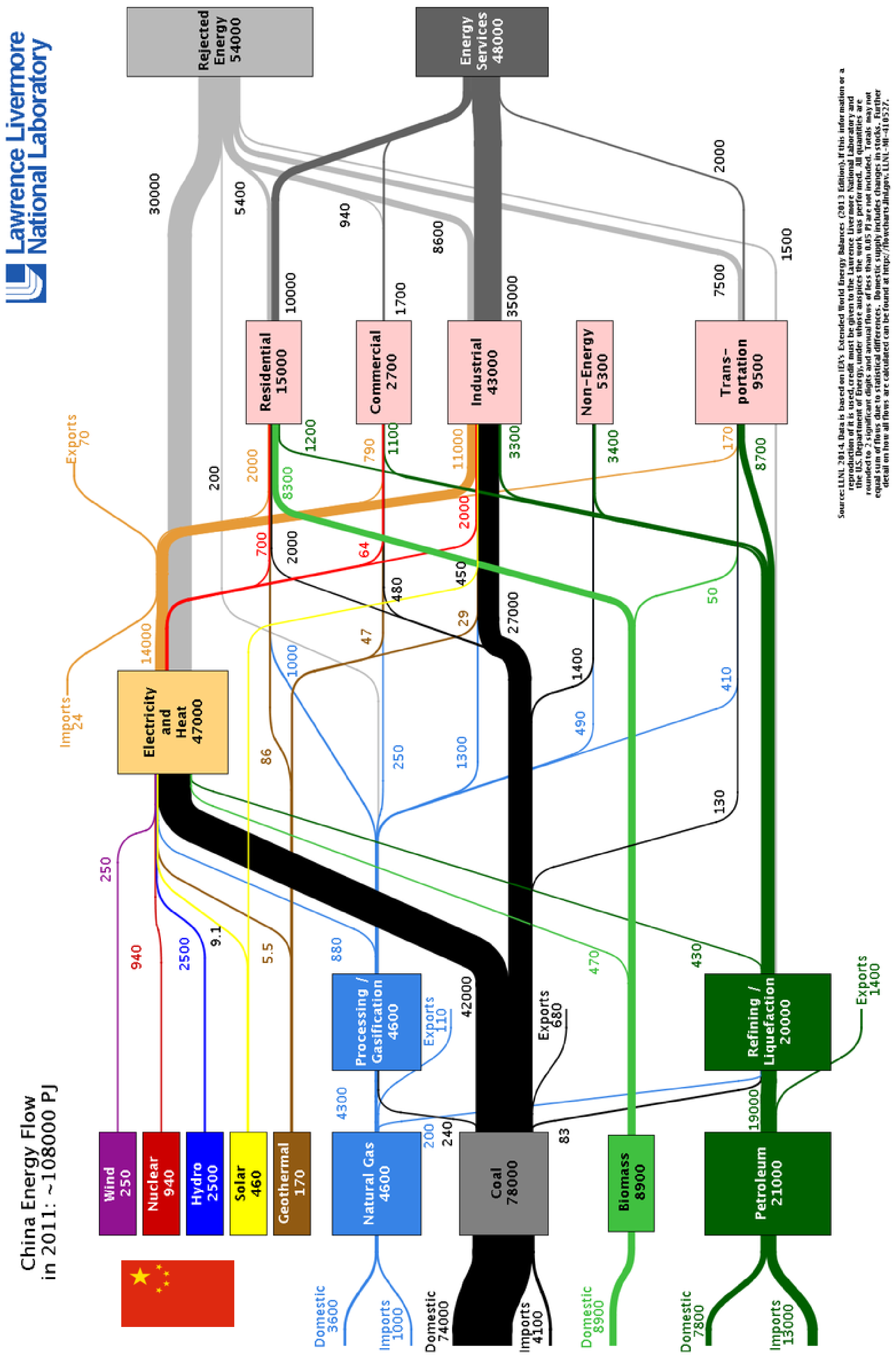


Figure 5.13. China energy flow between energy source and application
(Source: Lawrence Livermore National Laboratory Energy Flow Charts)

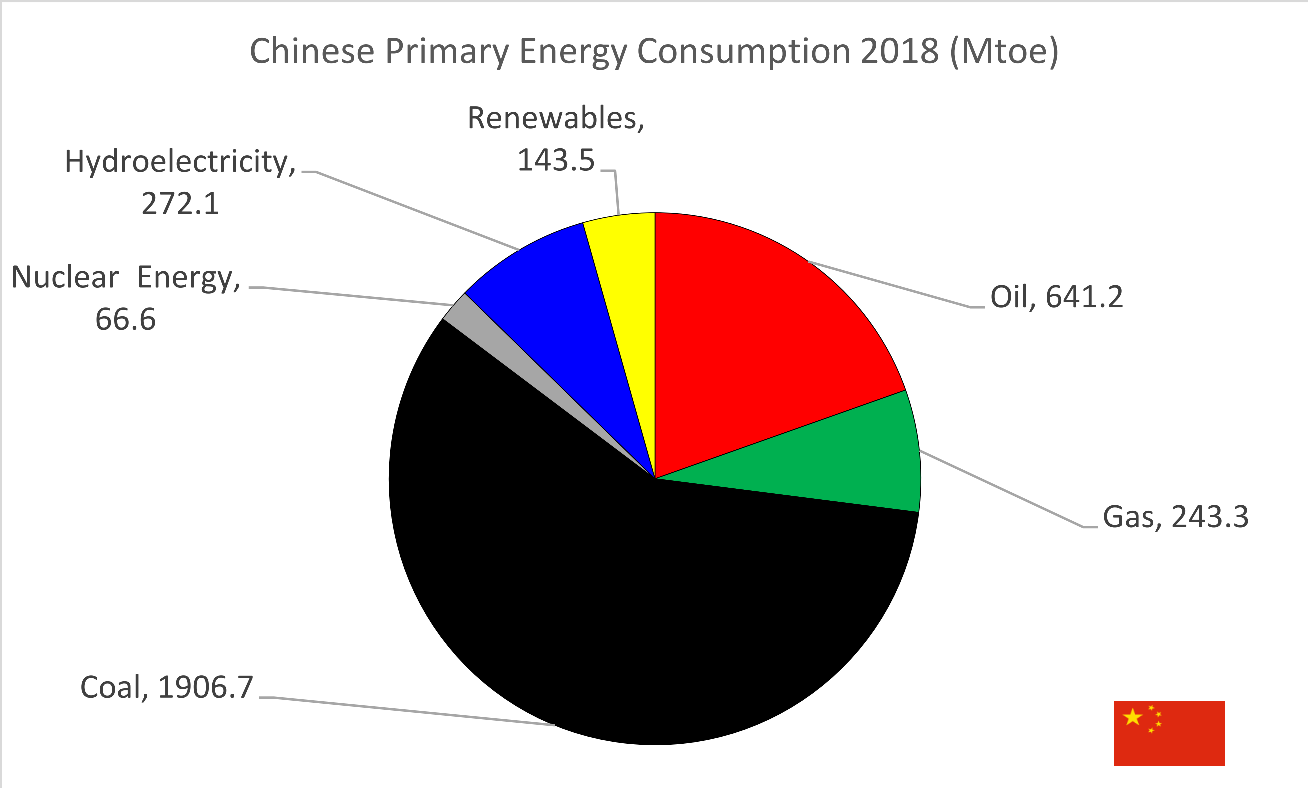


Figure 5.14. Chinese primary energy consumption by raw material source
(Source: BP Statistical Review of World Energy 2019 & Appendix A)

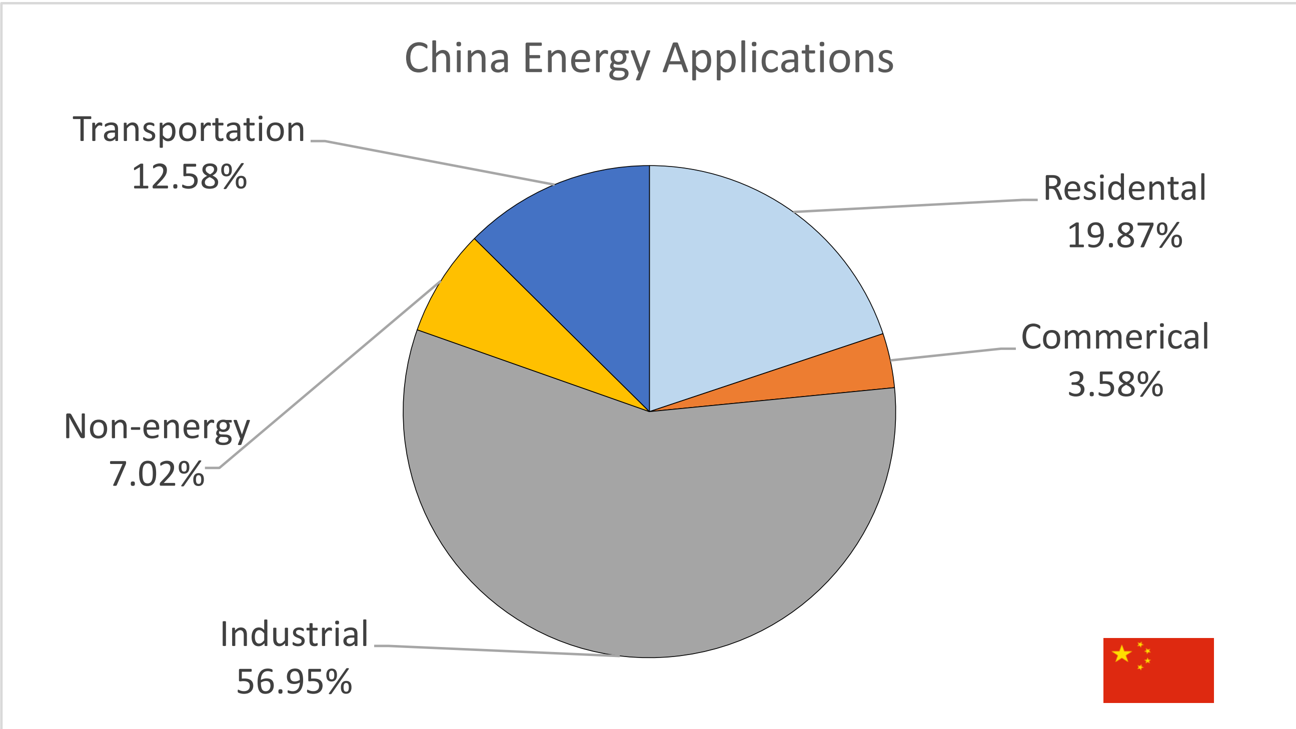


Figure 5.15. Chinese energy applications
(Source: Lawrence Livermore National Laboratory 2017, EIA 2017)

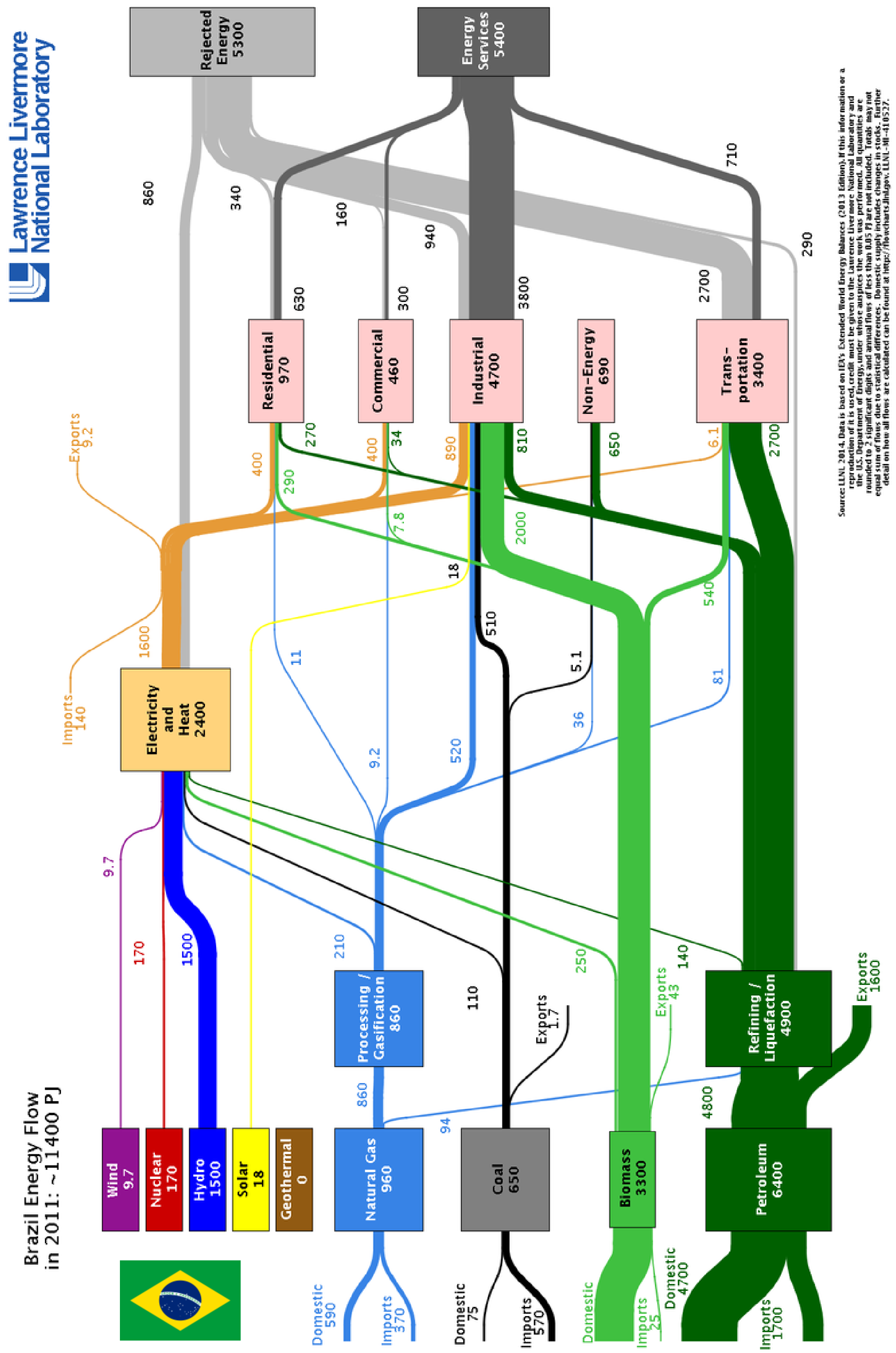


Figure 5.16. Brazil energy flow between energy source and application
(Source: Lawrence Livermore National Laboratory Energy Flow Charts)

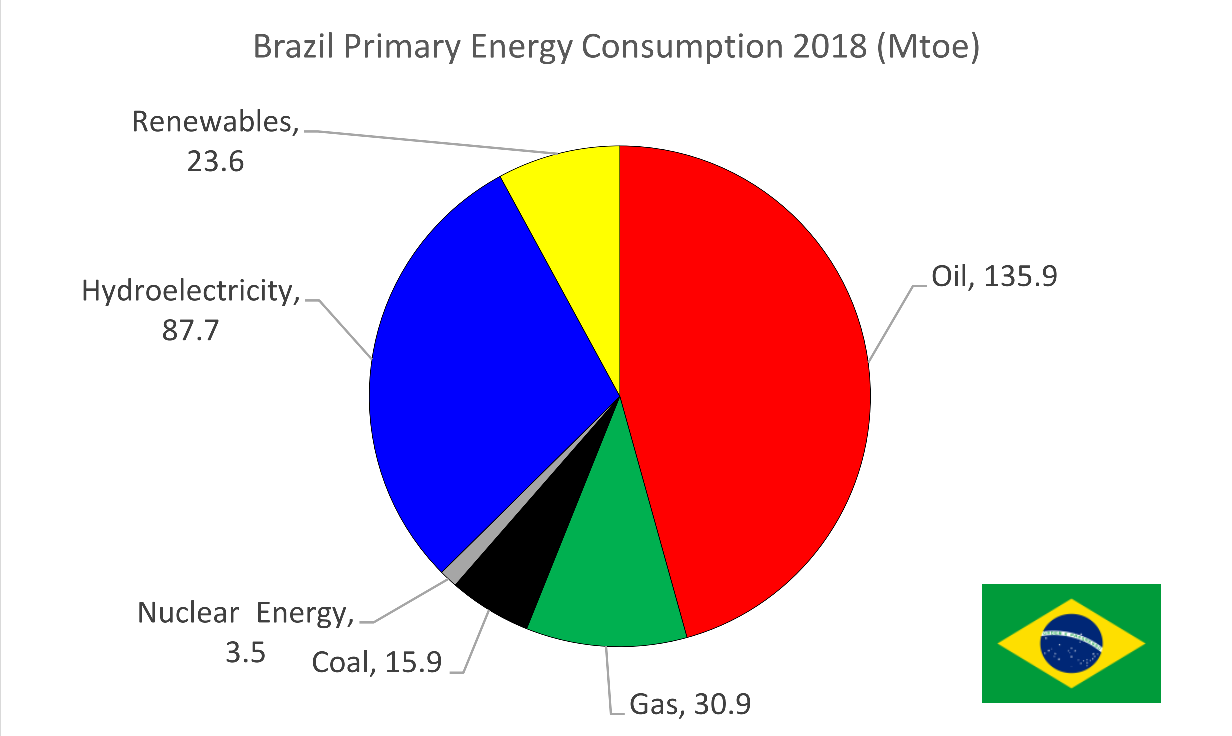


Figure 5.17. Brazil primary energy consumption by raw material source
(Source: BP Statistical Review of World Energy 2019 & Appendix A)

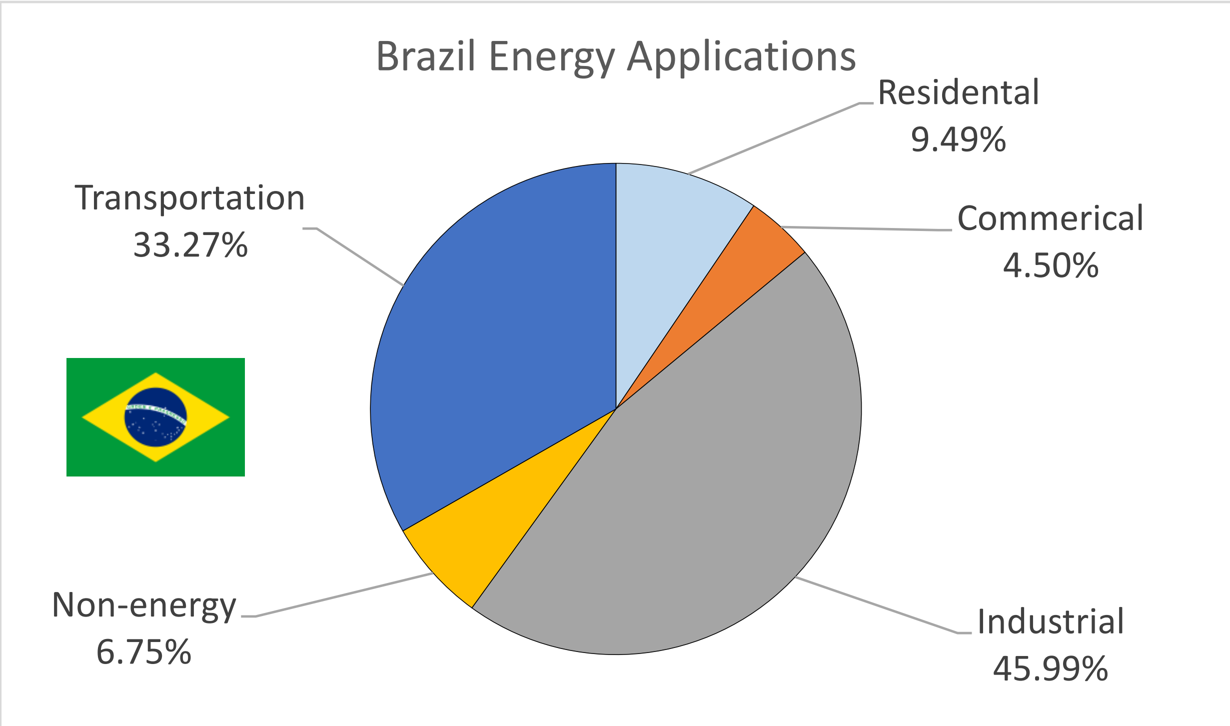


Figure 5.18. Brazil energy applications
(Source: Lawrence Livermore National Laboratory 2017, EIA 2017)

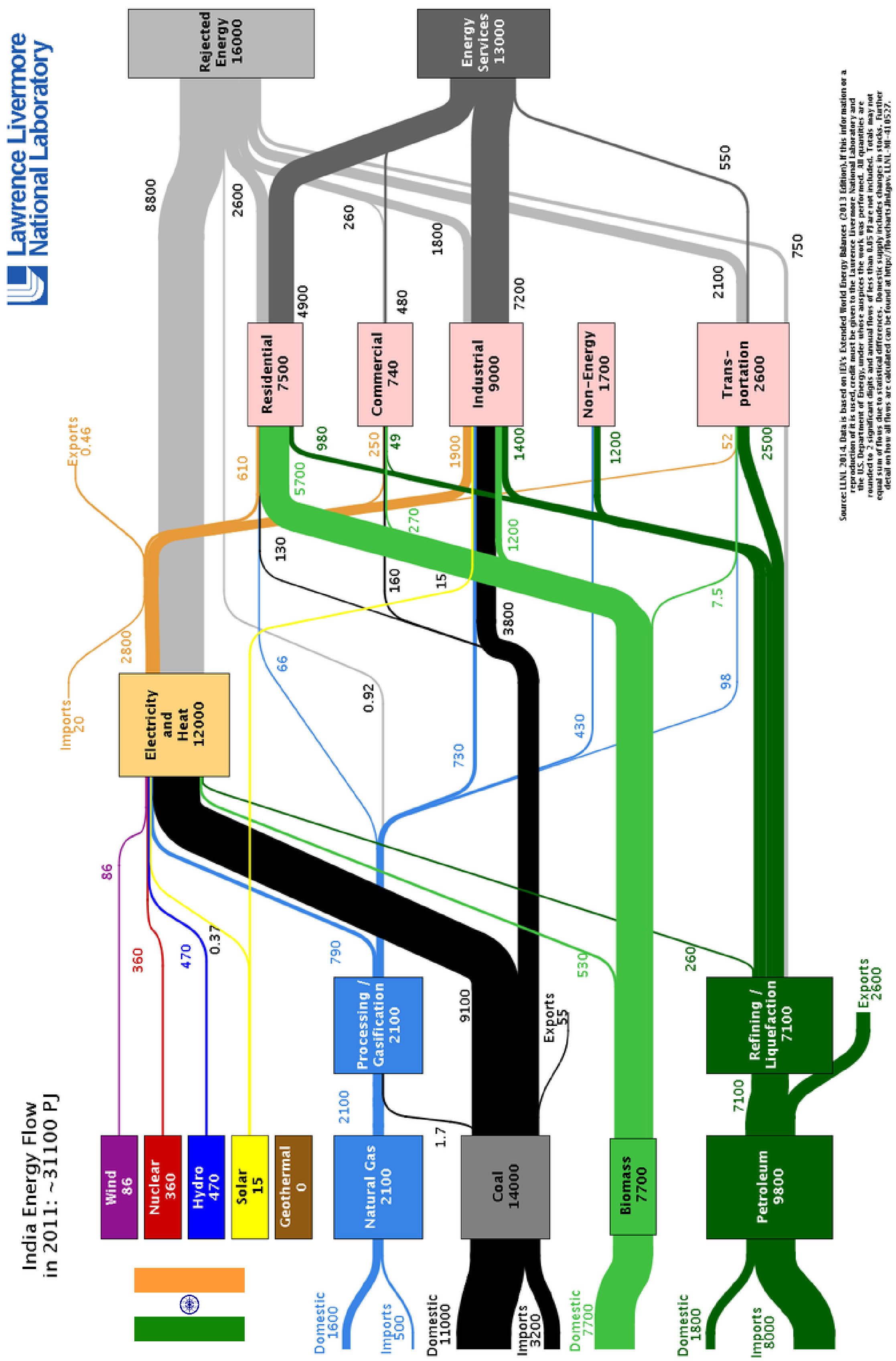


Figure 5.19. India energy flow between energy source and application
(Source: Lawrence Livermore National Laboratory Energy Flow Charts)

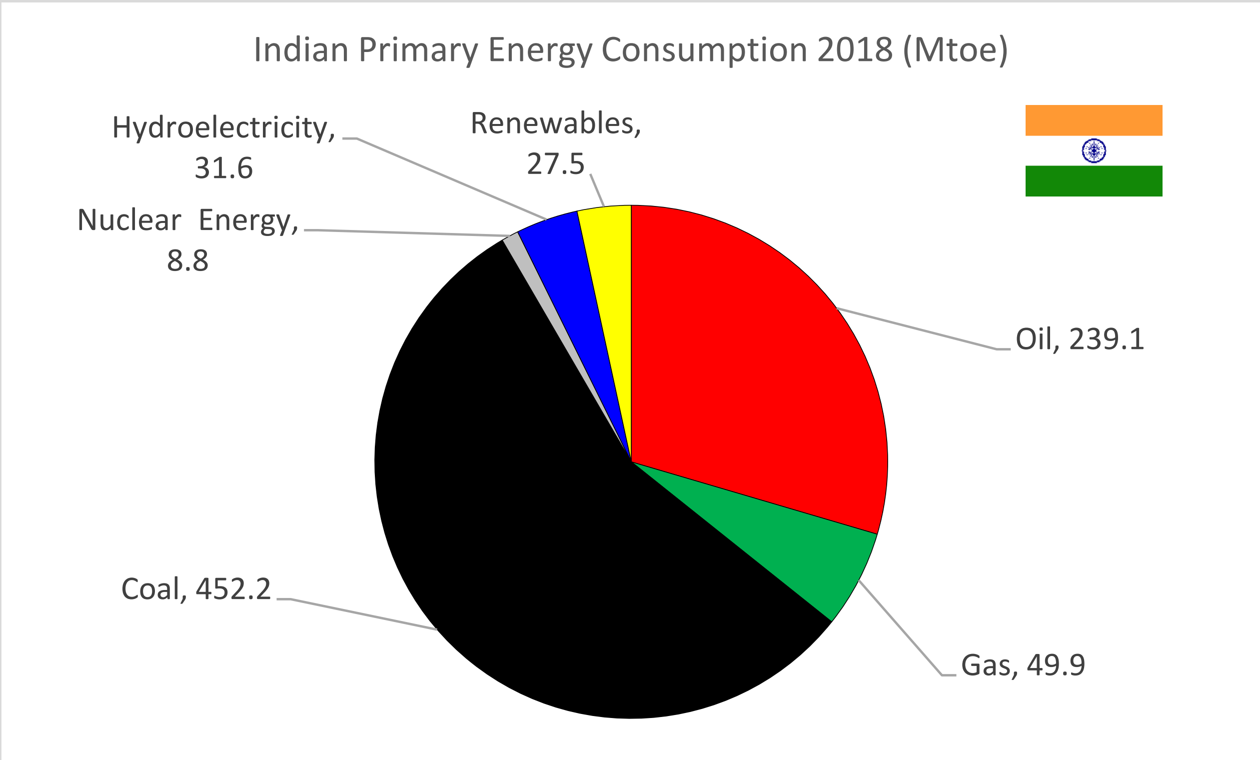


Figure 5.20. Indian primary energy consumption by raw material source
(Source: BP Statistical Review of World Energy 2019 & Appendix A)

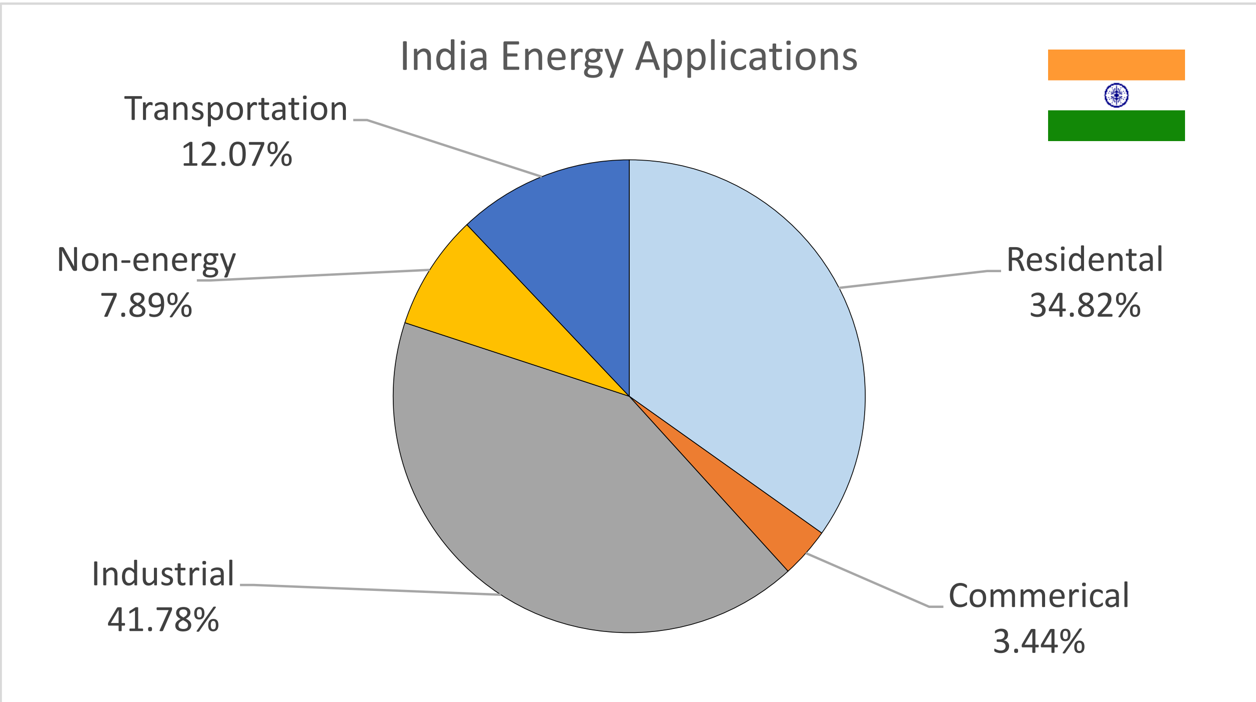


Figure 5.21. Indian energy applications
(Source: Lawrence Livermore National Laboratory 2017, EIA 2017)

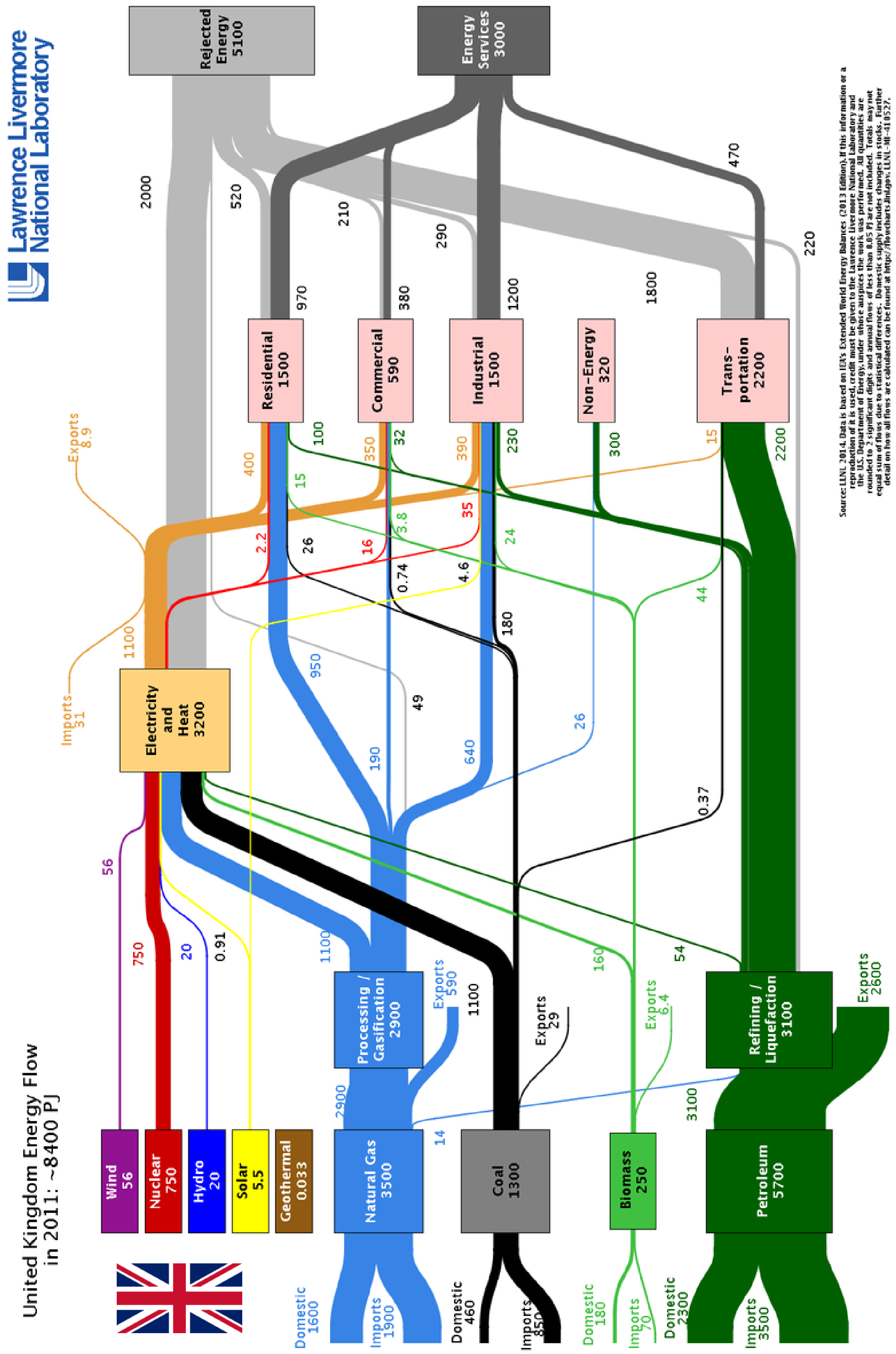


Figure 5.22. United Kingdom energy flow between energy source and application (Source: Lawrence Livermore National Laboratory Energy Flow Charts) (Copyright License: https://creativecommons.org/licenses/by-nc-sa/4.0/)

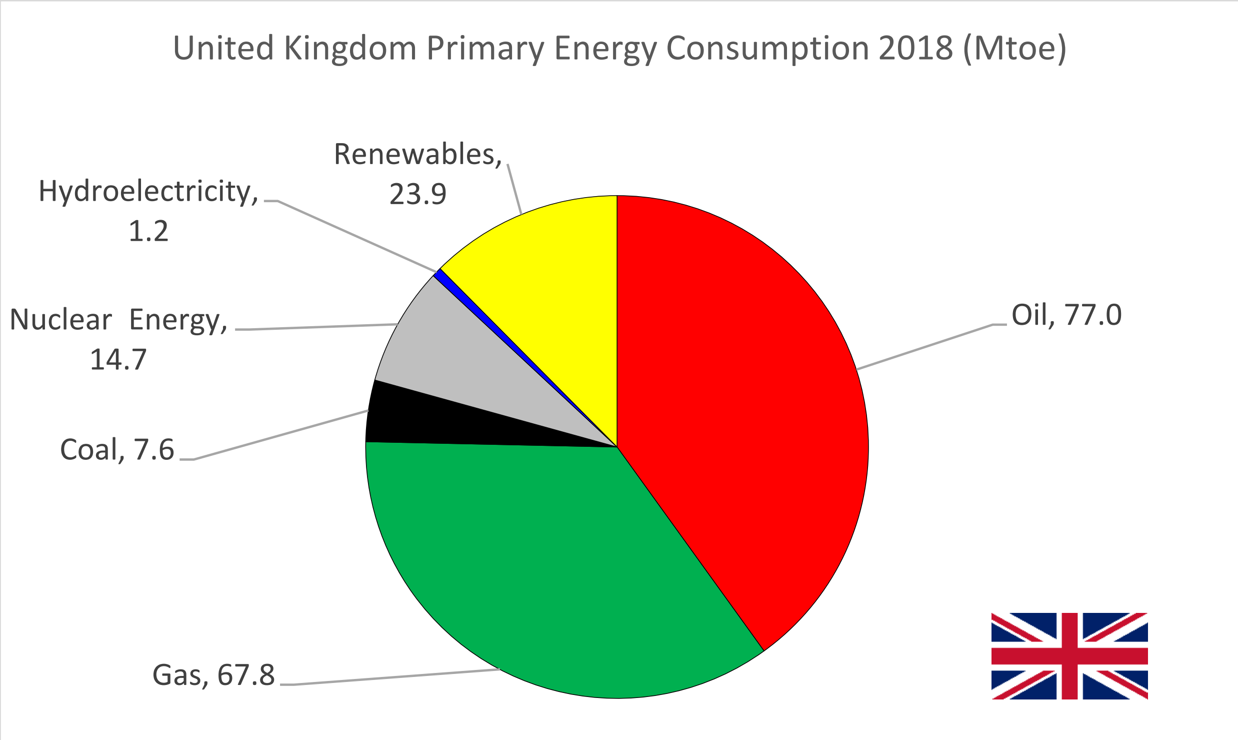


Figure 5.23. United Kingdom primary energy consumption by raw material source
(Source: BP Statistical Review of World Energy 2019 & Appendix A)

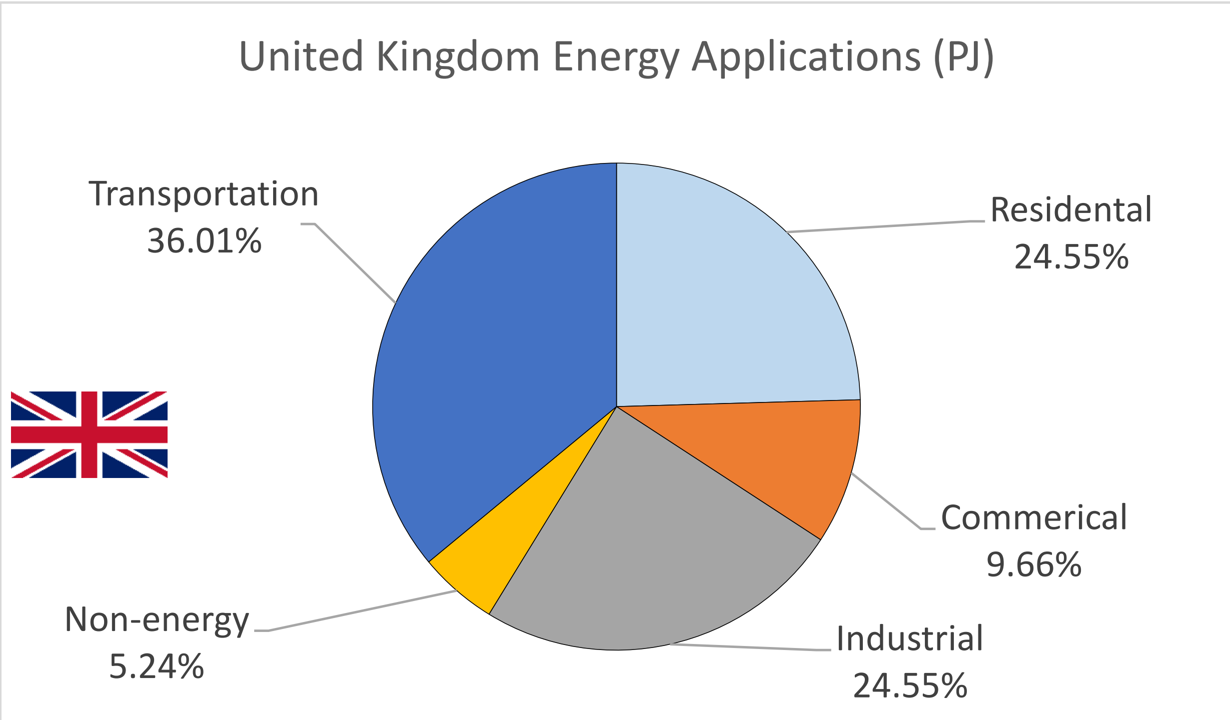


Figure 5.24. United Kingdom energy applications
(Source: Lawrence Livermore National Laboratory 2017, EIA 2017)

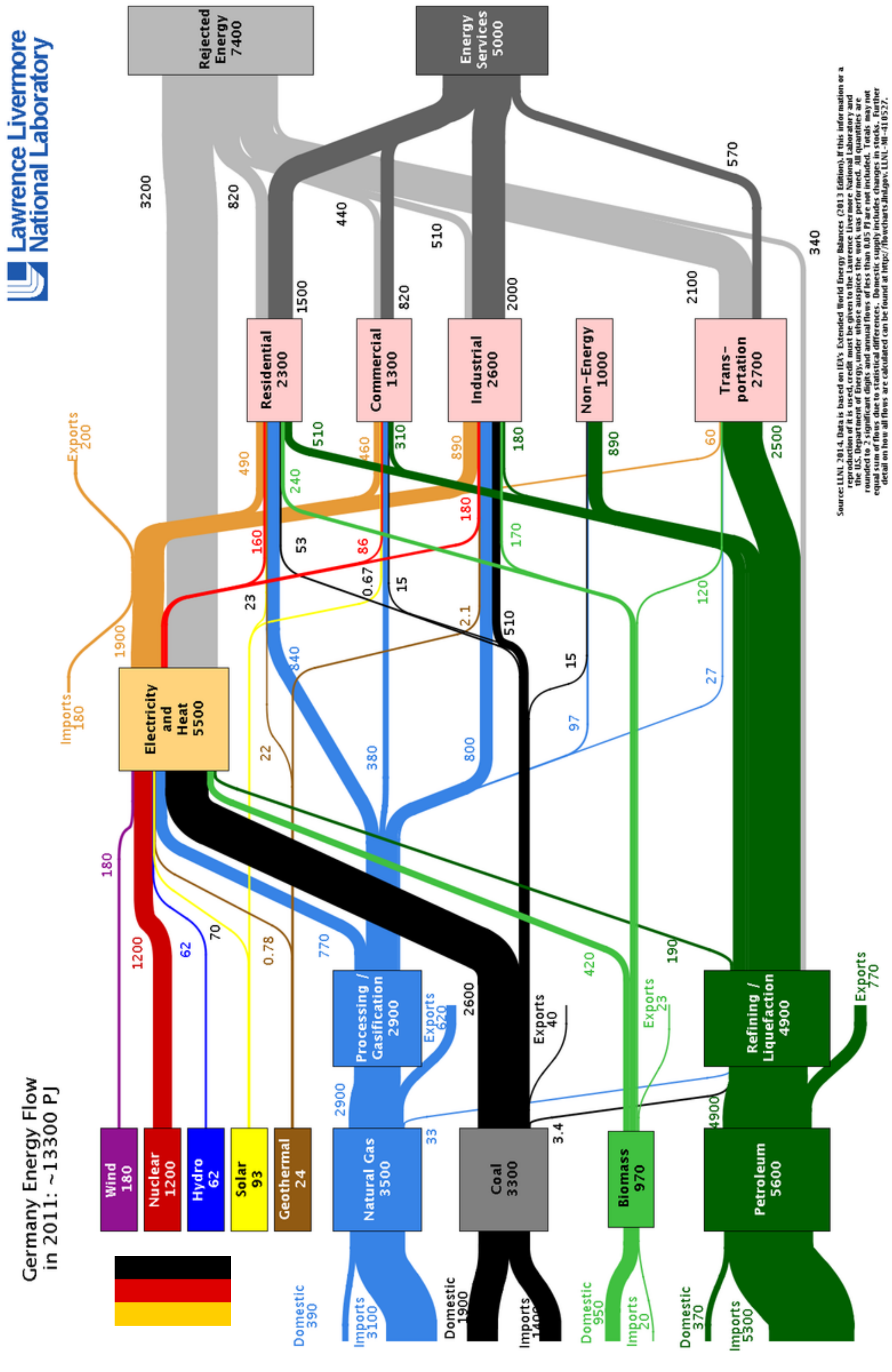


Figure 5.25. Germany energy flow between energy source and application
(Source: Lawrence Livermore National Laboratory Energy Flow Charts)

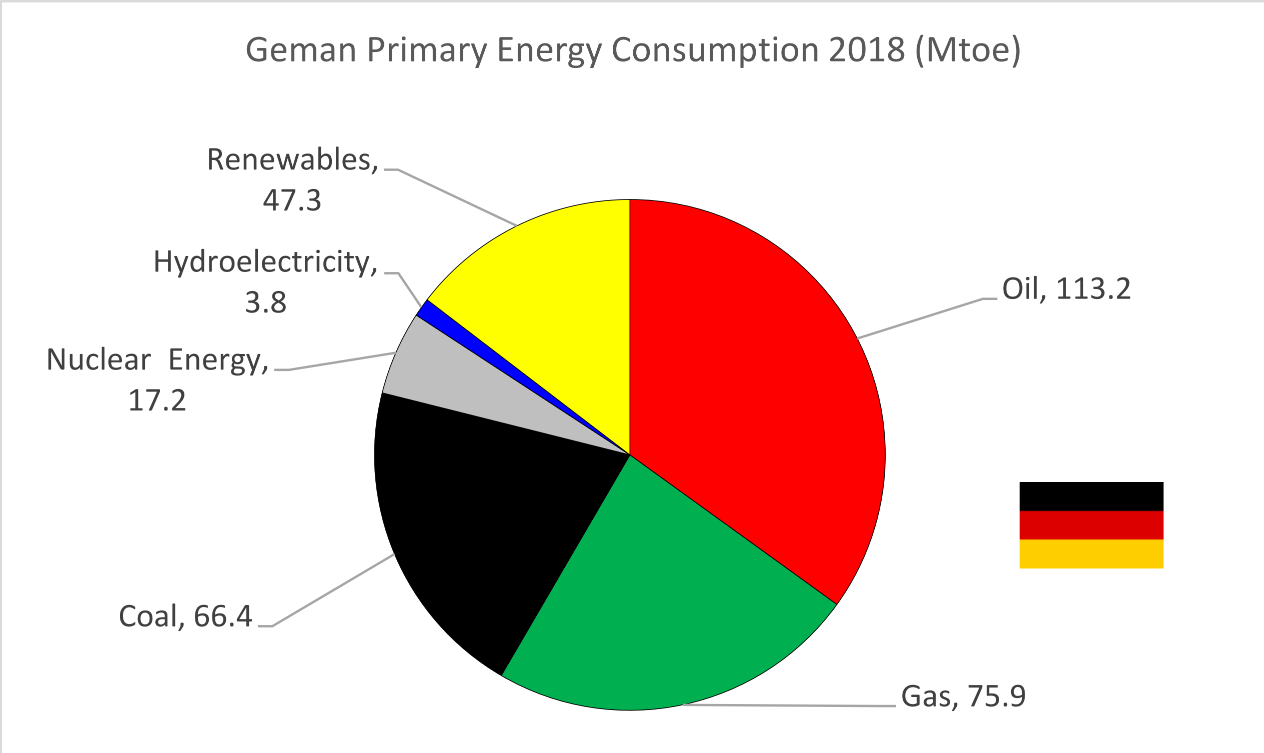


Figure 5.26. German primary energy consumption by raw material source
(Source: BP Statistical Review of World Energy 2019 & Appendix A)

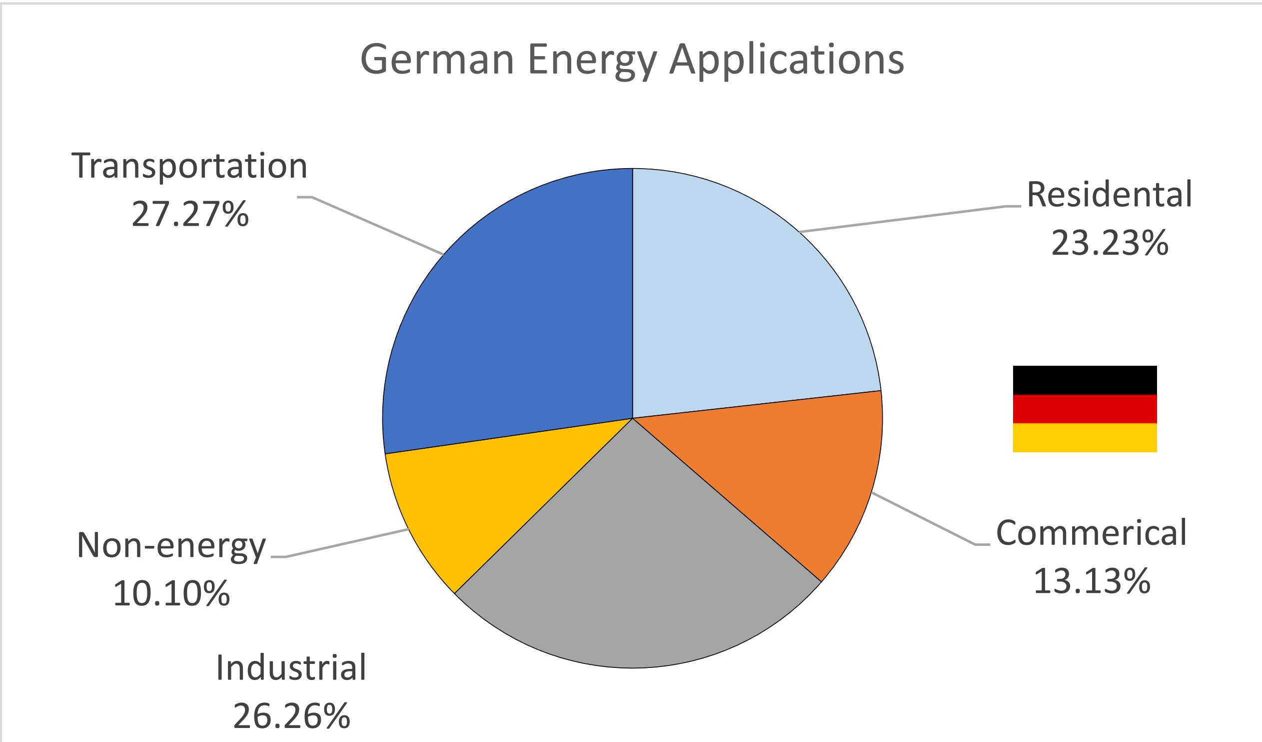


Figure 5.27. German energy applications
(Source: Lawrence Livermore National Laboratory 2017, EIA 2017)

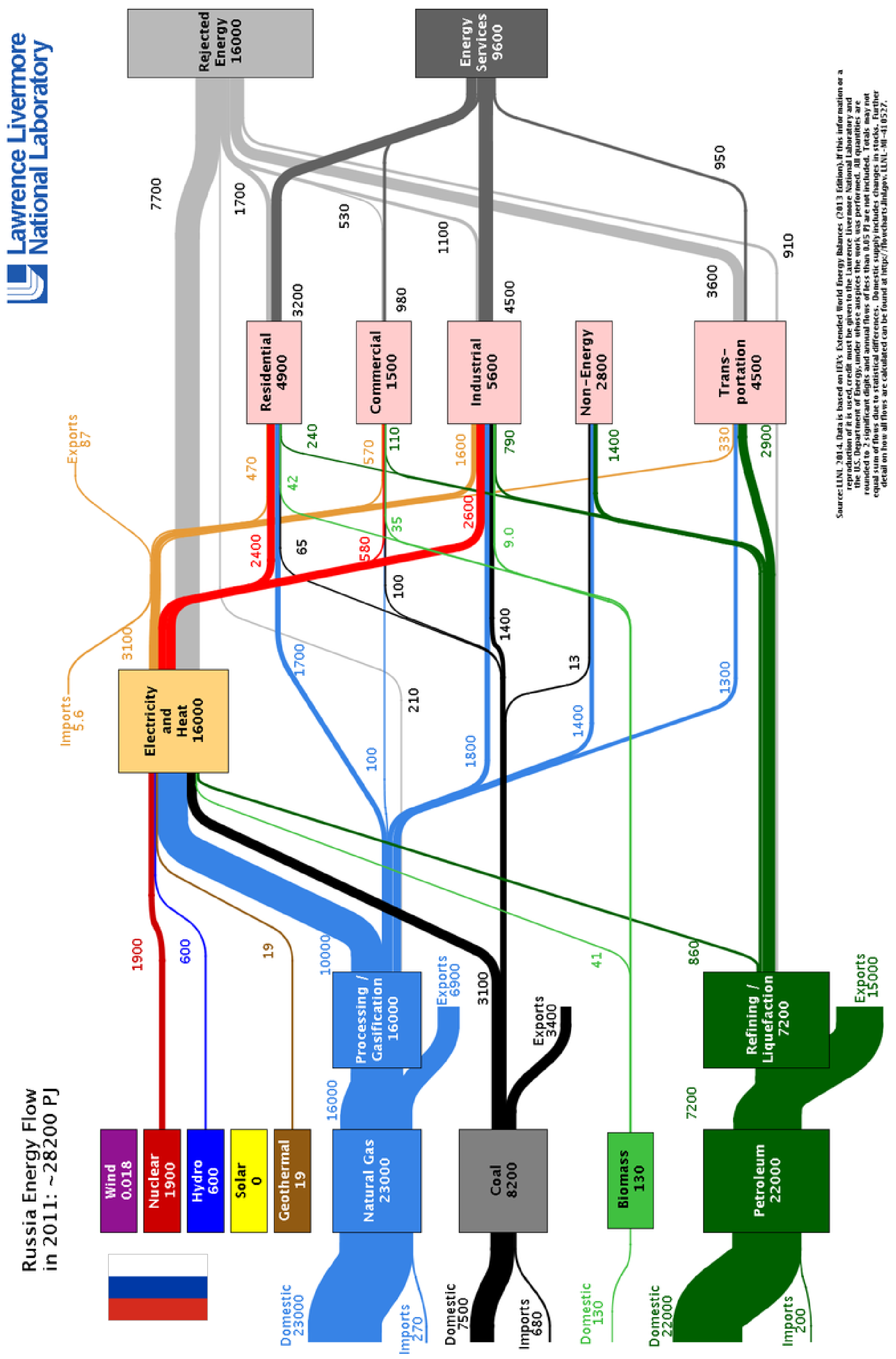


Figure 5.28. Russia energy flow between energy source and application
(Source: Lawrence Livermore National Laboratory Energy Flow Charts)

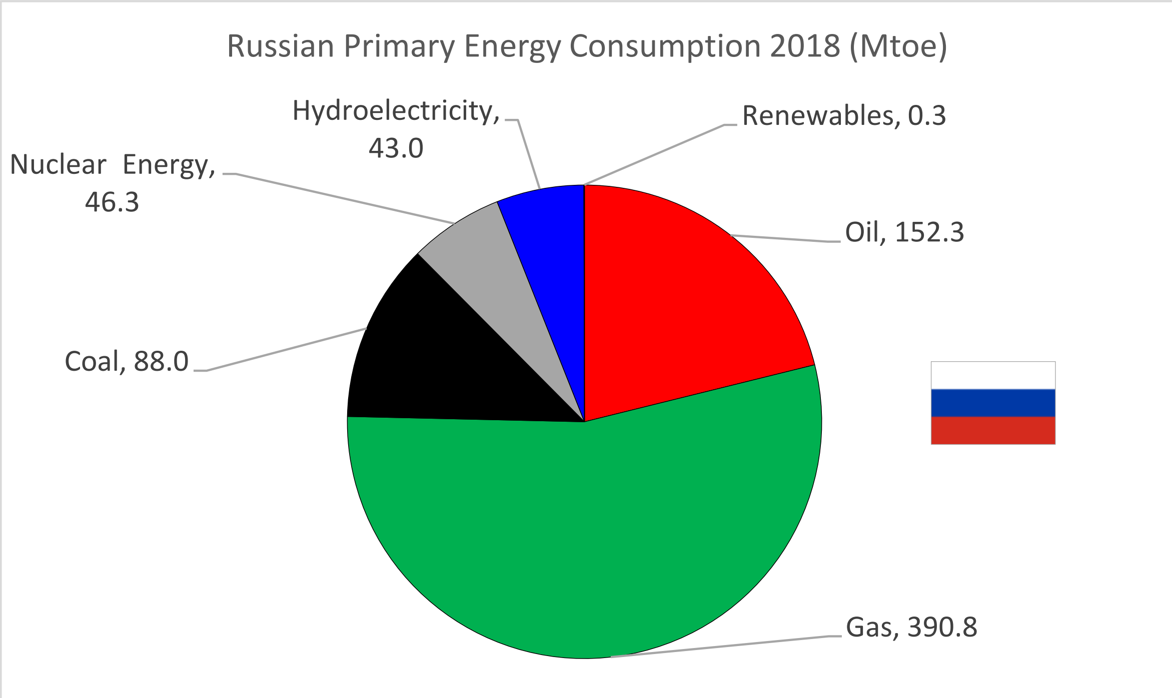


Figure 5.29. Russian primary energy consumption by raw material source
(Source: BP Statistical Review of World Energy 2019 & Appendix A)

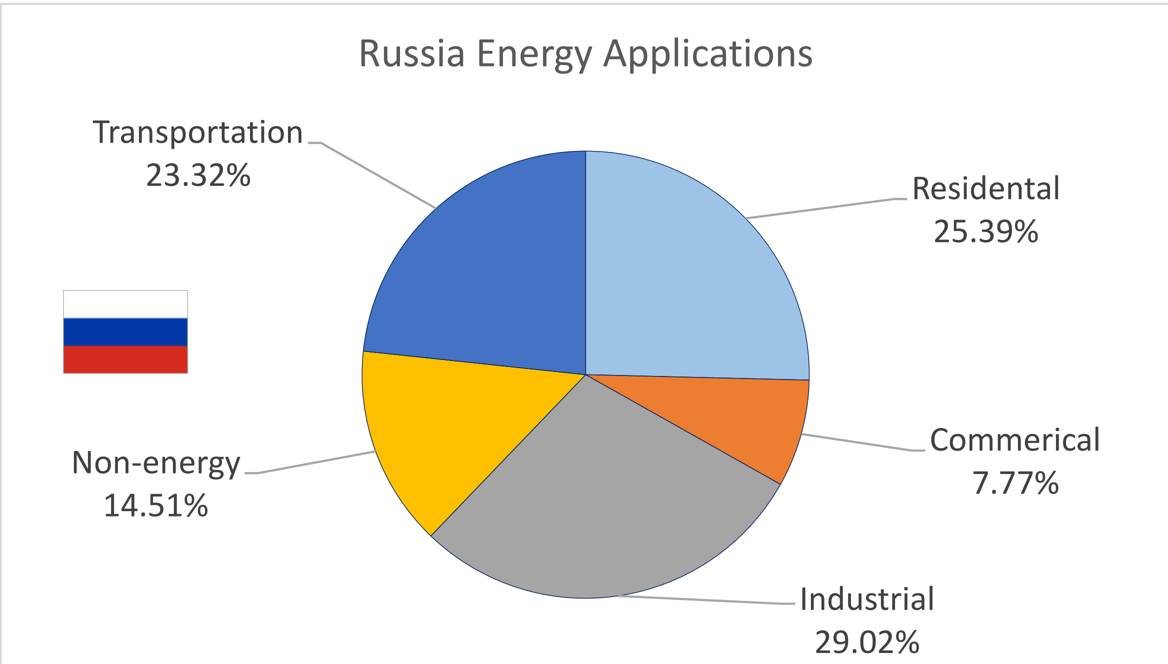
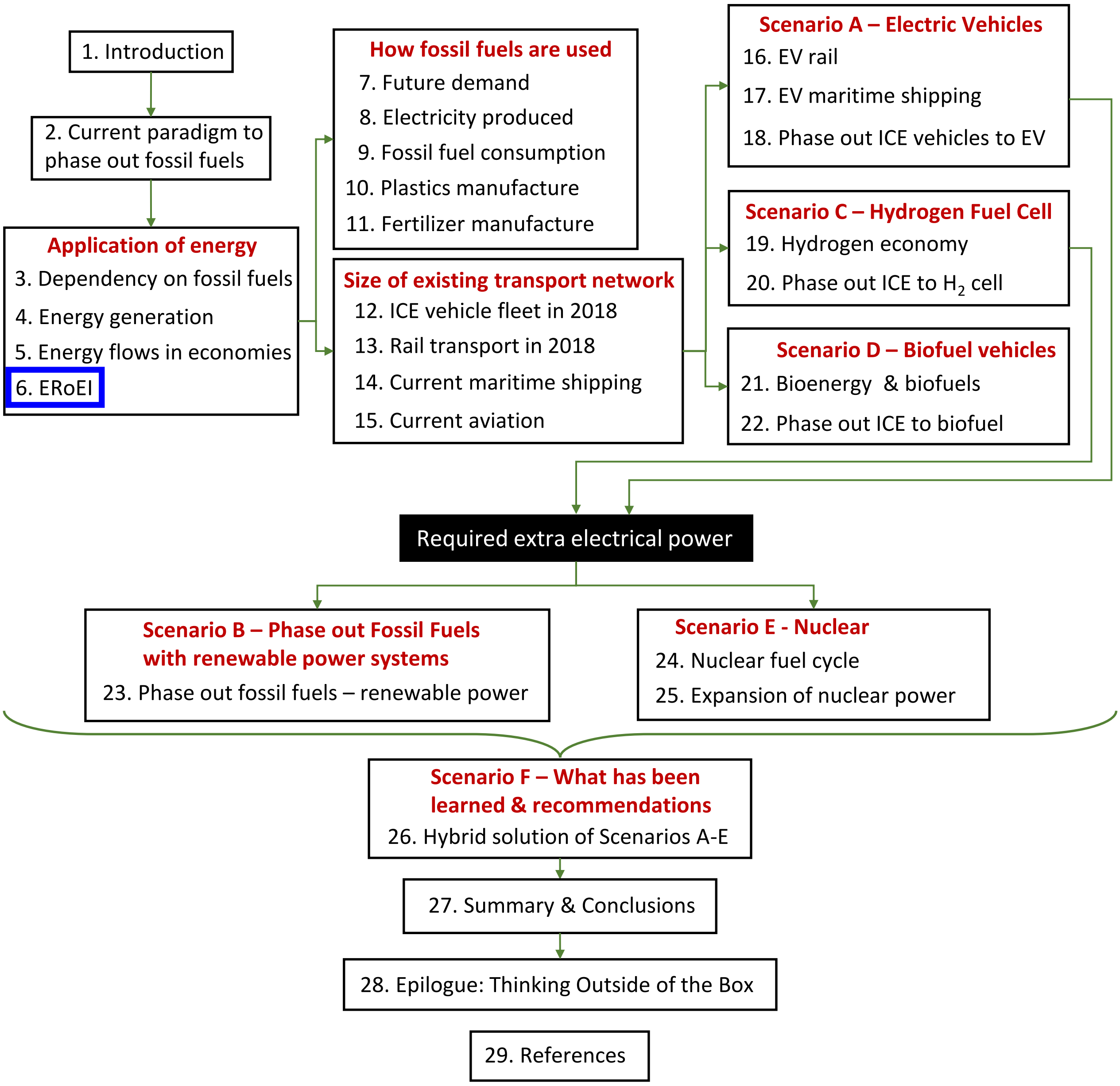


Figure 5.30. Russian energy applications
(Source: Lawrence Livermore National Laboratory 2017, EIA 2017)

Figures 5.2 to 5.30 show a clear pattern. Each and every one of the economies examined is heavily dependent on all three main fossil fuels, oil, gas, and coal. Phasing them out will require a structural refit of the whole industrial ecosystem.

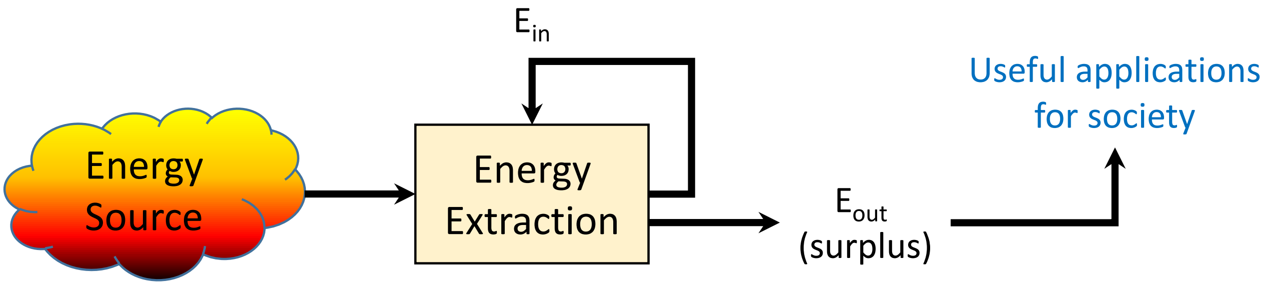
6 ENERGY RETURNED ON ENERGY INVESTED (EROEI RATIO) OF ENERGY RESOURCES

The purpose of Section 6 is to show that all energy systems are not the same in context of efficiency and effectiveness. How do the renewable electricity generation systems like solar and wind compare to coal and gas electricity generation systems? This is a pertinent question as it will answer the question to why so many renewable systems will be needed to replace just one coal/gas fired power station. This section will also show how energy effectiveness has been decreasing for some time. The majority of the current fossil fuel supported infrastructure was built when much higher quality energy sources were available to now, with future systems likely to be lower again.



Assessment of the Extra Capacity Required of Alternative Energy Electrical Power Systems to Completely Replace Fossil Fuels

Oil when it was first discovered was the most concentrated source of energy the world had ever seen. It did not require much in the way of processing. It could be stored easily and transported easily. It is now understood is that as time has progressed, the quality of energy has deteriorated in practical terms. The ERoEI ratio for energy sources (sometimes termed EROI) in general but in particular for oil have all sharply reduced since their first discovery (Hall *et al.* 2014).



$$\text{Energy Return on Investment (ERoEI)} = \frac{E_{out}}{E_{in}}$$

Figure 6.1. Energy Return on Energy Invested ratio basic form
(Image: Simon Michaux)

6.1 ERoEI of Internal Combustion Technology Example

Oil based technology developed in capability and complexity, with each passing decade. More net resources are consumed for each task, and each task is done at a much higher degree of sophistication. Compare for example the 1921 Hudson Super Six Speedster (Figure 6.2) to the 2013 Lamborghini Aventador (Figure 6.3).

In 1921, the Hudson Super Six Speedster was powered by a 289 cubic-inch six-cylinder engine rated at 76 horsepower (57 kW). The Hudson Model Six-54 Advertisements claimed a maximum speed of 65 mph for the car and the ability to reach 58 mph (93.3 km/hr) from rest in half a minute. This vehicle would sell for less than $1,000 U.S. dollars (equivalent to approximately $27,885 in 2018 $USD funds). This was considered to be the fastest automobile of its day.

As a modern contrast (2013), the Lamborghini Aventador LP 700–4 had a top speed of approximately 354 km/hr, delivered a power of 510 kW and cost $4,500,000 U.S. dollars (in 2018 $USD funds). The manufacturer claims that it can accelerate from 0–97 km/h (0–60 mph) in 2.9 seconds and will achieve a top speed of 217 mph (349 km/h) (https://www.lamborghini.com/en-en/).

Figure 6.2. The 1921 Hudson Super Six Speedster Phaeton was powered by a 289 cubic-inch six-cylinder engine rated at 76 horsepower (57 kW). (Source: Image by David Mark from Pixabay)

Figure 6.3. The Lamborghini Aventador LP 700–4 uses Lamborghini's new 700 PS (510 kW; 690 bhp) 6.5 litre 60° V12 engine weighing 235 kg. (Source: Image by Ola Wirdenius from Pixabay)

Not only had the effort to extract oil based energy gotten more complex and expensive, but the applications in its use also became more technologically complex and expensive. More effort, capital cost, infrastructure support, raw materials of a greater purity is now required to get the best fast ICE car of the day. Yes, the resulting vehicle is much more capable, but so much more is required for the production of each unit. This example can be extended to every part of our industrial society.

6.2 Capability comparison between the different power generation systems

To show why ERoEI should be used as a metric to rank and compare different electricity generation systems, a comparison of the delivery capability of each kind of power plant system has been done.

Table 6.1 (which is drawn from data in Table 8.2 and 8.3 in Section 8, where a more in depth discussion is shown) shows the performance of a single average sized power plant (as reported in 2018), for each electrical generation system.

Table 6.1. Number of power plants to deliver 1000 TWh of electricity to the power grid (drawn from Table 8.2 and 8.3) (Appendix B & Agora Energiewende and Sandbag 2019)

Power Generation System Source	Power Produced by a **Single** Average Plant in 2018 (kWh)	Power Produced by a **Single** Average Plant in 2018 (TWh)	Number of power plants to deliver 1000 TWh of electricity to the power grid (number of plants)
Coal	7,028,812,030	7.029	142
Gas	2,223,247,834	2.223	450
Nuclear	12,803,184,576	12.803	78
Hydroelectric	1,325,746,584	1.326	754
Wind	81,241,809	0.081	12,309
Solar PV	33,040,663	0.033	30,266
Solar Thermal	76,970,000	0.077	12,992
Geothermal	603,226,027	0.603	1,658
Biowaste to energy	34,581,818	0.035	28,917
Fuel Oil Diesel	850,797,343	0.851	1,175

Figures 6.4 and 6.5 show a comparison between the different power generation plants, both in the annual production of individual average sized plants (or arrays of units) and how many such plants would be required to deliver 1000 TWh of electricity on an annual basis.

As can be observed, to replace a single average coal or gas fossil fuel powered electricity generation plant would require many average renewable power plants. This reflects the relative effectiveness of each of these power systems. These numbers would have to be balanced against the physical size (capital cost) of each kind of plant. Constructing a solar panel array farm is an entirely different matter to constructing and commissioning a nuclear power plant.

It is to be remembered that the operating life after commission of these plants is also different, where a wind turbine and solar panel has a useful working life of approximately 20 years (WWEA (2019), whereas a coal fired power plant is assumed to be 30 years (Spath *et al* 1999). A nuclear power plant operating life is assumed to be 40 years (Generation II Plant) to 60 years for a Generation III+ plant (World Nuclear Association 2019).

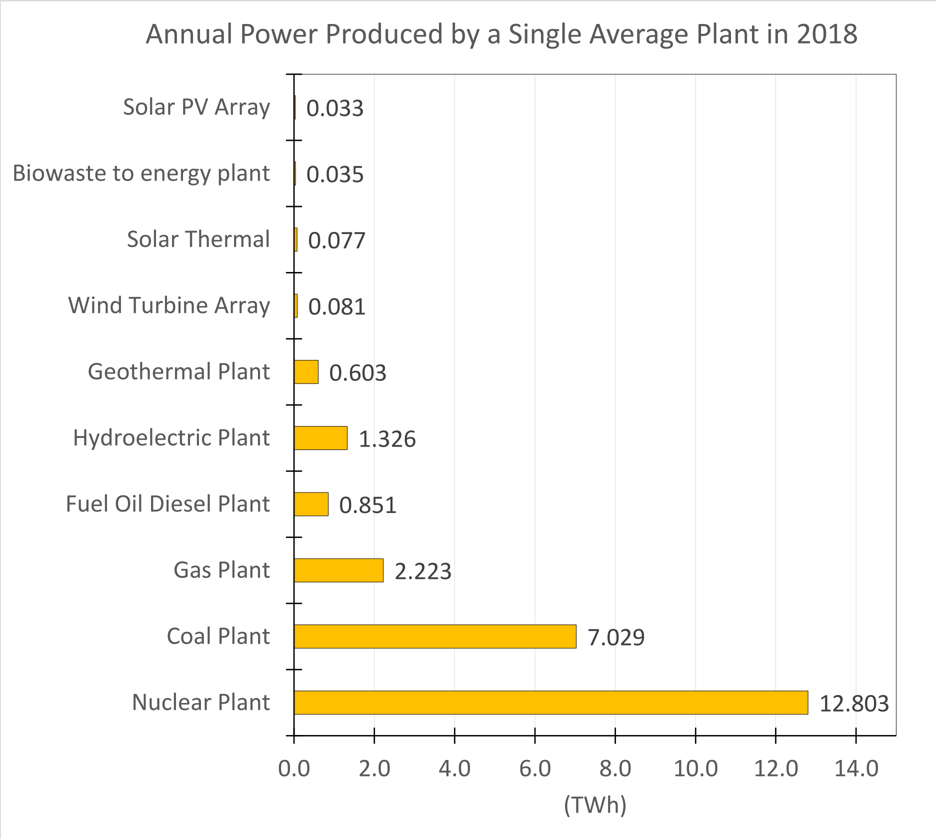


Figure 6.4. Annual Power Produced by a Single Average Plant in 2018 (Image: Simon Michaux)

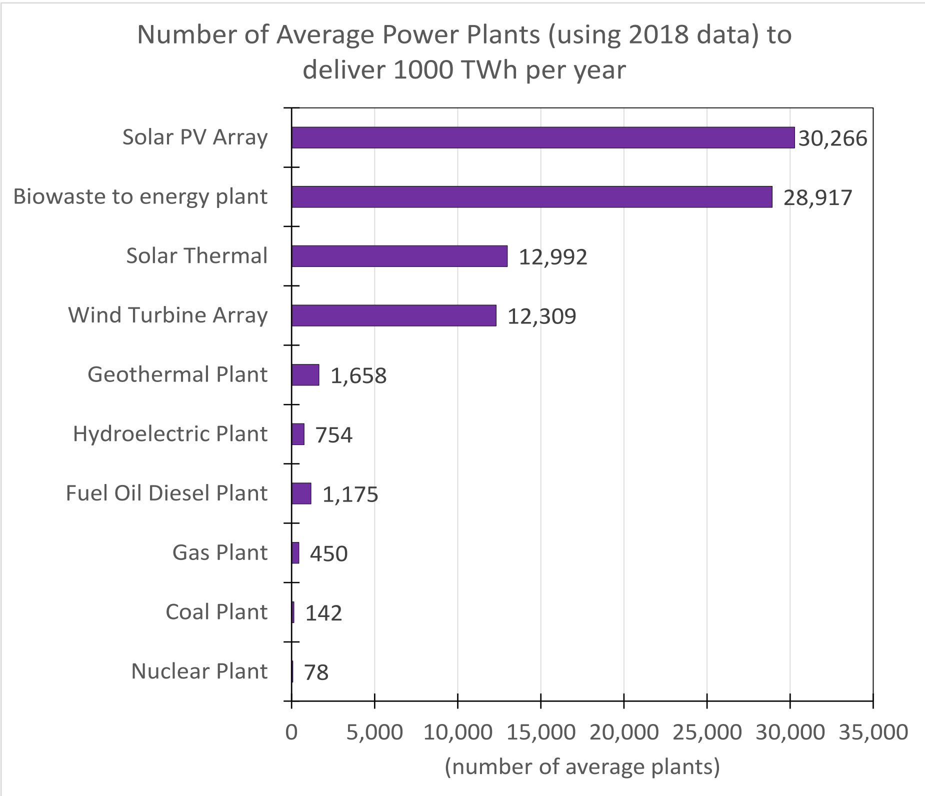


Figure 6.5. Number of Average Power Plants (using 2018 data) to deliver 1000 TWh per year (Image: Simon Michaux)

Comparing the systems shown in Figures 6.4 and 6.5 to oil and petroleum products can get complicated. The renewable energy power systems produce electricity, which is then used in various applications. An Internal Combustion Engine (ICE) vehicle uses petroleum products directly as a fuel, most in transport applications. These are two very different technology vectors that are often put in direct comparison in ERoEI studies. To do this appropriately, a complex study as to be done to directly compare two systems being applied to exactly the same task, then back calculated to fundamental origins of each system. An example of this could be a petroleum fuelled ICE vehicle is compared to an EV vehicle of the same passenger and cargo carrying capacity travelling the same distance and at the same speed. Figure 6.6 could be an appropriate calculation flow sheet to do this (not done to date).

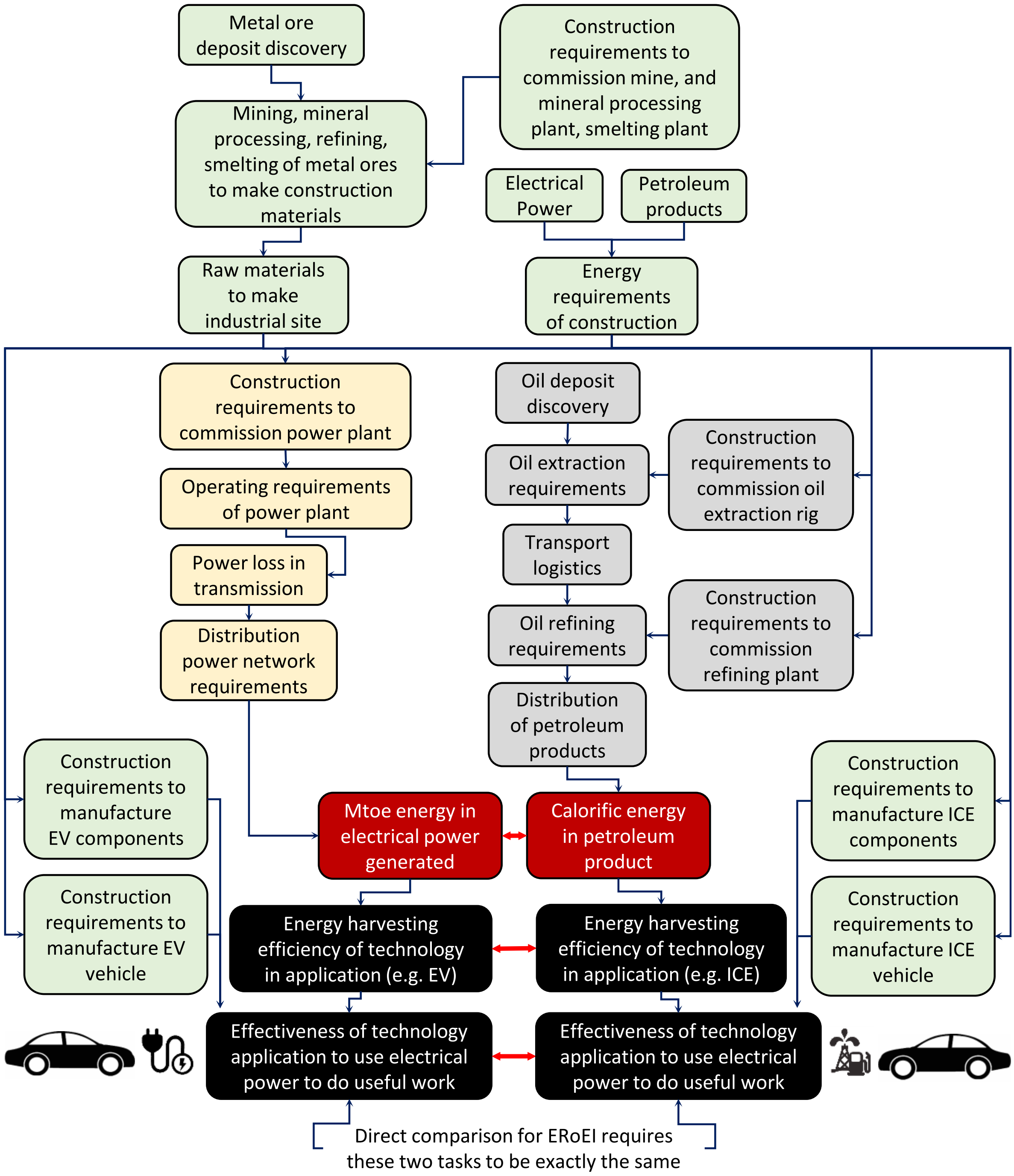


Figure 6.6. Calculation flowsheet proposed to do a direct Energy Returned on Energy Invested comparison between Electric Vehicles and Internal Combustion Engine vehicles (Image: Simon Michaux)

This should be looked in some form though as oil based petroleum products is the largest energy source in global annual primary energy consumption (Appendix A and BP Statistical Review of the World Energy 2019), as shown in Figures 3.2 and 3.4 in Section 3. This is a relevant discussion as to phase out fossil fuels, an alternative system is required to replace petroleum fueled ICE vehicles.

A study in what Figure 6.6 proposes has not yet been done at the time of writing this report.

The following example shown in Figure 6.7 is a very crude comparison. In the year 2018, global oil consumption was 4662.1 mtoe (million tonnes of oil equivalent) (BP Statistical Review of the World Energy 2019). Converting mtoe units to TWh, global annual oil consumption in 2018 was 54 220.2 TWh (4 662.1 Mtoe = 54 220.2 TWh). Assuming that an ICE engine has an efficiency of 25%, this represents 13 555.1 TWh of useful work done. If this 13 555.1 TWh was supplied annually with just one of the replacements systems shown in Figure 6.34, how many average power plants would be required to be operational? Figure 6.7 shows the answer graphically. While this is a very crude comparison, it shows that replacing oil will be a very challenging task with the non-fossil fuel systems available. Section 18 provides a more sophisticated calculation of this task.

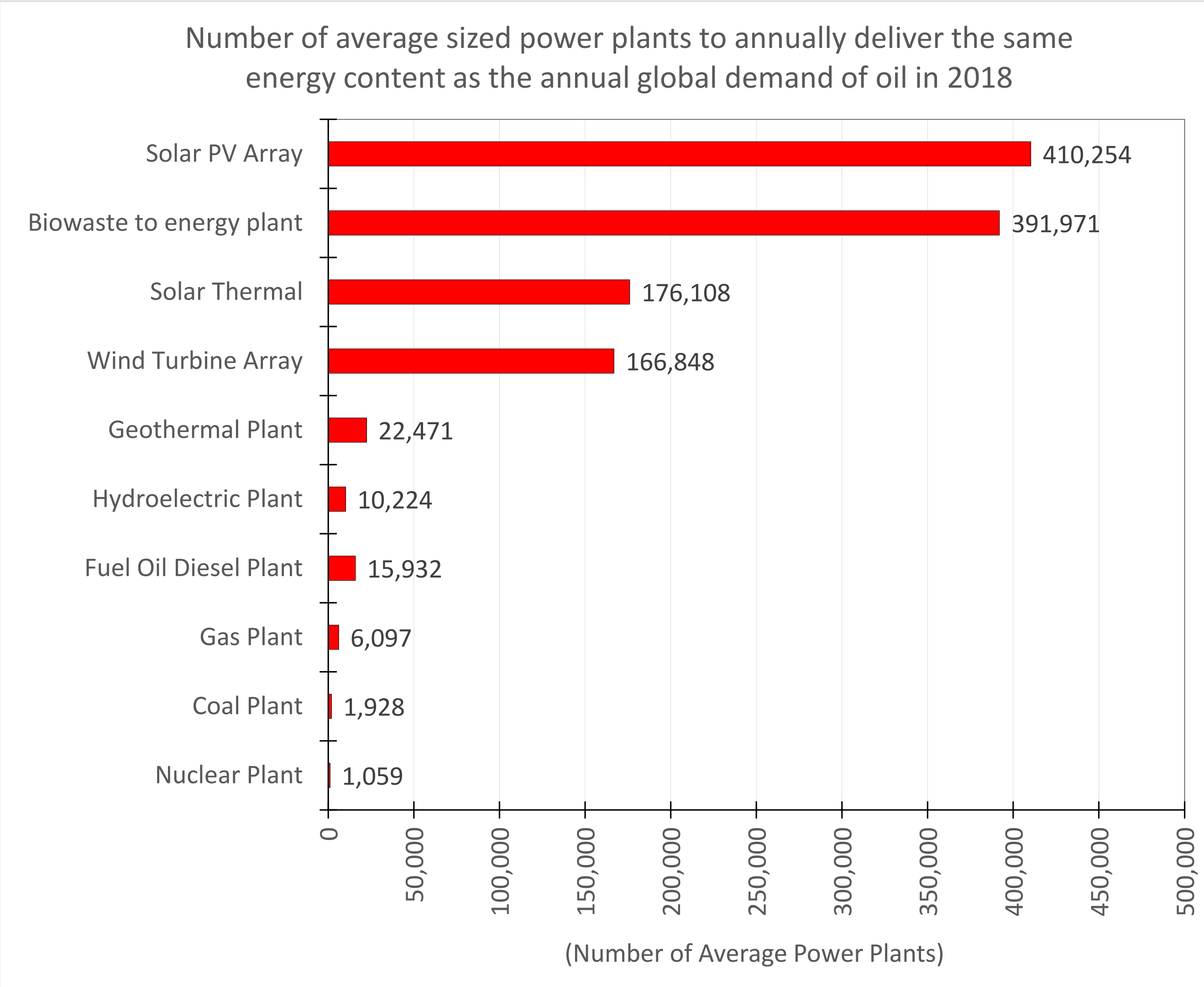


Figure 6.7. Number of average sized power plants to annually deliver the same energy content as the annual global demand of oil in 2018 (Source: Table 6.1, BP Statistics 2019) (Image: Simon Michaux)

6.3 Calculation of ERoEI

The steps in producing the for example crude oil have become more expensive. This includes having to construct deep water wells, extract bitumen from oil sands, and then upgrade to crude oil, or extensive drilling required in tight oil fields. The quality of oil being refined has also been declining. Most (not all) of the light sweet crude is now been extracted and used. Now most refineries have to be upgraded to refine heavy sour crude with higher sulfur content. The net energetic value of oil produced in 2019 is much less than what was produced in the early 1900's (graphically described in Figure 6.8).

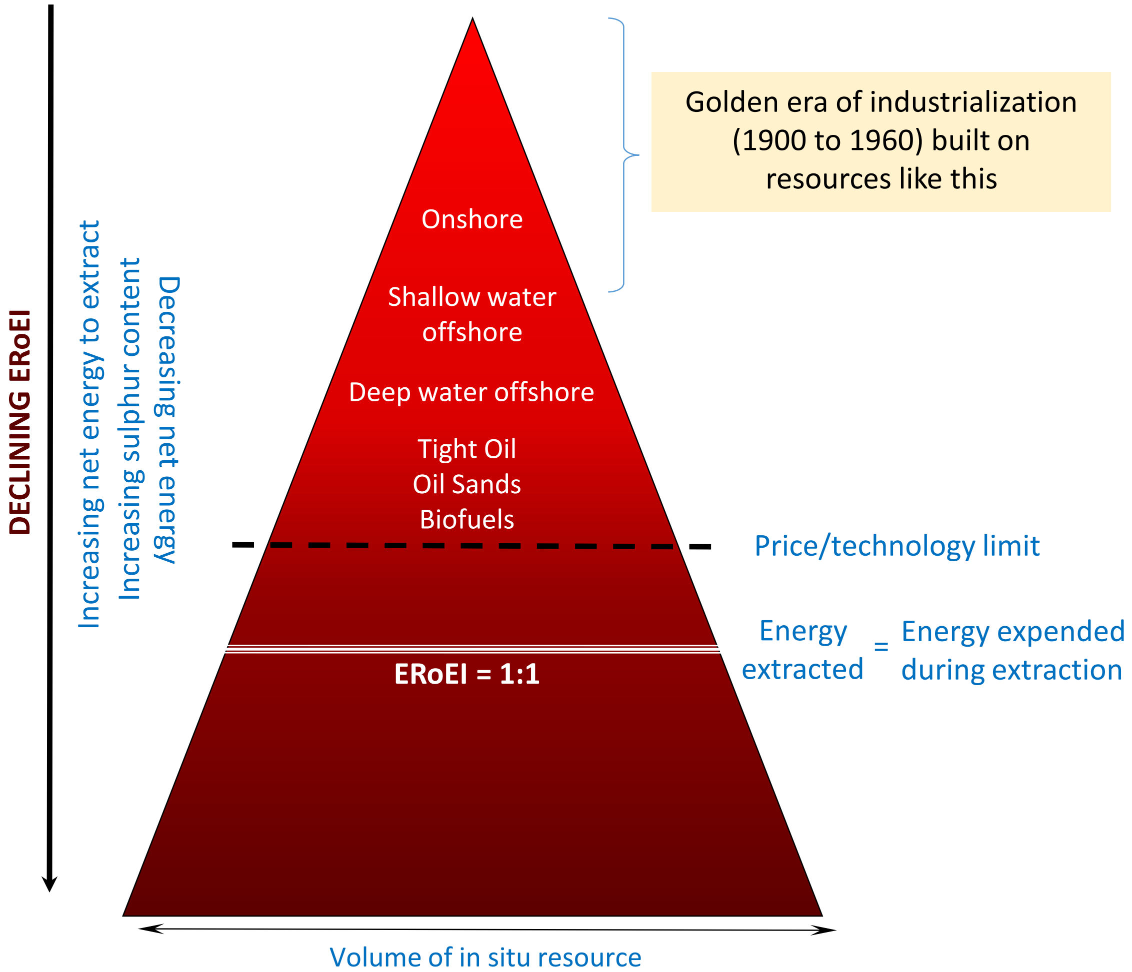


Figure 6.8. The pyramid of oil and gas resource volume versus resource quality (Image: Simon Michaux)

What is challenging to consider, is to phase out petroleum products (and fossil fuels in general), the entire global industrial ecosystem will need to be reengineered, retooled, and fundamentally rebuilt. This will be perhaps the greatest industrial challenge the world has ever faced historically. To do this, the energy resources available are much poorer in quality and quantity than when the current ecosystem was built in the golden age of industrialization (1900 to 1960).

Resource depletion can be modelled with Hubbert Curve analysis to predict peak production. This does not cater for some aspects of demand, nor economic viability of price. It also does not allow for the impact of credit money creation (printing of money or Quantitative Easing, QE) to make unviable projects viable. As finite non-renewable natural resources deplete, cost of ERoEI ratio declines and cost of extraction increases.

As cost of extraction increases, the sale price of the commodity also increases. There comes a point where the real economy cannot function smoothly as the fundamental raw materials that allow it to function are too expensive. This leads to a price crash. In the last few years, there were low commodity prices in conjunction with persistent stagnation of the real economy. This has been punctuated by severe economic downturns as the fiat economy has been printing money to continue to grow at its needed 2% per annum (to service existing debts) in this business environment. There is a serious risk that a significant drop off in oil production as the market sustainable oil price drop too low to make production viable.

In addition to this, the effort and complexity in extracting useful energy out of each of these resources has been degrading over time. The golden era of the last century when much of our industrialization technology was developed and constructed, energy resources had a much higher return. A method of analysis that describes this deterioration is the Energy Returned on Energy Invested (ERoEI). The ratio of energy extracted to the energy expended in the process is often referred to as the Energy Return on Energy Investment (ERoEI or EROI). Should the ERoEI drop to one, or equivalently the Net energy gain falls to zero, the oil production is no longer a net energy source. The ERoEI ratio is defined in Equation 6.1.

$$\text{ERoEI} = \frac{\textbf{\textit{E}}\text{nergy }\textbf{\textit{R}}\text{eturned to do useful physical work from resource}}{\textbf{\textit{E}}\text{nergy }\textbf{\textit{I}}\text{nvested through consumption of energy to gather resource}} \quad \text{(Equation 6.1)}$$

There are a number of excellent references that examine ERoEI analysis more completely than shown in this report (Mearns 2016, Hall *et al*. 2012, Hall *et al*. 2014, Hu *et al*. 2011, Ferroni & Hopkirk 2016, Fizaine & Court 2016, and Murphy et al. 2011). In doing so, an attempt is made to directly compare all energy sources into the same analysis, where the effort expended to operate at different time periods is also compared. This is not to be confused with the Economic Cost of Energy (Equation 6.2) (Hall and Klitgaard, 2012). Much of the modern economic development has been assumed that Equation 6.2 matches reality.

$$\text{Economic Cost of Energy} = \frac{\textit{Dollars to buy energy}}{\textit{GDP}} \quad \text{(Equation 6.2)}$$

In reviewing the literature, it becomes clear that conducting these studies is not that straight forward. Different studies included different parameters in their calculations, resulting in different outcomes. For example, the straight energy consumption from the relevant resource to power equipment in extraction is just the beginning process. The energy consumed in extracting the raw materials to make the equipment also needs to be considered. As does refining and transportation from source to point of application, in all forms. Where matters get unclear is how to include human labor, efficiency of extraction, the development and application of new technologies, maintenance and replacement cycles, depreciation, and deterioration of assets and how to include all of this in the same analysis where the outcome makes logical sense. It is for this reason that many ERoEI studies differ in their conclusions.

There is much disagreement on how to approach this topic. There are many methodological discrepancies related to the functional units used in analysis. For example, joules of heat energy versus joules of grid electricity. For a difference in boundaries used where the analysis starts and stops. For example, the well head versus the end use or energy technology versus energy system.

Boundaries used in the literature for ERoEI analysis can be summarized as:

Standard ERoEI calculation is applied to fuel at the point where it leaves the extraction or production facility (well head for oil & gas, or Run of Mine for coal, farm gate for biofuels). Standard ERoEI includes the on-site and offsite (energy needed to make the products used on site) energy requirements to get energy. For example, to build, operate and maintain a power plant.

Point of use ERoEI includes the energy costs to get and deliver the fuel to the point of use for society. For example, refinement and transportation.

Extended ERoEI includes the energy required to get, deliver, and use a unit of energy. For example, the energy required to produce the machinery and devices used to build, operate, and maintain a power plant or a transport facility as well as the energy required for exploration, investment, communication, labor, etc. in the energy system.

Calculating these terms can get complex, but if they are done appropriately though, they relate as follows:

$$\text{Standard ERoEI} > \text{Point of use ERoEI} > \text{Extended ERoEI} \qquad \text{(Equation 6.3)}$$

To produce a useful results, dynamic ERoEI analysis should be used where possible, where the net energy sued by society is examined, accounting for operating consumption of a given energy system (Equation 6.1 and Figure 6.2), where Equation 6.4 is applied to each box in Figure 6.9, then summed together.

$$Net\ Energy = energy\ returned \times \left(1 - \frac{1}{ERoEI}\right) \qquad \text{(Equation 6.4)}$$

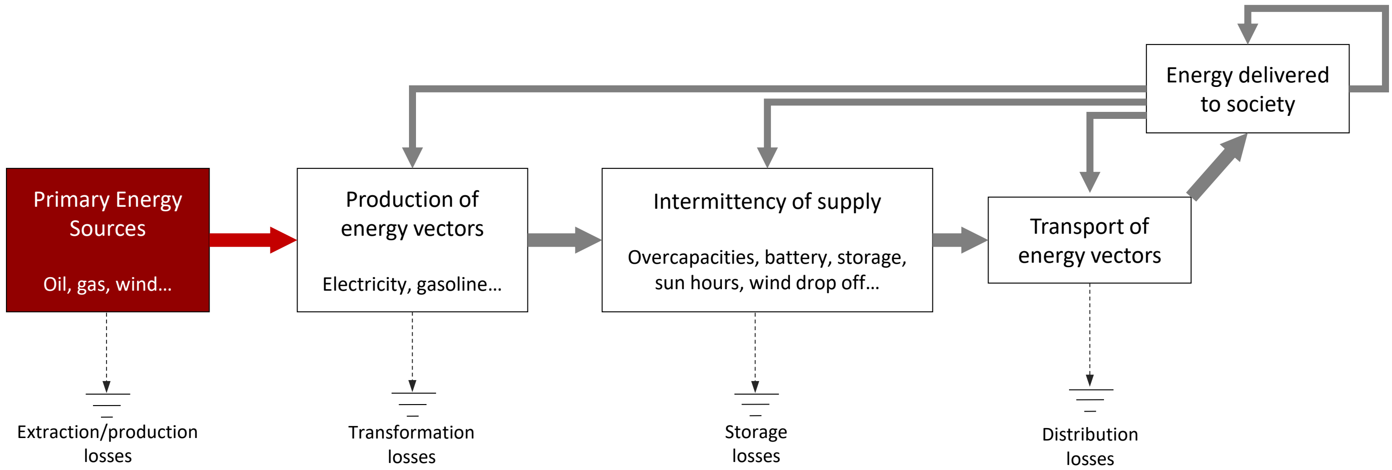


Figure 6.9. An approach for the analysis of energetic metabolism of a society (Source. Developed from Capellán-Pérez *et al* 2019)

A graphical method to describe the relevance of ERoEI has been developed by a number of analysts on the internet blog The Oil Drum (http://www.theoildrum.com/) (Mearns 2016) called the Net Energy Cliff (Figure 6.10). The dark grey section is the net energy available for society to use. The pale grey section is proportion of energy consumed in collecting that energy to make it useable. Declining ERoEI will exacerbate the problem of peak fossil fuels.

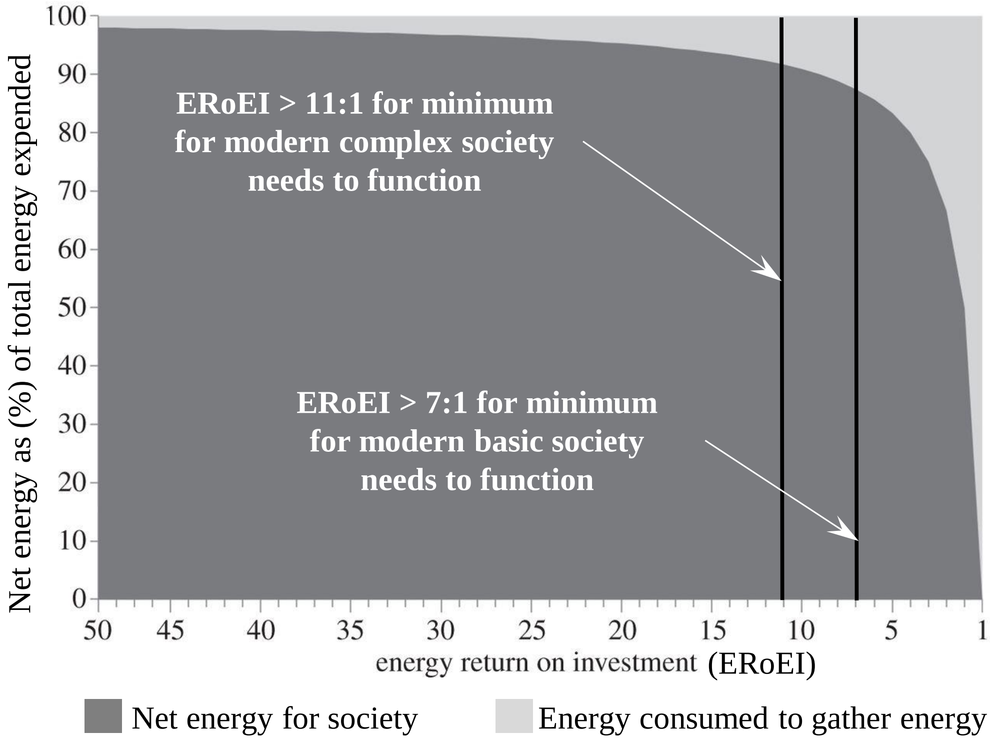


Figure 6.10. The Net Energy Cliff
(Image: Simon Michaux)

There are two ERoEI thresholds below which the modern western society will struggle to function at (Hall et al 2014):

- ERoEI 11:1 The minimum to maintain complex technology and information based structures like the internet, credit banking finance transfer system, just in time supply grid, integrated electronics manufacture, regional continuous grid supplied smooth sinusoidal wave quality electrical power supply, tertiary level hospitals, etc.
- ERoEI 7:1 The minimum to maintain the bare necessities of public utility services like potable drinking water supply, sewerage sanitation, localized intermittent supply of poor quality rough wave electrical power supply, an intermittent physical goods supply grid with a 6 month lag time, etc.

Capellán-Pérez et al 2019 calculates that the thresholds are lower again than what is shown above. This may be appropriate as society transitions out of fossil fuels, depending on how this is done.

Current Western society is comparatively fragile compared to historical societies. Once current society falls below one of these thresholds for a relatively short time (estimated 3 - 6 months), and/or does not receive aid from an external source, transformation and evolution of that society will be desired/required/forced (Smil 2008).

Conventional oil and gas are considered together as they are often extracted together and processed in the same refinery. There is great variation on the ERoEI of different fields and operations. Does the study include:

- Is the operation on land or offshore?
- If it’s offshore, in how deep water out in the ocean?
- How deep is the drill depth?
- What is the quality of the oil? (For example, sulfur content)
- What steps in refining are required to make a saleable product?

When oil extraction first started and ‘oil gushers’ were observed, ERoEI for oil was an extraordinary 500:1. In the 1900-1930 era, ERoEI for oil was still 100:1. In 1970, ERoEI for oil was approximately 30:1. In 2019, oil and gas ranged between 10:1 and 20:1, with the occasional study reporting 65:1. These studies are inconsistent in what was used for their calculations. It is the authors opinion that the ERoEI for oil and gas in 2019 (before the Covid-19 quarantines) was on average 12:1 to 15:1.

What a decline in ERoEI means in context of an oil resource is a decline in quality, and that the deposit is harder to access (deeper in drilling depth) or under the ocean floor (more expensive in terms of CAPEX and OPEX). Once the oil has been extracted, the quality of the oil itself is heavier and sourer in sulfur content. This requires more refining steps, which decreases the net value of the oil.

6.4 Conventional Oil & Gas ERoEI

An excellent example of what a change in ERoEI over time looks like industrially, has been the conventional oil industry. Just so, the required physical work done between different extraction methods for the same final product (per unit/quantity and quality) for different eras of oil extraction are compared.

When oil was discovered in the Pennsylvania oil rush from 1859 to the early 1870s, the first oil boom in the United States began. Oil quickly became one of the most valuable commodities in the United States and railroads expanded into Western Pennsylvania to ship petroleum to the rest of the country. By the mid-1870s, the oil industry was well established, and the "rush" to drill wells and control production was over. Pennsylvania oil production peaked in 1891 and was later surpassed by western states such as Texas and California.

In this early period of oil exploration and extraction, oil was comparatively easy to gain energy from. Crude oil would often bubble to the surface in small springs, which still occur in small examples today.

Most of the oil found in the 1860 to 1920 time period would today be classified light sweet crude, containing small amounts of hydrogen sulfide and carbon dioxide (less than 0.42%). This kind of oil requires very little (and in some case none at all) processing steps before use as a saleable commodity (Burrough 2010)

Drilling depths were very shallow by current standards. During this time period, a drill depth of 1,300ft (400m) was considered standard (Burrough 2010), with some producing wells as shallow as 200ft (60m). Also, some of these early reserves had extraordinary oil pressure. There are many examples where oil would blowout and fountain high into the air (Figure 6.11). There were initially all kinds of logistical problems in managing these gusher blowouts as a single spark could cause an uncontrollable fire. Figure 6.11 shows multiple examples of oil gushers, demonstrating that this was not unusual.

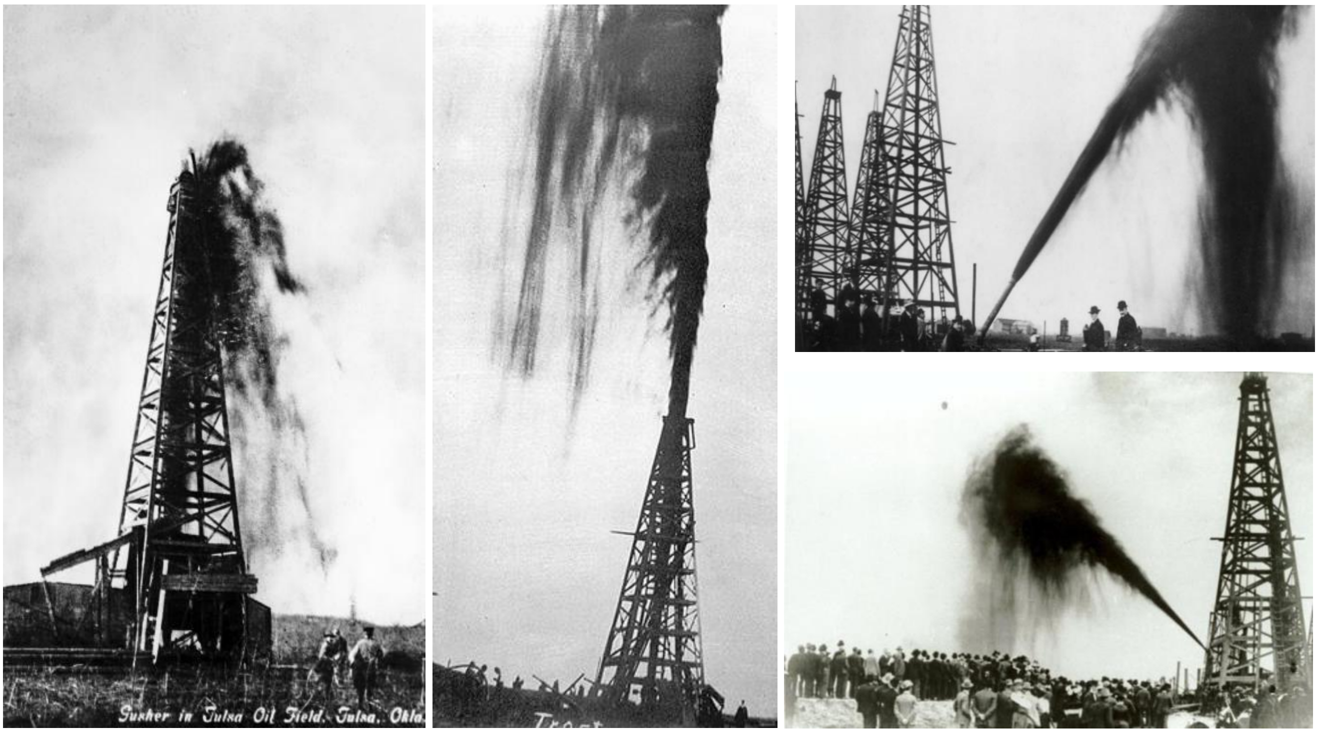


Figure 6.11. The Pennsylvania oil rush in northwestern Pennsylvania from 1859 to the early 1870s
(LHS) The Tulsa gusher at Oaklahoma and (Middle) The Lucas gusher at Spindletop and (RHS) Gusher in Port Arthur, Texas Oil Well in 1901

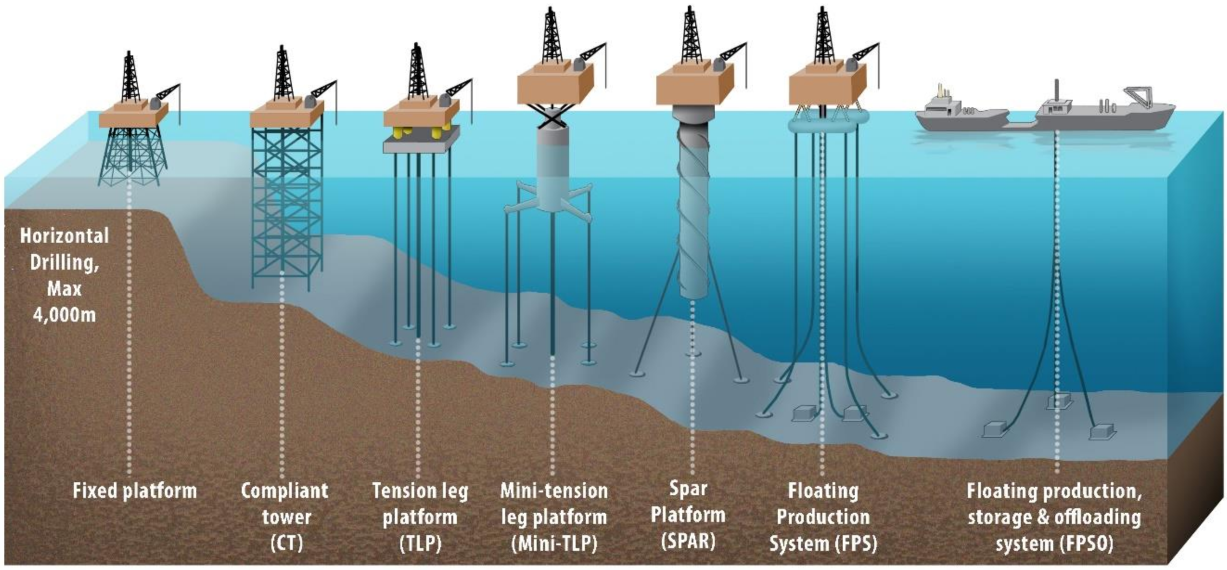
Very quickly the oil boom took hold and oil became the foundation master resource for the industrial economy (Burrough 2010). In this era of oil extraction, ERoEI was approximately 100:1 with examples of even higher values. What is interesting to note that investment culture at the time also saw oil in terms of 100:1 for return on investment (with some examples up to 500:1 in 1880). As in, for every dollar you invest, you would get a return of 100 dollars. So, in 1900, the difference between Equation 6.1 and Equation 6.2 would be very little compared to the same comparison in 2017. Coal and steam power were made obsolete by the internal combustion engine. Extensive infrastructure was constructed to exploit vast oil fields in the United States as quickly as possible (Figure 6.12). Figure 6.12 shows two iconic pictures of Signal Hill oil field, Long Beach in 1937.

In 2017 however, much more effort is required to get the same unit of oil compared to 1900 in Texas. Processing and refining steps are now much more complex. The startup CAPEX capital expenditure costs of commissioning an oil extraction well have been steadily increasing.

In terms of oil extraction infrastructure, offshore drill platforms are now accounting for 1/3 of global oil production. These structures are quite large in size and scale (Figure 6.13). In addition to this, these large scale industrial structures are required to operate in increasingly deep areas of ocean and drill to increasingly deep drill depths starting from the ocean floor (Figure 6.14).

Figure 6.12. A forest of oil derricks sprouts up on the Signal Hill oil field, Long Beach, California, in 1937 (top & bottom) (at the time, an unincorporated area just north of Long Beach)

Figure 6.13. LHS Deep water oil & gas drilling platform (Image by PublicDomainPictures from Pixabay)
RHS (Image by Bruno Glätsch from Pixabay)



	Fixed platform	Compliant tower (CT)	Tension leg platform (TLP)	Mini-tension leg platform (Mini-TLP)	Spar Platform (SPAR)	Floating Production System (FPS)	Floating production, storage & offloading system (FPSO)
Water depth (m)	600m	450-900m	450-1,800m			450-2,100m	1,000-3,000m
Total drilling depth (m)	9,000+m	9,000+m	10,000+m			10,000+m	12,000+m

Figure 6.14. Types and depth capabilities of different offshore drilling platforms
(Image: Tania Michaux)

Also, as most oil extracted now is classified as sour crude, the stages of oil refining have become more complex (Michaux 2019). The size and scope of an oil refinery have become much more complex than oil refining in 1900 (Figure 6.15). The energy cost of refining is also getting more difficult.

Figure 6.15. Oil refinery in Indiana USA
(Image by David Mark from Pixabay)

Figure 6.12 shows the global energy-return-on-investment (EROI) of oil, from the beginning of reported production in 1860 (Court and Fizaine 2017).

As can be observed in Figure 6.16, the EROI (ERoEI) of global oil production reached its maximum values in the 1930's–1940's, around 50:1, and have declined subsequently. In 1970, ERoEI for conventional oil was approximately 30:1. This means that the best industrially useful returns from oil as an energy source is now decades in the past.

Figure 6.17 shows that the EROI for gas peaked around 1930. Since approximately 1970, gas EROI (ERoEI) has been declining at an increasing rate over time.

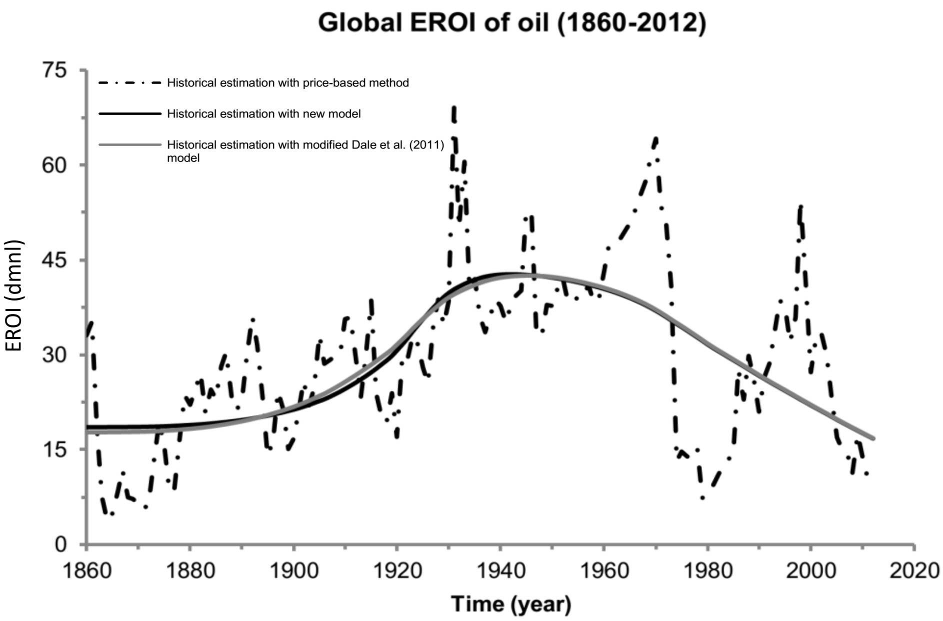


Figure 6.16. Global EROI of oil 1860 to 2012
(Source: Court and Fizaine 2017) (Copyright granted)

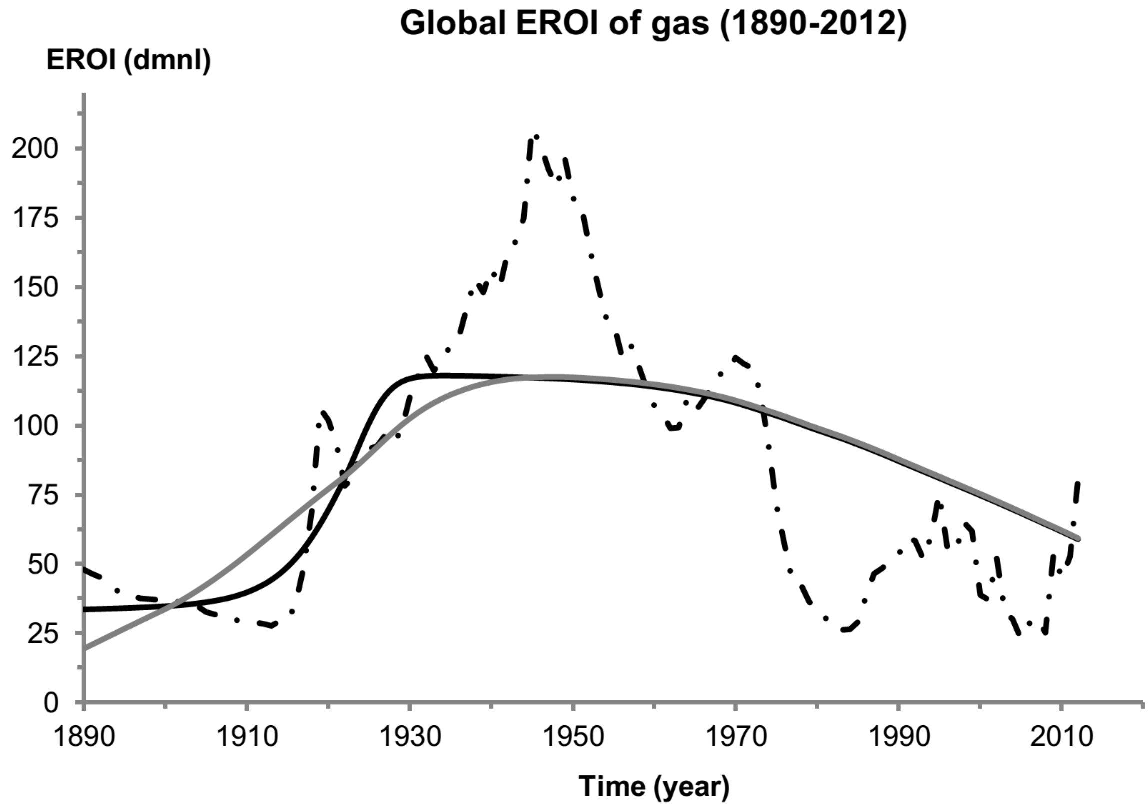


Figure 6.17. Global EROI of gas 1860 to 2012
(Source: Court and Fizaine 2017) (Copyright granted)

Figure 6.16 and 6.17 show how more physical work and infrastructure has gone into producing a given unit volume of oil or gas in 2013 compared to 1900. More energy has been invested than ever before for the same return. Thus, the ERoEI ratio for both oil and gas has degraded and reduced.

6.5 Unconventional Oil & gas ERoEI

Sources like shale oil and shale gas or Coal Seam Gas (CSG) have ERoEI ratios of around 29:1 depending on circumstance. What this does not account for at is the environmental impact these methods have.

Hydraulic fracturing (or Fracking) methods have a been a controversial oil and gas extraction method, with many Social License to Operate (SLO) challenges (Michaux 2019). Also, fracking often results in large quantities of saline water deposited on the surface, which can lead to sterilization of arable land previously used for agriculture. Including these issues that are unique to fracking operations in an ERoEI study to date has been difficult. If they were included, it is possible that the fracking of shale oil or shale gas would result in an ERoEI less than 1. This will need to be quantified in future work in a fair and comprehensive study.

6.5.1 Coal ERoEI

Coal had a comparatively large ERoEI ranging from 50-80:1. Technological advances in coal extraction had made a big difference in the efficiency and ERoEI in the 1970's creating the range in quoted values. Considering coal as a useful resource is currently politically incorrect due to its propensity to generate anthropogenic greenhouse gas emissions (GHG) when it is used in industrial applications. Figure 6.18 shows that coal EROI (ERoEI) is still increasing. It is the only energy source to be doing so.

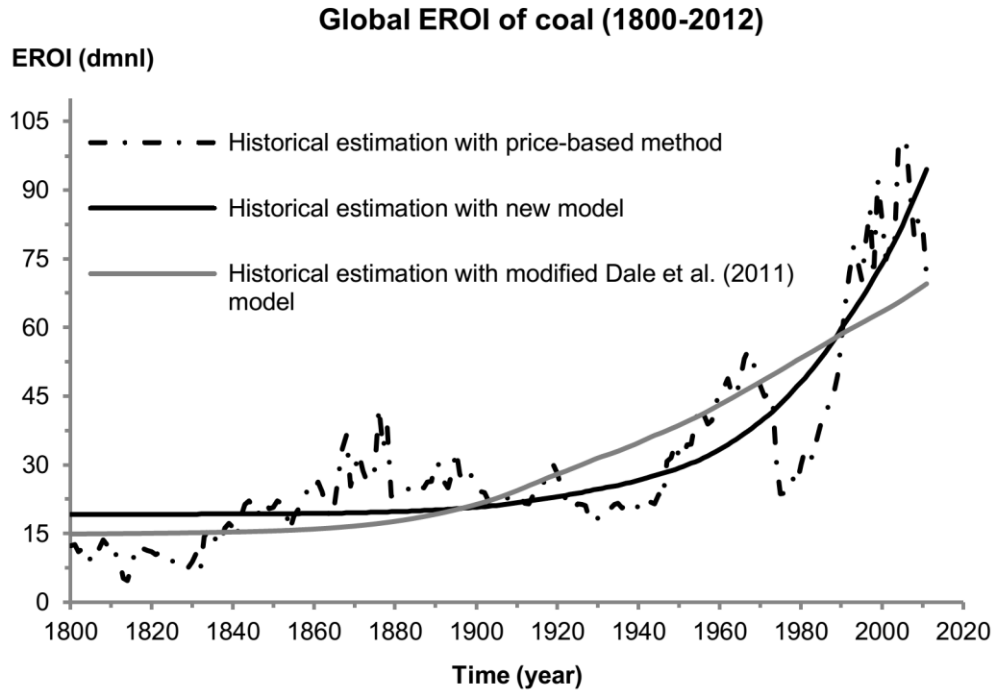


Figure 6.18. Global EROI of coal 1800 to 2012
(Source: Court and Fizaine 2017) (Copyright granted)

6.5.2 Nuclear power ERoEI

Nuclear power has a number of issues associated with it that other energy resources do not have. Some references quote nuclear power ERoEI at 15:1 (Hall *et al* 2011). These studies often do not account for the mining of uranium, refining/conversion/enrichment of uranium, manufacture of nuclear fuel assemblies, and most commonly, storage of spent fuel (SNF) for 10 years in a power cooled facility. As there is not technical solution to deal with nuclear waste beyond dry storing it underground for 100 thousand of years (after powered cooling for 10 years), the true ERoEI is unknown. The value of 5:1 is an estimate of conventional fission based nuclear power (Lenzen 2008).

6.5.3 Solar Power ERoEI

Solar ERoEI studies varied immensely. Descriptions of the system itself made a big difference and its application has complex implications. Geographic position has an influence in efficiency and effectiveness. Current solar systems have a dependence on fossil fuels for manufacture (as does most other energy systems and current industrial operations) and maintenance (Weber 2015). Whether or not the system was grid tied vs. off grid was decisive in its positive ERoEI. An off grid system requires a battery bank. Current battery technology is expensive and makes the ERoEI negative. Solar Photo Voltaic (PV) systems using 2015 technology had an ERoEI of approximately 7 to 9:1. But this estimate did not include batteries. The costs associated with batteries are not included within the ERoEI boundaries.

Whereas solar concentrating systems using heat had an ERoEI of approximately 2.4:1 at the plant output (de Castro & Capellán-Pérez 2018). Solar technology certainly has its place and purchase of such systems is a useful exercise in some applications. In its current form, solar power generation is not effective enough to be the fundamental underpinning energy source of an industrial society, which will need something like 11:1 to maintain the existing western European society (Hall *et al* 2014).

Due to the intermittent nature of renewable power in general (especially solar), a large battery bank is required to act as a buffer to variable charging rates and to provide a constant power supply. The size of the battery bank needed changes with the size of the solar panel array. Battery technology is evolving fast, where a difference in 6 months of the age of the battery bank could result in a significant difference in performance. This aspect of solar power needs to be quantified and included in an ERoEI study, for it to be genuinely useful. Currently this has proven to be quite complex.

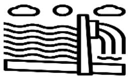
6.5.4 Wind Power ERoEI

Manufacture and maintenance of large wind turbines will be difficult without fossil fuels. All existing industrial manufacture is dependent on fossil fuel supported systems in multiple forms. Resource consumption and energy consumption of manufacture is usually not included. Once established, an average onshore wind turbine with a capacity of 2.5 to 8 MW (with a current maximum of 8 MW) at an estimated ERoEI of 18:1 (Kubiszewski *et al* 2010). Wind power is not practically effective everywhere and is relatively limited to where it can geographically be sited (and still be viable). Wind power generation is very sporadic, intermittent, and variable in when it is charging and by how much (Huang *et al* 2014). A power storage facility of some kind is required to act as a buffer in the same way as solar. This is not included in most ERoEI calculations.

As such, it becomes very difficult to compare wind power generation systems to fossil fuel systems in an appropriate ERoEI context. For the purposes of this report, wind is not compared to fossil fuels in this context.

6.5.5 *Hydro power ERoEI*

This energy resource shows promise to be useful in the future. References ranged from 40-100:1. It is not clear what industrial support this solution would require. It is very limited to where it can geographically be sited. That being stated, this may be the best and most viable renewable energy source and has been recommended in all the scenarios in this report.



6.5.6 *Biofuels ERoEI*

These fuels have their place in society and are useful in some applications. Their ERoEI of 1-3:1 (Capellán-Pérez *et al* 2017, and Pimental *et al* 2005) make them impractical as an underpinning energy source of an industrial society. This does not account for the impact biofuel manufacture has on agricultural food supply. Growing feed stock for biofuels when there is a compelling case for a perceived future global food shortage and global sanitized drinking water shortage (Johnson 2013) would be difficult to justify.

6.5.7 *Geothermal ERoEI*

The ERoEI for geothermal electricity generation systems has been estimated at 7:1 (Capellán-Pérez et al 2017). This innovative energy source, once set up, could be the most sustainable energy source in a long term context. Getting a geothermal power station established can be challenging however and can only be done in some geographic areas. This is dependent on the size, depth and form of the geothermal deposit.

6.5.8 *Tidal ERoEI*

The ERoEI for oceanic wave (also called tidal) has been estimated at 3.25:1 (Capellán-Pérez et al 2017). The technical challenge this system faces is that saltwater corrosion will degrade effectiveness and require high levels of maintenance.

6.6 ERoEI Comparison

Table 6.2 shows a summary of the ERoEI calculations from the literature (not exhaustive) for fossil fuels. These have been quoted separately from renewable energy's sources. The products of these energy systems are a physical fuel which is then burnt to convert it to energy. Note the range of ERoEI ratios by country. Not all fossil fuel sources are the same in effective source of energy. Note that the peak ERoEI for fossil fuels was observed in approximately the year 1960. Since then it has been decreasing. Figure 6.19 shows the same analysis for all fossil fuel energy (oil, gas, and coal). This figure shows that the usefulness of fossil fuels is also in the past, with a collective peak at around 1960.

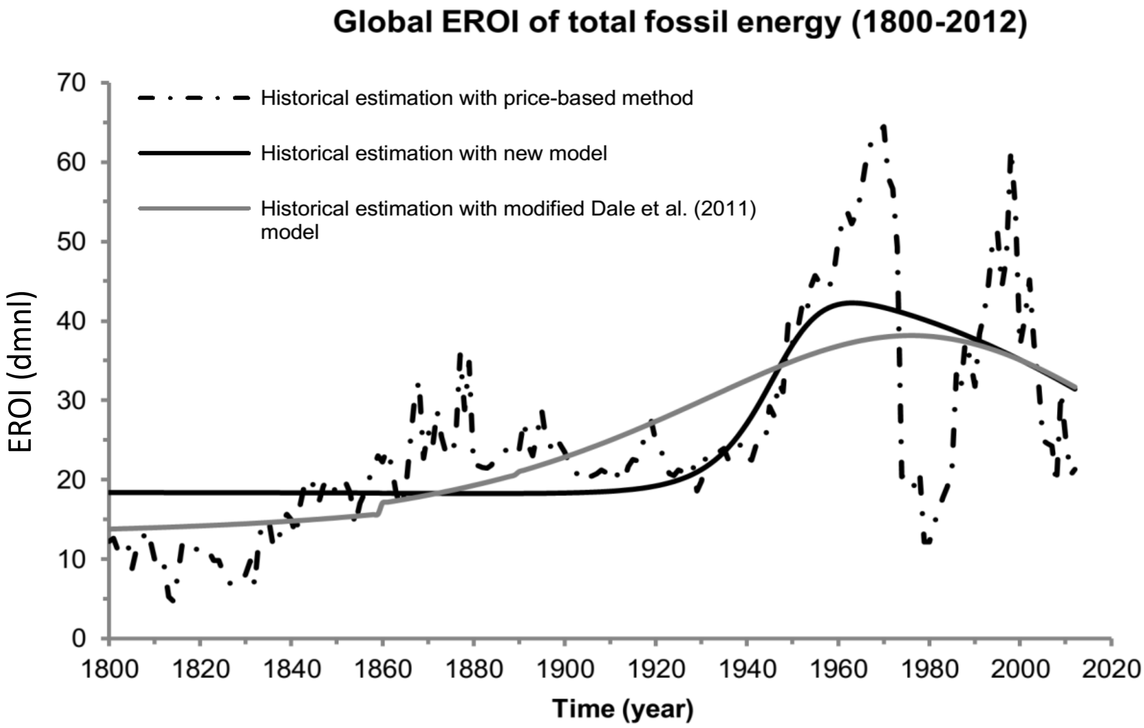


Figure 6.19. Global EROI of total fossil energy 1800 to 2012
(Source: Court and Fizaine 2017) (Copyright granted)

Table 6.2. Energy Returned on Energy Invested for fossil fuel sources (References taken from several sources, as quoted)

Energy Source	Year	Country	ERoEI	Reference
Conventional Oil & Gas production	1999	Global	35:1	Gagnon 2009
Conventional Oil & Gas production	2006	Global	18:1	Gagnon 2009
Conventional Oil & Gas (Domestic)	1970	United States	30:1	Cleveland et al 1984, Hall et al 1986
Discoveries	1970	United States	8:1	Cleveland et al 1984, Hall et al 1986
Production	1970	United States	20:1	Cleveland et al 1984, Hall et al 1986
Conventional Oil & Gas (Domestic)	2007	United States	11:1	Guilford et al 2011
Conventional Oil & Gas (Imported)	2007	United States	12:1	Guilford et al 2011
Conventional Oil & Gas production	1970	Canada	65:1	Freise 2011
Oil & Gas production	2010	Canada	15:1	Freise 2011
Conventional Oil & Gas production	2008	Norway	40:1	Grandell 2011
Conventional Oil production	2008	Norway	21:1	Grandell 2011
Conventional Oil & Gas production	2009	Mexico	45:1	Ramirez 2013
Conventional Oil & Gas production	2010	China	10:1	Hu et al 2011
Hydraulic Fracking oil	2015	United States	29:1	Brandt et al 2015
Oil tar sands	2010	Canada	11:1	Poisson & Hall 2013
Hydraulic Fracking Natural Gas	2005	United States	67:1	Sell et al 2011
Natural Gas	1993	Canada	38:1	Freise 2011
Natural Gas	2000	Canada	26:1	Freise 2011
Natural Gas	2009	Canada	20:1	Freise 2011
Coal (Run of Mine)	1950	United States	80:1	Cleveland et al 1984
Coal (Run of Mine)	2000	United States	80:1	Hall et al 2011
Coal (Run of Mine)	2007	United States	60:1	Hall et al 2014 and Balogh et al 2012
Coal (Run of Mine)	1995	China	35:1	Hu et al 2013
Coal (Run of Mine)	2010	China	27:1	Hu et al 2013

Table 6.3 shows a summary of the ERoEI calculations for the non-fossil fuel energy systems. These systems are used to generate electricity. Table 6.5 shows the calorific density energy content of the fossil fuel products and the relative efficiency of energy conversion in the Internal Combustion Engine (ICE) technologies. In comparison, Table 6.4 shows the calorific density energy content of the non-fossil fuel systems and their relative efficiencies in electrical power generation.

Table 6.3. Energy Returned on Energy Invested for non-fossil fuel sources

Energy Source	ERoEI	Reference
Nuclear	15:1	Hall et al 2011
Nuclear (incuding U mining & enrichment)	5:1	Lenzen 2008
Hydroelectricity	50:1	Capellán-Pérez et al 2019
Geothermal	7:1	Capellán-Pérez et al 2017
Oceanic wave	3.25:1	Capellán-Pérez et al 2017
Wind Turbine	18:1	Kubiszewski et al 2010
Solar Thermal	1.3 to 2.4:1	de Castro & Capellán-Pérez 2018
Solar PV (conventional EROEI analysis)	9 to 10:1	Raugei et al 2017
Solar PV (dynamic EROEI analysis)	7 to 8:1	Raugei et al 2017
Ethanol (sugarcane)	0.8 to 10:1	Yuan et al 2008 and Pimental et al 2005
Corn based ethanol	0.8 to 1.6:1	Pimental et al 2005 and Farrell et al 2006
Biodiesel	1.3 to 1.5:1	Capellán-Pérez et al 2017, and Pimental et al 2005

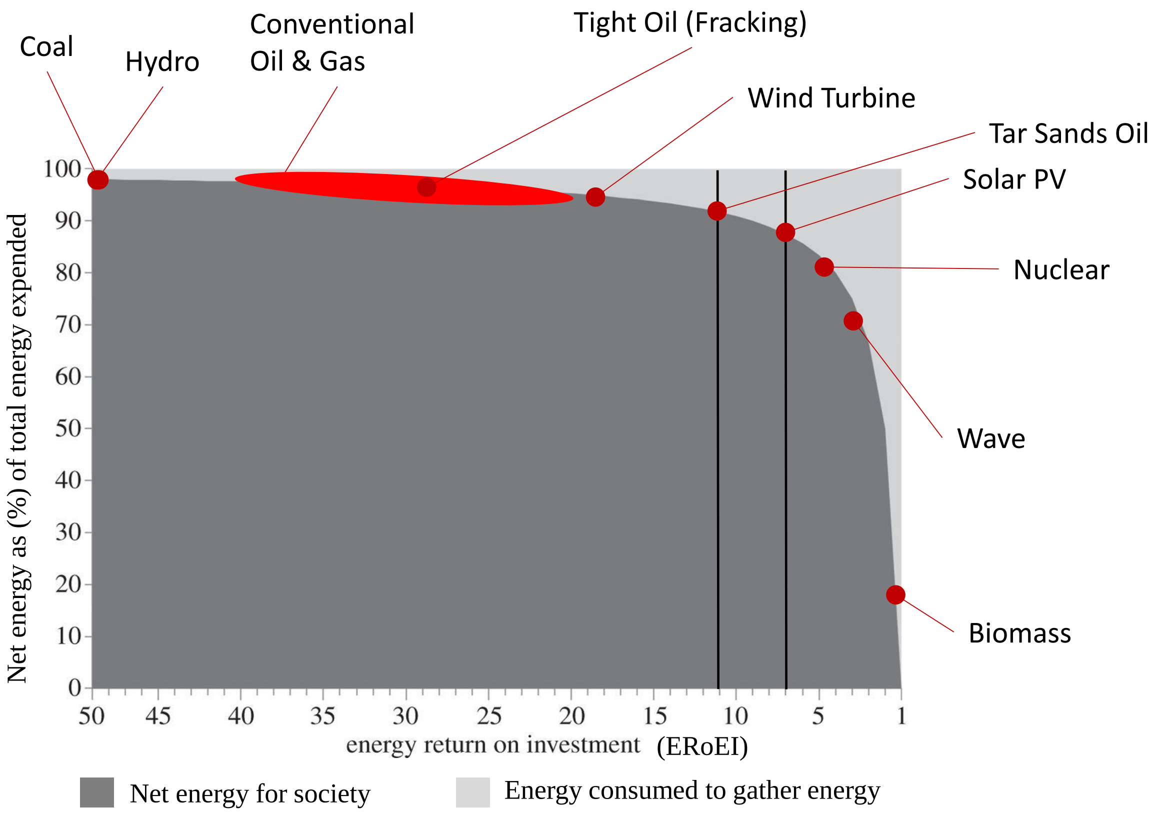


Figure 6.20. The net energy cliff with published numbers of ERoEI from Tables 6.1 and 6.2 (Image: Simon Michaux)

Table 6.4. Efficiency of electric power generation by fuel source (Referenced from Table 3.4)

Power Generation System	Fuel	Energy Content of Fuel	Efficiency of Power Generation from Fuel	Reference
Coal	Coal	8.06 MJ/kg	32-42%	Kiameh 2013
Gas	Gas	40.6 MJ/m^3	32-38%	Kiameh 2013
Nuclear	Enriched Uranium	2000 MJ/Kg	0.27%	Kiameh 2013
Hydroelectric	Moving water	-	85-90%	Abu-Rub et al 2014
Wind	Moving air	-	35-45%	Abu-Rub et al 2014
Solar PV	Sunlight	-	15-20%	Abu-Rub et al 2014
Solar Thermal	Sunlight	-	20 %	Abu-Rub et al 2014
Geothermal	Geological heat	-	10-35%	Abu-Rub et al 2014
Biowaste to energy	Biowaste	12-35 MJ/kg	13 %	Biswas 2009
Fuel Oil Diesel	Crude Oil	46.6 MJ/kg	38 %	Kiameh 2013

Table 6.5. Refined Petroleum Products (Source: OECD Data Statistics Database and Table 3.4)

Fuel	Energy Content of Fuel	ICE Technology	Energy Efficiency of ICE Technology	Reference
Crude Oil	41.87 MJ/kg	N/A		
Diesel Fuel Oil	45.6 MJ/kg	Diesel Engine	35-42%	Kiameh 2013
Heavy Fuel Oil	41.8 MJ/kg	Diesel Engine	35-42%	Kiameh 2013
Petrol (Gasoline)	46.4 MJ/kg	Petrol Engine	25-50%	Kiameh 2013
Jet Fuel	43.0 MJ/kg	Jet Turbine	36-48%	Griggs et al 2014

To appropriately compare Table 6.1 and Table 6.2 together a consistent and comprehensive dynamic ERoEI needs to be applied to the same macro scale industrial ecosystem, where each of these sources supply energy in some form. Each one of these studies have been done to a separate paradigm, using different input assumptions and boundaries and often have inconsistent material units. Most of these studies would have been done with a static or standard ERoEI paradigm using just Equation 6.1.

Figure 6.21 shows a proposed ERoEI study architecture for future work. This could be done for all energy systems. What would be useful is the use of a new metric for comparison that could be used universally. It is recommended to refit the ERoEI calculation to accommodate exergy as a base metric.

Exergy is uniquely suited as it allows direct comparison between all metals, minerals, and fuels. Exergy is the application of thermodynamics to the accounting of natural resources and material fluxes. It examines the real energy costs, that is, the replacement costs, relative to a standard reference environment (RE). Therefore, one can compare in the same units the costs of different industrial operations in context of natural resources: Exergy (in Joules, J).

In thermodynamics, the exergy of a system is the maximum useful work possible during a process that brings the system into equilibrium with a heat reservoir, reaching maximum entropy (Rant 1956). The maximum fraction of an energy form which (in a reversible process) can be transformed into work is called exergy. The remaining part is called anergy, and this corresponds to the waste heat (Honerkamp 2002). Using an exergy standard states makes it possible to express these enthalpy and entropy data as Exergy by using for example the methodology and standard states expressed in Szargut (2005).

When the surroundings are the reservoir, exergy is the potential of a system to cause a change as it achieves equilibrium with its environment. Exergy is the energy that is available to be used. After the system and surroundings reach equilibrium, the exergy is zero. Determining exergy was also the first goal of thermodynamics. The term "exergy" was coined in 1956 by Zoran Rant (1904–1972) by using the Greek ex and ergon meaning "from work" (Rant 1956 and Grubbström 2007).

Energy is neither created nor destroyed during a physical process, but changes from one form to another (as per the 1st Law of Thermodynamics). In contrast, exergy is always destroyed when a process is irreversible, for example loss of heat to the environment (As per the 2nd Law of Thermodynamics). This destruction is proportional to the entropy increase of the system together with its surroundings. The destroyed exergy has been called anergy (Honerkamp 2002).

This means that the results shown in Figure 6.20 should be treated as rough guide, not a precise calculation. As such comparing sources in this context is not that useful beyond the application of very blunt statements:

- The fossil fuels (oil, gas, and coal) being extracted now are much lower in ERoEI (12 to 15:1) than what was extracted 80 to 100 years ago (when ERoEI was 100:1 or better).
- The non-fossil fuel systems being examined to replace fossil fuels, are generally lower in ERoEI.
- This trend of decline in ERoEI is likely to continue as most non-fossil fuel systems depend on fossil fuels in some form to function.

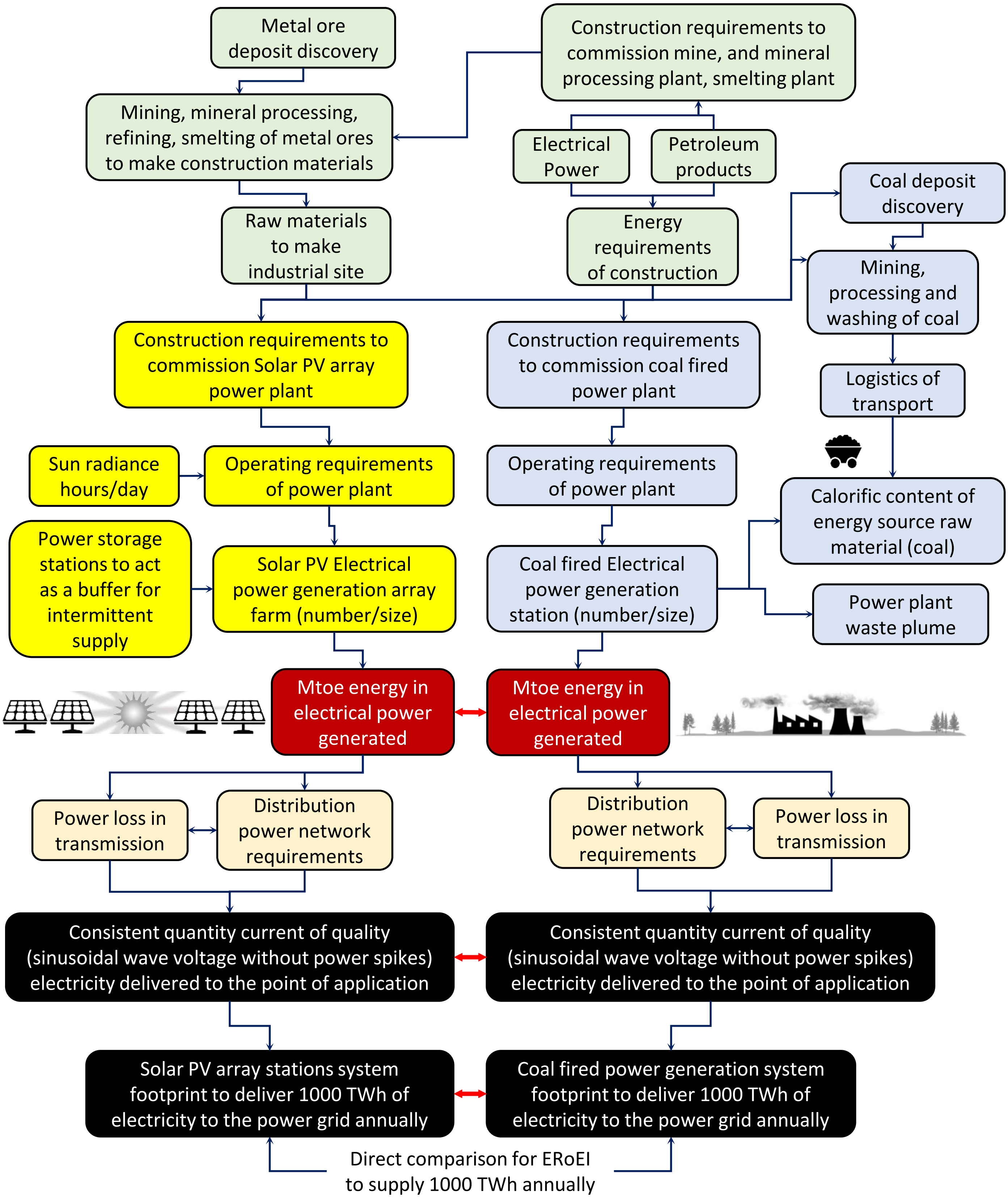
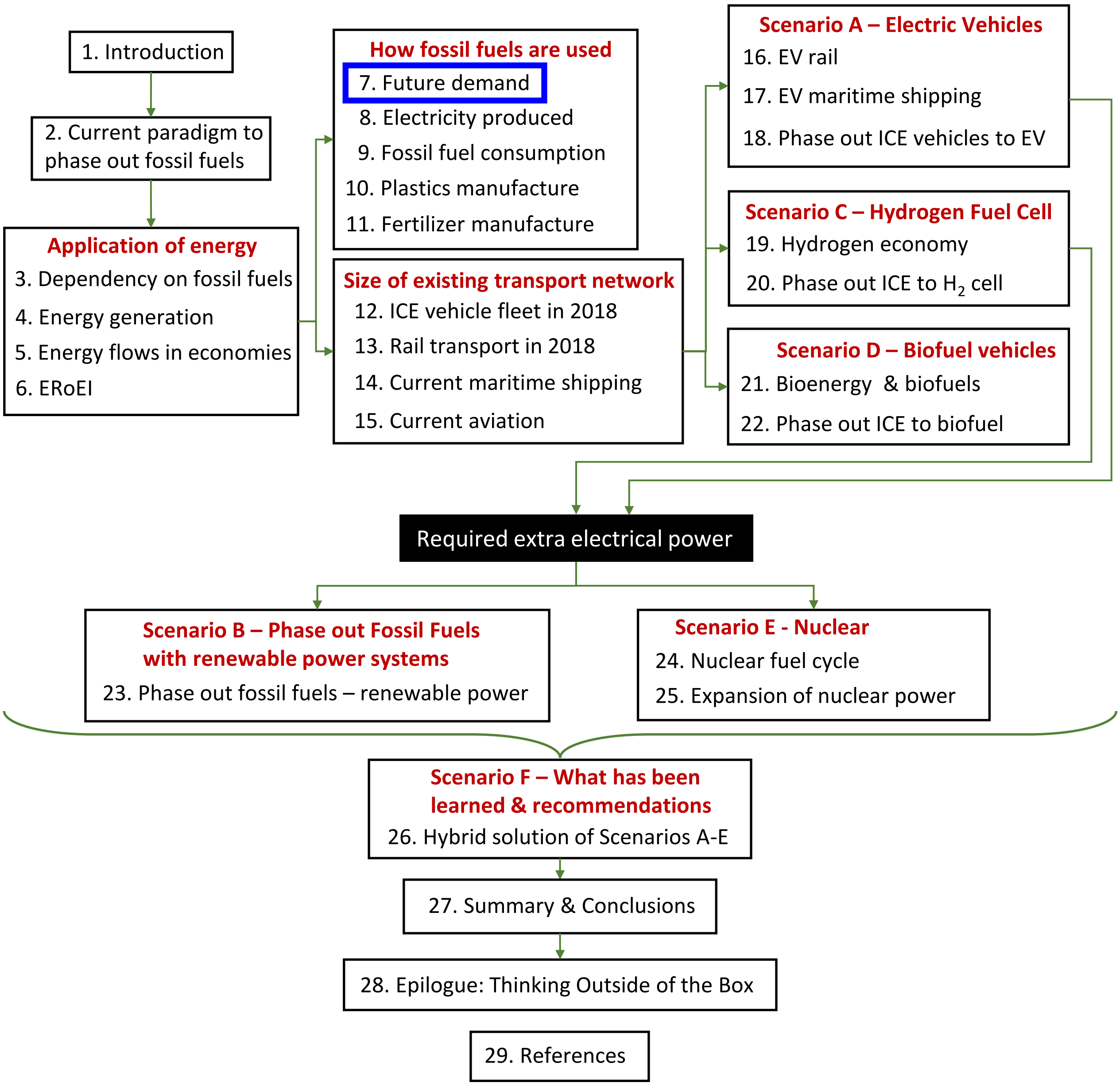


Figure 6.21. Proposed ERoEI study to compare coal fired power generation and solar PV power generation to deliver 1000 TWh annually to the electrical power grid (Image: Simon Michaux)

7 PREDICTED FUTURE DEMAND FOR ENERGY

As shown in Section 2, current policies in Europe is to become more efficient as fossil fuels are phased out. Is this reflected in context of what current industrial/residential systems are predicted to need in future applications? This Section has been written to examine what might future demand for energy might be, in context of existing industrial profiles in a global context.



Assessment of the Extra Capacity Required of Alternative Energy Electrical Power Systems to Completely Replace Fossil Fuels

Most of energy generated is supported by a nonrenewable natural resource as a fuel. Currently we are a petroleum dominated society (Martenson 2011, Ruppert 2007, Tainter 1988), with a heavily dependency on other fossil fuels like gas and coal. Nuclear power is no different. It requires uranium to be mined then refined. This is a finite resource like any other and has a limit (Zittel et al 2013). Renewable power sources like photovoltaic solar require minerals to manufacture solar panels in vast numbers. These minerals are also nonrenewable natural resources.

The different sources of energy are not equal in calorific content. Nor are they used in the same applications. Transfer of energy source to power technology from one resource to another is often not possible. With the exception of oil and to a lesser extent gas, once these energy resources are used to generate power, those power stations have to run at a consistent supply to grid level or suffer degradation in their infrastructure. Oil and gas are flexible in use, coal and nuclear are not.

The global resources consumed to produce energy is shown since the beginning the industrial revolution (IR2 and IR3). The majority proportion of energy consumption has always been fossil fuels and are projected to be so in the future. Also note that the demand for the resources has been increasing consistently in an exponential fashion (as opposed to demand decreasing, or even remaining static). Global energy consumption increased by 2.9% in 2018, which is the strongest Year on Year (YOY) growth since 2010. The demand for all fuels increased but growth was particularly strong in the case of gas (168 mtoe, accounting for 43% of the global increase) and renewables (71 mtoe, 18% of the global increase) (BP Statistical review of World Energy 2019). Over the last decade, world primary energy consumption grew at an average annual rate of 1.8 percent. It's important to note, that in per-capita terms the rate of energy growth has significantly slowed since the 1980s, increasing at an average annual rate of 0.4% since that time, compared to 1.2% in the century prior (Jancovici 2011). This could be because of a change in the CAGR of the oil industry (Michaux 2019).

The U.S. Energy Information Administration's (EIA) International Energy Outlook (IEO) Reference case projections are not considered a prediction of what is most likely to happen, but rather they are modeled projections under various alternative assumptions (EIA 2019 b). As stated in the EIA 2019 International Energy Outlook (IEO):

> *The Reference case reflects current trends and relationships among supply, demand, and prices in the future. It is a reasonable baseline case to compare with cases that include alternative assumptions about economic drivers, policy changes, or other determinants of the energy system to estimate the potential impact of these assumptions.*

The Reference case includes some anticipated changes over time:

- Expected regional economic and demographic trends, based on the views of leading forecasters
- Planned changes to infrastructure, both new construction and announced retirements
- Assumed incremental cost and performance improvements in known technologies based on historical trends

This case does not include some of the potential future changes:

- Changes to national boundaries and international agreements
- Major disruptive geopolitical or economic events
- Future technological breakthroughs
- Black Swan events like a pandemic

World primary energy consumption is projected (EIA 2019 reference case) to rise by approximately 50% between 2018 and 2050 (Figure 7.1).

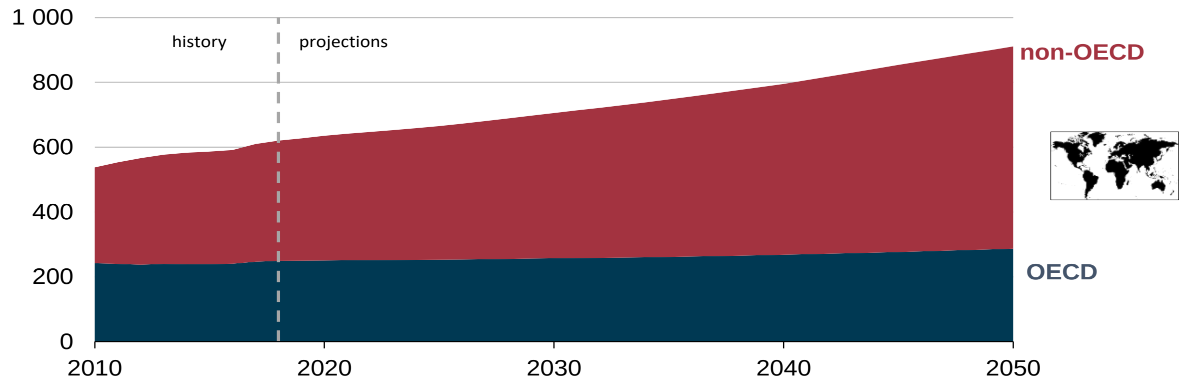


Figure 7.1. World primary energy consumption quadrillion British thermal units
(Source: EIA International Energy Outlook 2019 with projections to 2050)
(World Map Image by Clker-Free-Vector-Images from Pixabay)

Figure 7.2 shows predicted global energy demand by sector. As can be seen, the industrial sector is the largest consumer of primary energy (accounting for more than half of demand).

The Organization for Economic Co-operation and Development (OECD) is an intergovernmental economic organization with 36 member countries, founded in 1961 to stimulate economic progress and world trade.

The industrial sector, which includes refining, mining, manufacturing, agriculture, and construction, accounts for the largest share of energy consumption of any end-use sector—more than 50% of end-use energy consumption during the entire projection period. World industrial sector energy use increases by more than 30% from 2018 to 2050, reaching about 315 quadrillion British thermal units (Btu) by 2050.

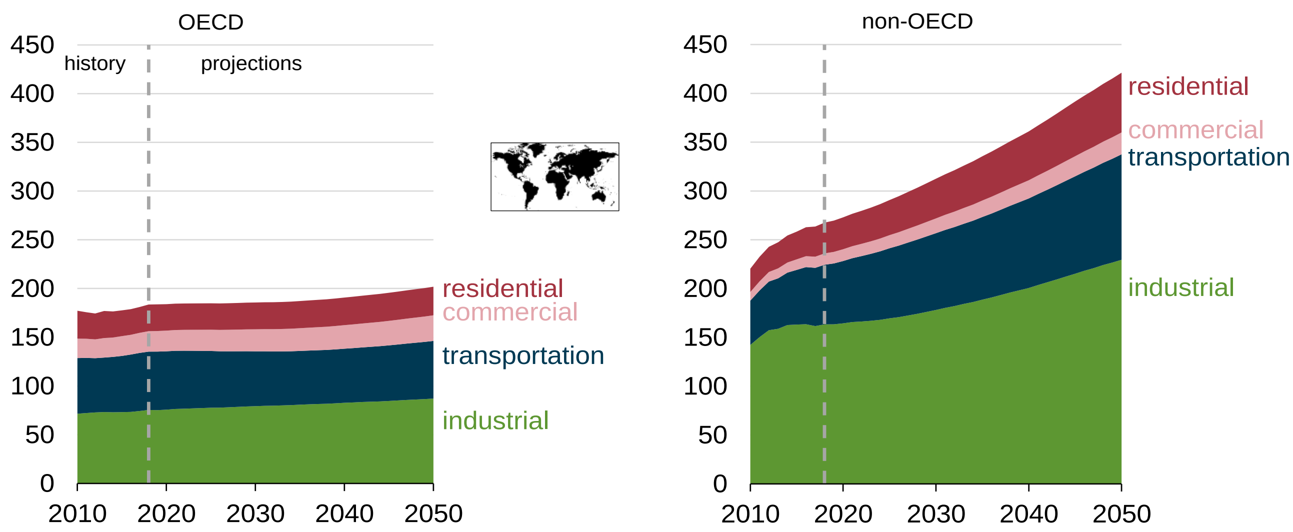


Figure 7.2. Energy consumption by sector quadrillion British thermal units
(Source: EIA International Energy Outlook 2019 with projections to 2050)
(World Map Image by Clker-Free-Vector-Images from Pixabay)

As shown in in Figure 7.2, most of the increase in industrial sector energy use occurs in non-OECD nations. Industrial sector energy use in non-OECD countries grows by more than 1.0% per year in the Reference case compared with an increase of 0.5% per year in OECD countries. The persistent pattern of growth in energy demand being in non-OPEC countries, could be due to most industrial production being in those countries. This means that OPEC countries have largely become consumers and are now dependent on non-OPEC countries for supply of components and some manufactured goods.

Figures 7.3 to 7.8 shows energy consumption by geographic region and by sector. Again, note how the non-OECD countries are accounting for most of the growth.

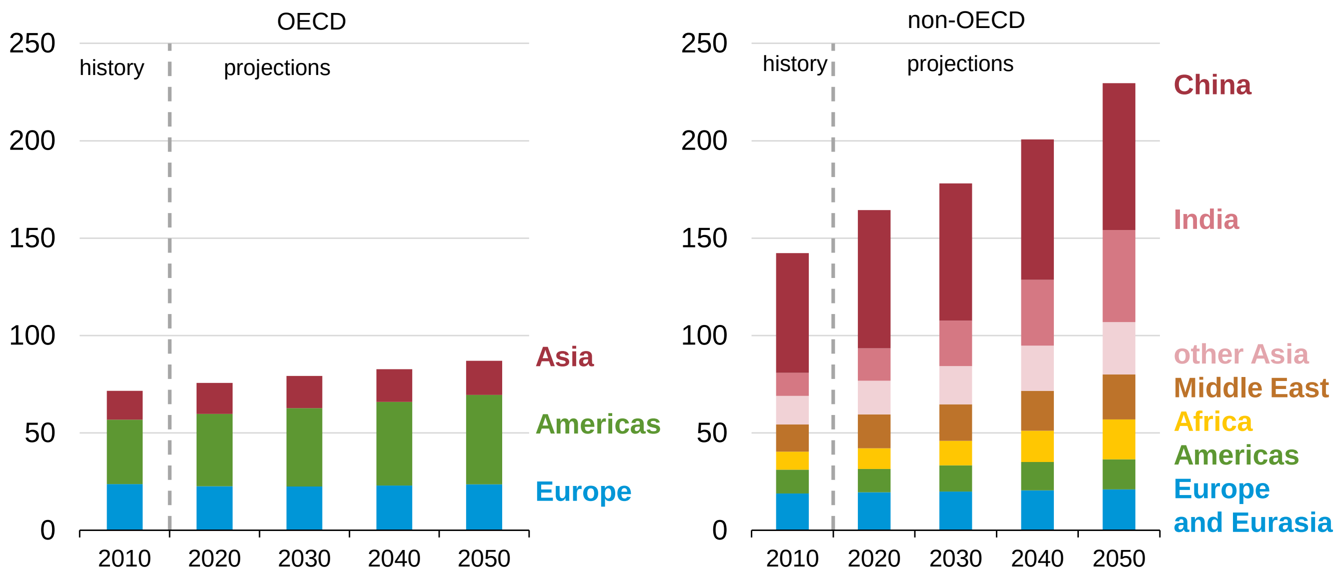


Figure 7.3. Industrial energy consumption by sector quadrillion British thermal units
(Source: EIA International Energy Outlook 2019 with projections to 2050)

China remains the world's largest single industrial energy consumer and India experiences the most growth in consumption. In 2018, China consumed 29% of the world's industrial energy, and although its energy consumption continues to increase modestly throughout the projection period, its share decreases to 24% by 2050. India's industrial energy consumption nearly triples, growing from 16 quadrillion British thermal units (Btu) in 2018 to 47 quadrillion Btu by 2050 at an average annual rate of 3.4%. India's 31 quadrillion Btu growth in energy consumption from 2018 to 2050 represents 40% of the total world increase of 78 quadrillion Btu.

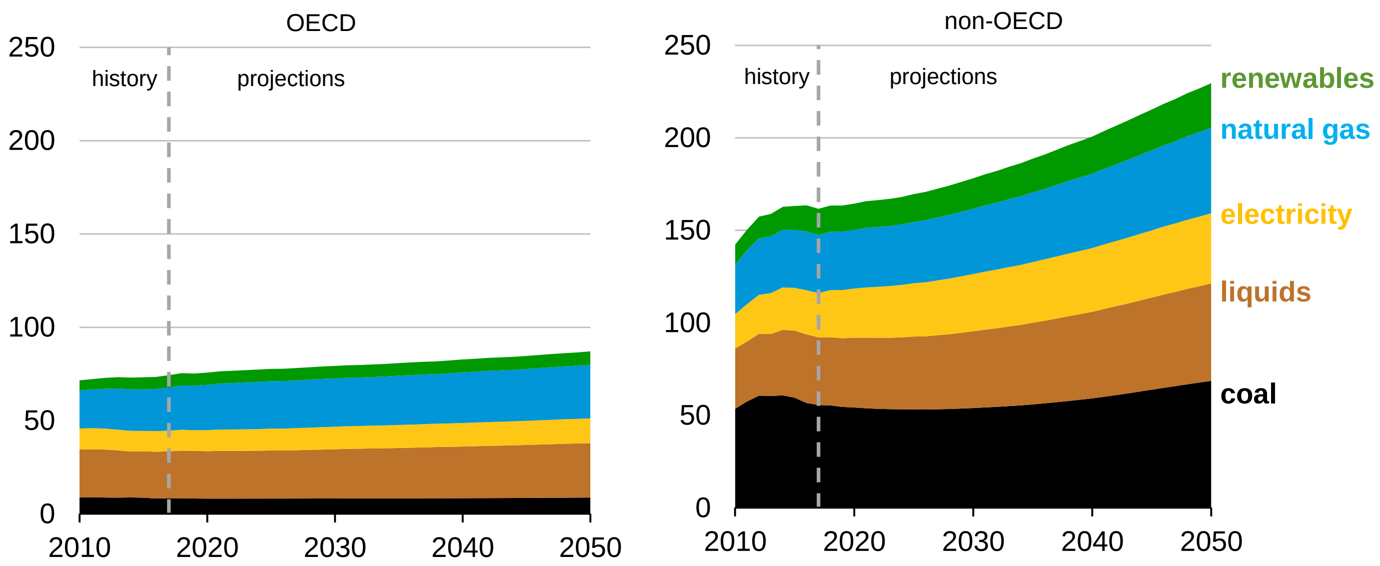


Figure 7.4. Industrial sector energy consumption by fuel, quadrillion British thermal units
(Source: EIA International Energy Outlook 2019 with projections to 2050)

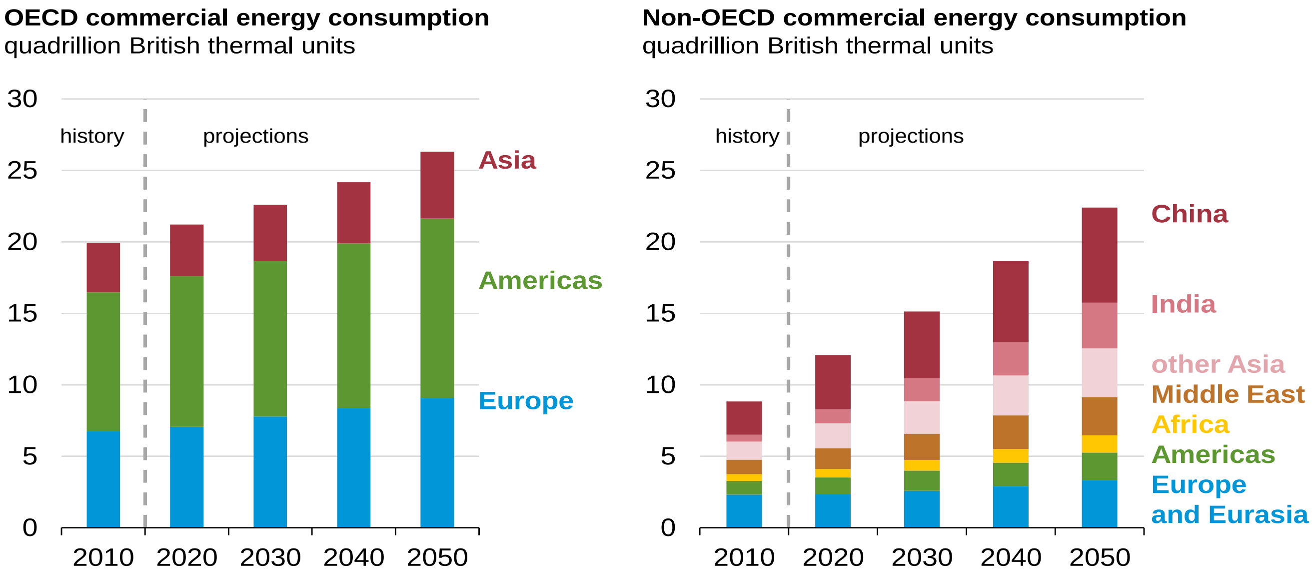


Figure 7.5. Commercial energy consumption by sector quadrillion British thermal units
(Source: EIA International Energy Outlook 2019 with projections to 2050)
(World Map Image by Clker-Free-Vector-Images from Pixabay)

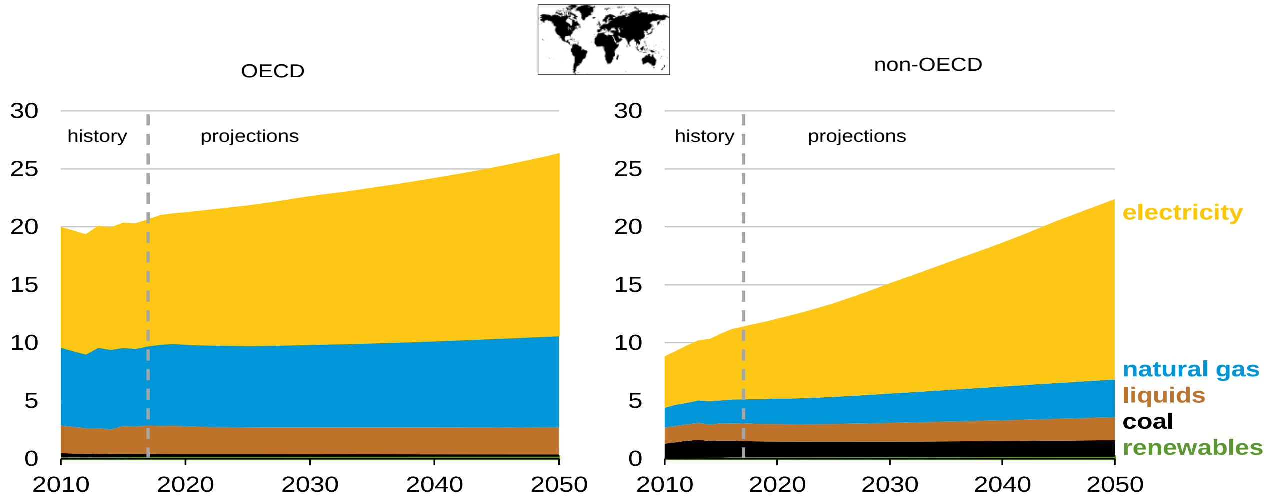


Figure 7.6. Commercial sector energy consumption by fuel quadrillion British thermal units
(Source: EIA International Energy Outlook 2019 with projections to 2050)
(World Map Image by Clker-Free-Vector-Images from Pixabay)

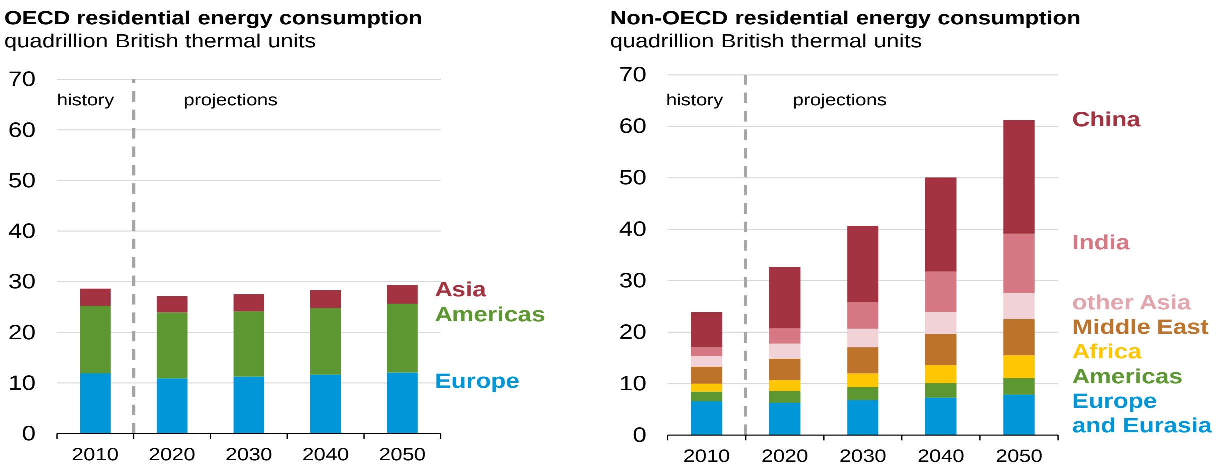


Figure 7.7. Residential energy consumption by sector quadrillion British thermal units
(Source: EIA International Energy Outlook 2019 with projections to 2050)

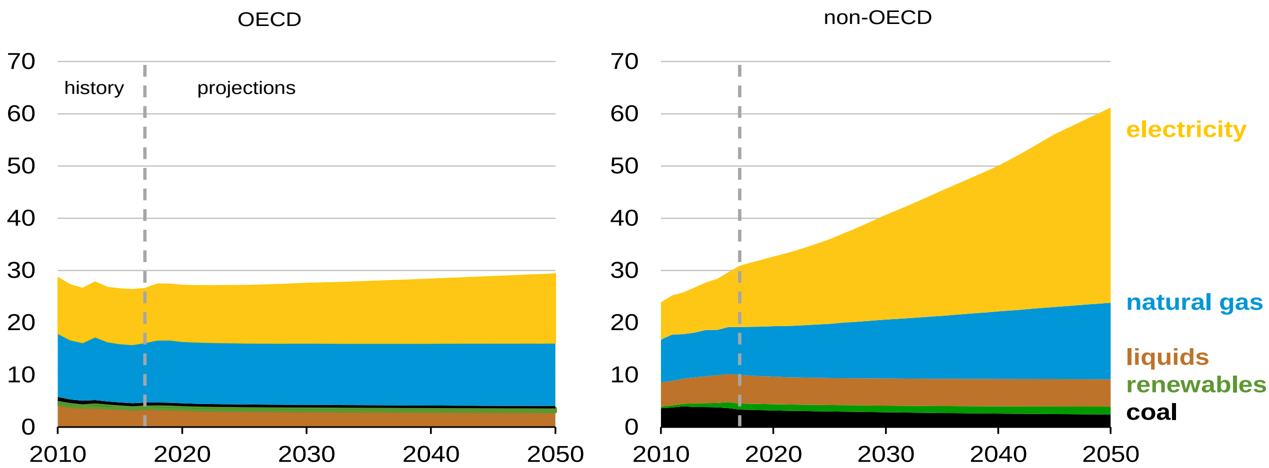


Figure 7.8. Residential sector energy consumption by fuel, quadrillion British thermal units
(Source: EIA International Energy Outlook 2019 with projections to 2050)

7.1 Increased demand within the global economy – if all nations became 'developed'

All of the demand scenarios discussed in this report so far have been based around assumptions that the world will continue in the same basic patterns it has for the last 75 years. The progression of the United States and the European Union (a large portion of the 'developed' world) has been relatively quantified, where the projected future footprint has been understood within the global market.

There are several emerging markets which are developing in a different evolutionary path to the existing developed economies. As such, their long term development is not that well understood. The relationship between some nation states that have the classification of being developed and other nation states that provide raw materials or manufactures goods is becoming more defined in the last 20 years. This difference is why strategic goals like the Circular Economy have been proposed.

Economies of note in this context are the BRIC nations, Brazil, Russia, India, and China, which represent 23% of 2018 global GDP, and 41% of global population in 2018. What resource demand would there be if all nation states in the global ecosystem became equally developed in complexity?

Energy consumption is a useful proxy for technology use and industrial application. Oil and gas are used in this context for a thought experiment:

> ***What would global energy consumption of oil and gas be, if the entire world became as developed as the nation Germany, and consumed energy at the same rate as Germany?***

The 2018 German economy was selected as the reference point. In this thought experiment, the BRIC emerging economies are projected to evolve in complexity, with the objective of becoming developed economies in a similar profile to the Germany (Germany has a high GDP, a complex and sophisticated manufacturing sector, high standard of living, and has complex developed infrastructure). This projection was then applied to the rest of the world (RoW).

The 2018 oil consumption per capita for Germany was 0.0285 (Table 7.1). This was multiplied by the human population of each of the target nation state economies, providing an estimate of the annual oil consumption as if each nation state was as developed as Germany. The results are graphically shown in Figure 7.9. Table 7.2 and Figure 7.10 show the same procedure for gas.

If just the BRIC economies (Brazil, Russia, India, and China) were successful in becoming as industrially developed as Germany in 2018, an extra 63 460 thousand barrels of oil a day (63.5 million barrels a day) would have to be brought to the market. India in particular would expand consumption significantly. To put this in perspective, an extra 16.7 new oil fields, the size of the Saudi Arabian Ghawar elephant field (producing 3.8 million barrels a day, would need to be discovered, developed and extra refining capacity commissioned) (Michaux 2019).

If the entire global system was successful in developing industrially similar capacity to Germany in 2018, extra 116 683 thousand barrels of oil a day (116.7 million barrels a day) would have to be brought to the market. This would need an extra 30.1 new oil fields, the size of the Saudi Arabia Ghawar elephant field. This represents a 117% expansion of oil consumption on top of global 2018 demand.

What was of note was in context of oil consumption, the United States was the only nation that would be required to reduce it consumption to just 46% of its 2018 consumption rate. In the context of gas consumption, Russia would have to reduce its consumption rate to 36% and the United States reduce its consumption rate to 43% of their 2018 rates of consumption. They would be required to become more efficient, although the Russian gas consumption could be due to a cold climate and the extra gas was used in heating.

Table 7.1. Projected oil consumption as all economies become as developed as the German Economy
(Source: data from BP Statistical Review of World Energy 2019, Appendix C, World Bank data, United Nations, Department of Economic and Social Affairs, Population Division (2017). World Population Prospects: The 2017 Rev)

Country	Population 2018 (000's)	Oil Consumption in 2018 (kbbls/day)	2018 oil consumption per capita (kbbls/day/capita)	Oil consumption at German 2018 rate per capita (kbbls/day/capita)	Percent Change (%)
Brazil	208 500	3 081	0,0148	5 945	193 %
Russia	146 900	3 228	0,0220	4 189	130 %
India	1 354 000	5 156	0,0038	38 606	749 %
China	1 392 730	13 525	0,0097	39 711	294 %
Germany	81 402	2 321	**0,0285**		
United States	327 170	20 456	0,0625	9 329	46 %
Europe EU-28	513 500	13 302	0,0259	14 641	110 %
World Total	7 594 000	99 843	0,0131	216 526	217 %

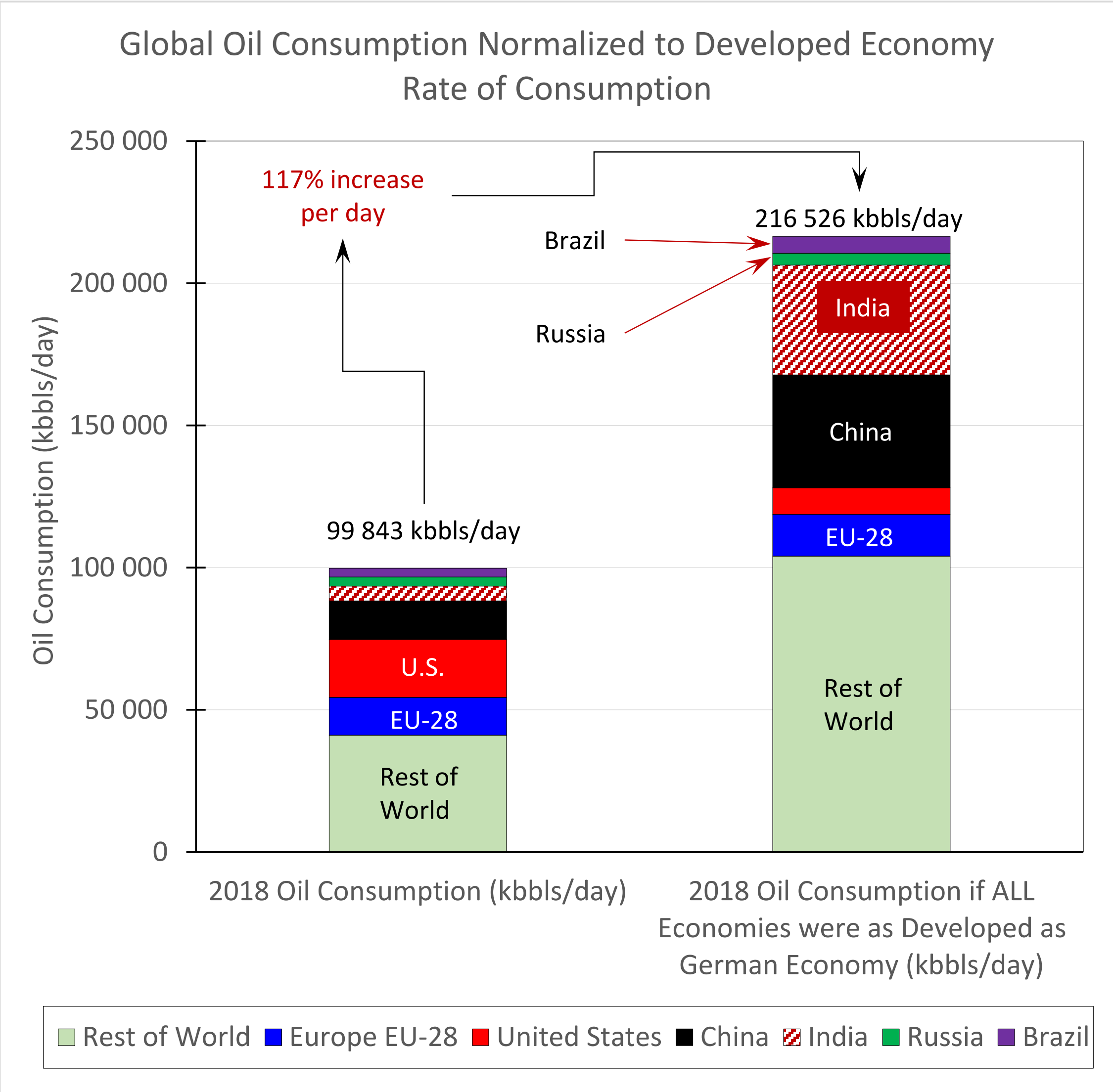


Figure 7.9. Projected oil consumption as all economies become as developed as the German Economy
(Source: data from BP Statistical Review of World Energy 2019, Appendices C and D, World Bank data, United Nations, Department of Economic and Social Affairs, Population Division (2017). World Population Prospects: The 2017 Rev)

Table 7.2. Projected gas consumption as all economies become as developed as the German Economy
(Source: data from BP Statistical Review of World Energy 2019, Appendix E, World Bank data, United Nations, Department of Economic and Social Affairs, Population Division (2017). World Population Prospects: The 2017 Rev)

Country	Population 2018 (000's)	Gas Consumption in 2018 (m^3/year)	2018 gas consumption per capita (m^3/year)	Gas consumption at German 2018 rate per capita (m^3/year)	Percent Change (%)
Brazil	208 500	35 900 000 000	172,2	226 168 275 964	630 %
Russia	146 900	454 500 000 000	3 093,9	159 348 296 111	35 %
India	1 354 000	58 100 000 000	42,9	1 468 737 868 848	2528 %
China	1 392 730	283 000 000 000	203,2	1 510 749 846 441	534 %
Germany	81 402	88 300 000 000	1 084,7		
United States	327 170	817 100 000 000	2 497,5	354 894 363 775	43 %
Europe EU-28	513 500	549 000 000 000	1 069,1	557 013 955 431	101 %
World Total	7 594 000	3 848 900 000 000	506,8	8 237 515 048 770	214 %

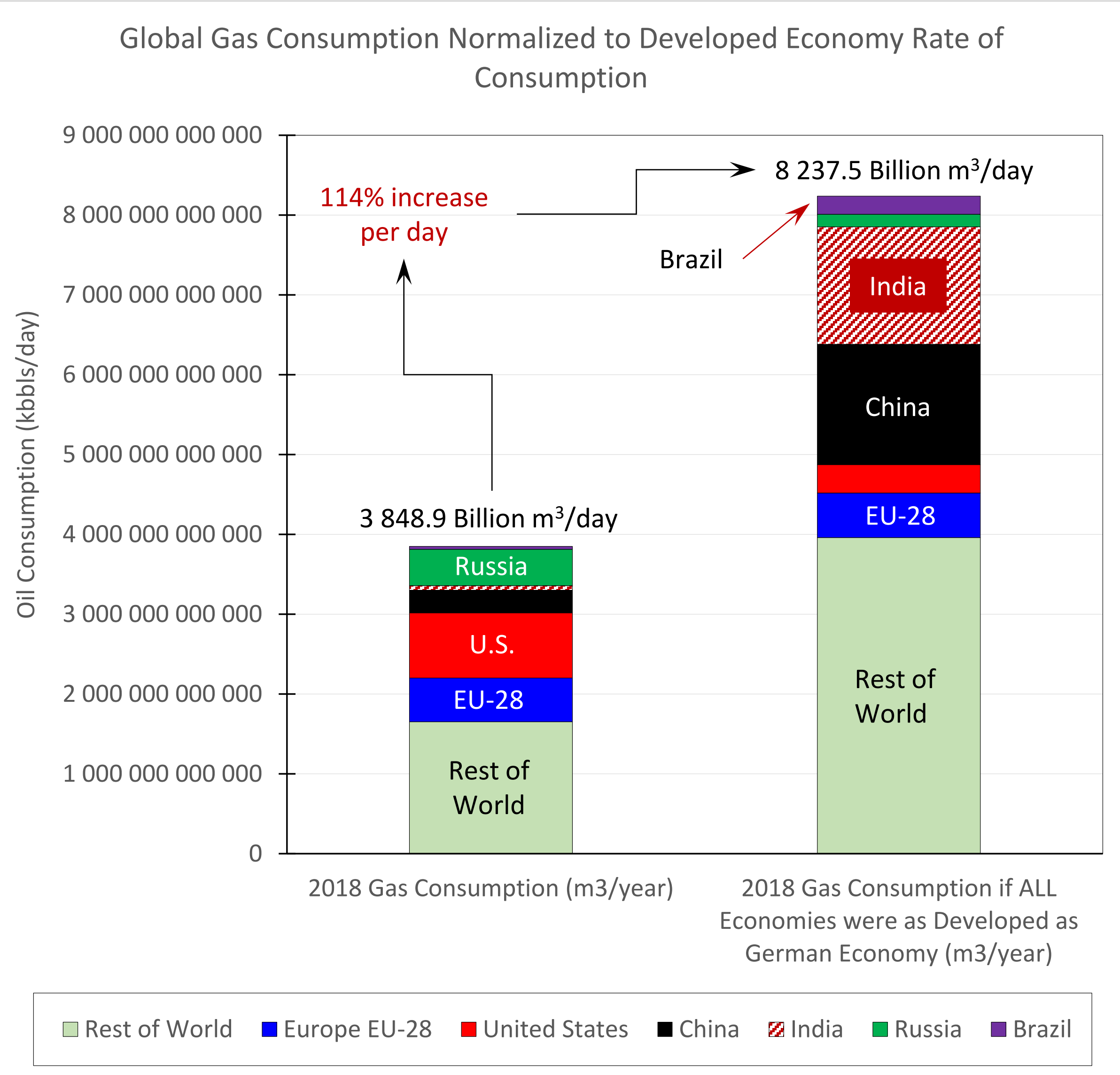


Figure 7.10. Projected gas consumption as all economies become as developed as the German Economy
(Source: data from BP Statistical Review of World Energy 2019, Appendix E, World Bank data, United Nations, Department of Economic and Social Affairs, Population Division (2017). World Population Prospects: The 2017 Rev)

This thought experiment showed that if all economies in the global industrial ecosystem was to become as developed as the German economy, then a vast quantity of extra oil and gas production rate is required to be developed. That is on top of what is being produced now. Due to the rate of oil deposit discovery falling since the mid 1960's and gas in the mid 1970's (Michaux 2019), and the record low for discovery being in 2017 (Rystad 2018, Davis 2017), this is probably not possible.

This means that it is highly unlikely that all nation states will develop to the same industrial, economic, and technological profile. This is unfortunate as this is the stated goal of organizations like the United Nations. Economic and industrial inequality is fundamentally implied as a consequence of a lack of available global resources in context of current global population.

This conclusion validates the basic outcome of the Club of Rome Limits to Growth study (Meadows *et al* 1972 and Turner 2008), where the current industrial ecosystem will at approximately 2020, will encounter limitations of operation (Figures 1.10 to 1.13 in Section 1). This will involve a radical transformation of the relationship between the industrial ecosystem and the raw materials it annually consumes.

How this happens is a matter of debate. At the time of writing this report, the Covid-19 pandemic, and associated quarantine lockdowns were in progress. This pandemic has resulted in a black swan for the global markets and data collected after 2019 has been anomalously different compared to data prior to 2019. Just so, the Covid-19 pandemic could be masking the data structures predicted by the Limits to Growth Study.

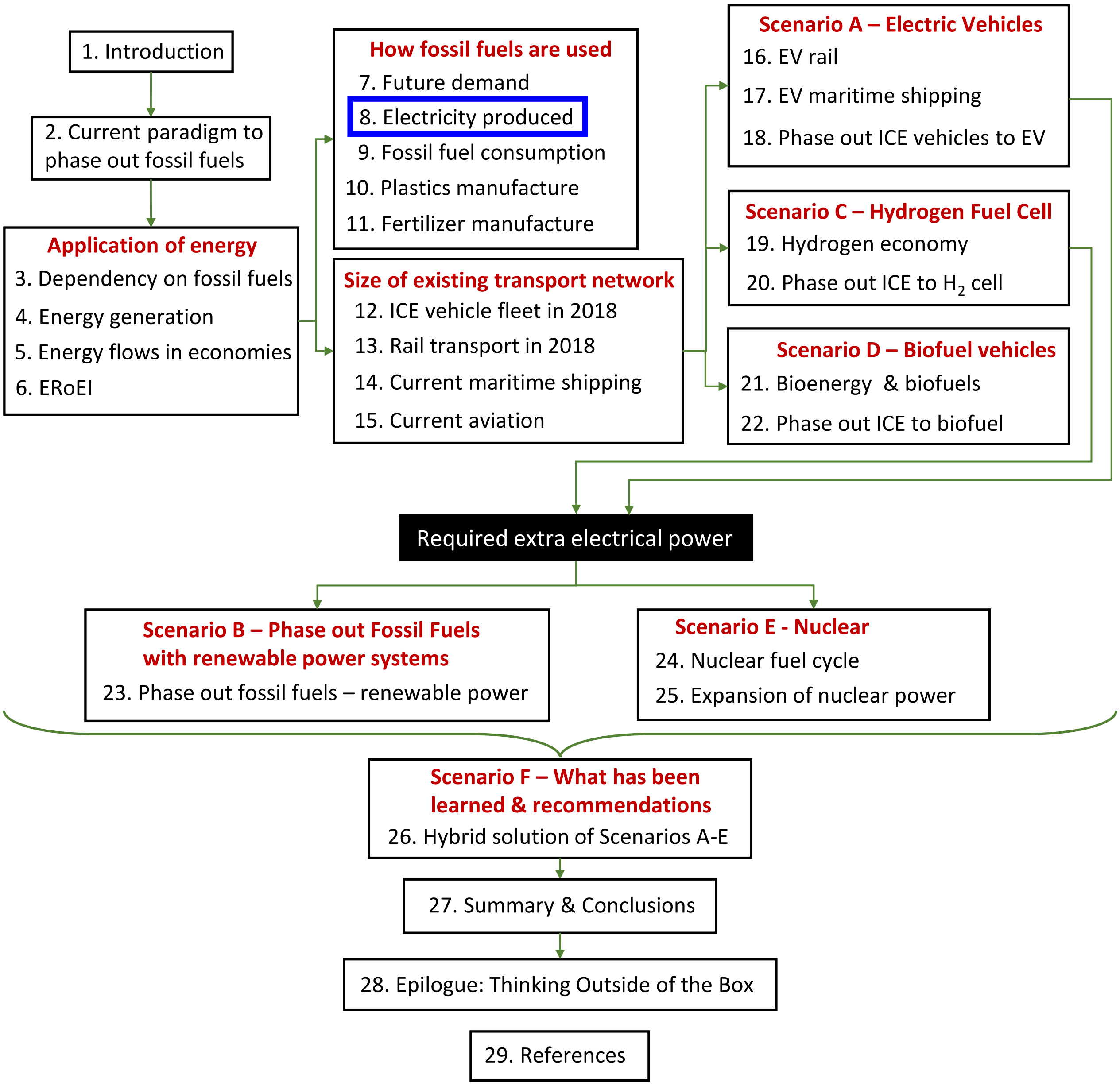
There have been a number of strategies proposed to meet this incoming challenge. The Circular Economy (European Commission 2018b) in Europe. In China there have been several resource security strategies, with the latest being Made in China 2025 (Lee & Reimer 2018, Lee 2019, Malkin 2018, Wübbeke *et al* 2016). Also, in China is the China Belt and Road Initiative (Economist 2019 and CCP Belt and Road Portal). Another proposal of note is the Steady State Economy, proposed by Herman Daly in 1973 (Daly 1973).

Most of these proposed strategies are developed in context of the long term interests of the nation state that developed them. Another possible strategy has been proposed is the Resource Balanced Economy (Michaux 2021). This challenge has the capacity to require the restructure the global industrial ecosystem to a new set of limitations. This in turn will require a different business model that underpins that ecosystem.

All of these different proposals should now be examined seriously to meet the challenge presented by future energy demand shown in Figures 7.9 and 7.10.

8 ELECTRICITY POWER PRODUCED

Electrical power underpins the whole industrial ecosystem, with the current exception of petroleum fueled ICE vehicles, gas heating and industrial refining. All of these will be phased out and replaced with electric alternatives. The purpose of Section 8 is to assemble data on how electrical power is generated now both in the global industrial ecosystem, and in invidual nation states. Performance metrics of different power generations stations are collected.



Assessment of the Extra Capacity Required of Alternative Energy Electrical Power Systems to Completely Replace Fossil Fuels

In 1831, scientist Michael Faraday discovered that when a magnet is moved inside a coil of wire, electric current flows through that wire. Though there are many sources of energy, almost all the equipment's in use today, need those energy sources to be converted to electrical energy before use. Electricity allows modern appliances and more convenience in our life. The current lifestyle in the modern developed economy is totally dependent on electricity so much so that most occupations for people are defined by electric technology. Society uses electricity for lighting, heating, cooling, and refrigeration and for operating appliances, computers, electronics, machinery, and public transportation systems.

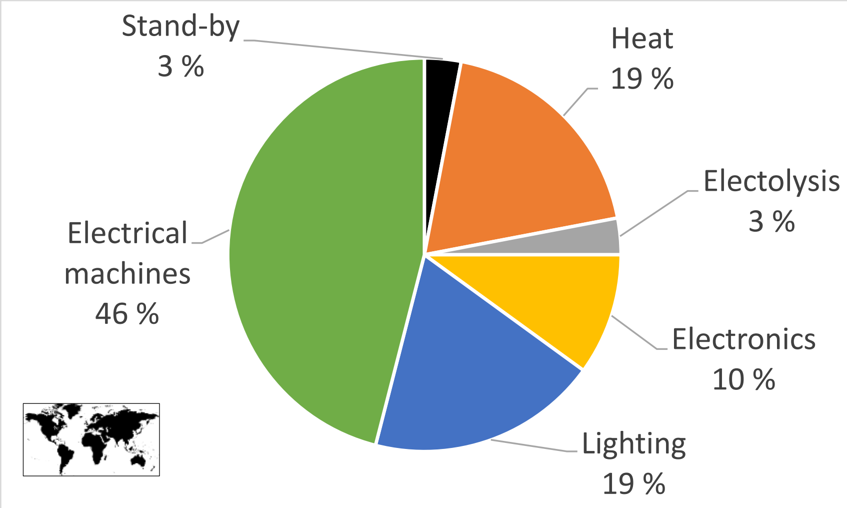


Figure 8.1. Global electricity demand by sector and end use (Source: Lei et al 2017)
(World Map Image by Clker-Free-Vector-Images from Pixabay)

Electric power is the rate, per unit time, at which electrical energy is transferred by an electric circuit. The SI unit of power is the watt, one joule per second. Electric power is usually supplied to businesses and homes (as domestic mains electricity) by the electric power industry through an electric power grid. Electric energy is usually sold by the kilowatt hour (1 kW·h = 3.6 MJ) which is the product of the power in kilowatts multiplied by running time in hours. Electric utilities measure power using an electricity meter, which keeps a running total of the electric energy delivered to a customer. Electrical power provides a low entropy form of energy and can be carried long distances and converted into other forms of energy such as motion, light, or heat with high energy efficiency.

Electricity has to be transmitted from large power plants to the consumers via extensive networks. The transmission over long distances creates power losses. The major part of the energy losses comes from Joule effect in transformers and power lines. The energy is lost as heat in the conductors.

An electricity generator is a device that converts a form of energy into electricity. Generators operate because of the relationship between magnetism and electricity. Generators that convert kinetic (mechanical) energy into electrical energy produce nearly all of the electricity that consumers use.

Currently, the energy mix that services the global industrial ecosystem (and all regional and national economies) is a group of different primary energy sources (oil, gas, coal, nuclear, etc.) from which secondary energy for direct use - such as electricity - is produced. Energy mix refers to all direct uses of energy, such as transportation and housing, so it is not be confused with power generation mix, which refers only to generation of electricity. Section 8 will focus on electricity generation. Section 9 will focus on how fossil fuels are consumed for what application.

Table 8.1. Global electricity generation by source and region
(Source: Appendix B, BP Statistical Review of World Energy 2019)

Geographic Region In 2018	Electricity Generated (Terawatt hours)	Oil (TWh)	Gas (TWh)	Coal (TWh)	Nuclear energy (TWh)	Hydroelectric (TWh)	Renewables (TWh)	Other (TWh)
Global	26 614,9	802,7	6 182,8	10 100,5	2 701,5	4 193,1	2 480,4	153,9
Total North America	5 447,3	66,3	1 833,9	1 334,3	963,2	708,4	525,2	16,0
Total Central & South America	1 305,2	90,2	227,9	76,5	22,5	731,3	156,3	0,5
Total Europe	4 077,3	56,0	731,3	862,7	937,5	642,1	761,1	86,6
Commonwealth of Independant States	1 417,4	13,7	686,1	259,0	206,6	244,8	2,5	4,7
Middle East	1 240,4	310,9	878,5	21,3	7,0	15,2	7,4	0,1
Total Africa	853,7	77,6	339,3	255,9	11,1	132,8	31,9	5,1
Total Asia Pacific	12 273,6	188,0	1 485,8	7 290,8	553,6	1 718,5	996,0	40,9
Nations								
United States	4 460,8	26,4	1 578,5	1 245,8	849,6	288,7	458,5	13,3
China	7 111,7	10,7	223,6	4 732,4	294,4	1 202,4	634,2	14,0
European Union	3 282,2	52,5	619,7	655,2	827,4	344,8	705,5	77,1
Russian Federation	1 110,8	11,4	521,5	177,5	204,5	190,2	1,3	4,4

8.1 Electricity Generation with Fossil fuels

Figures 8.2 to 8.9 show the global electricity generation by region and by fuel.

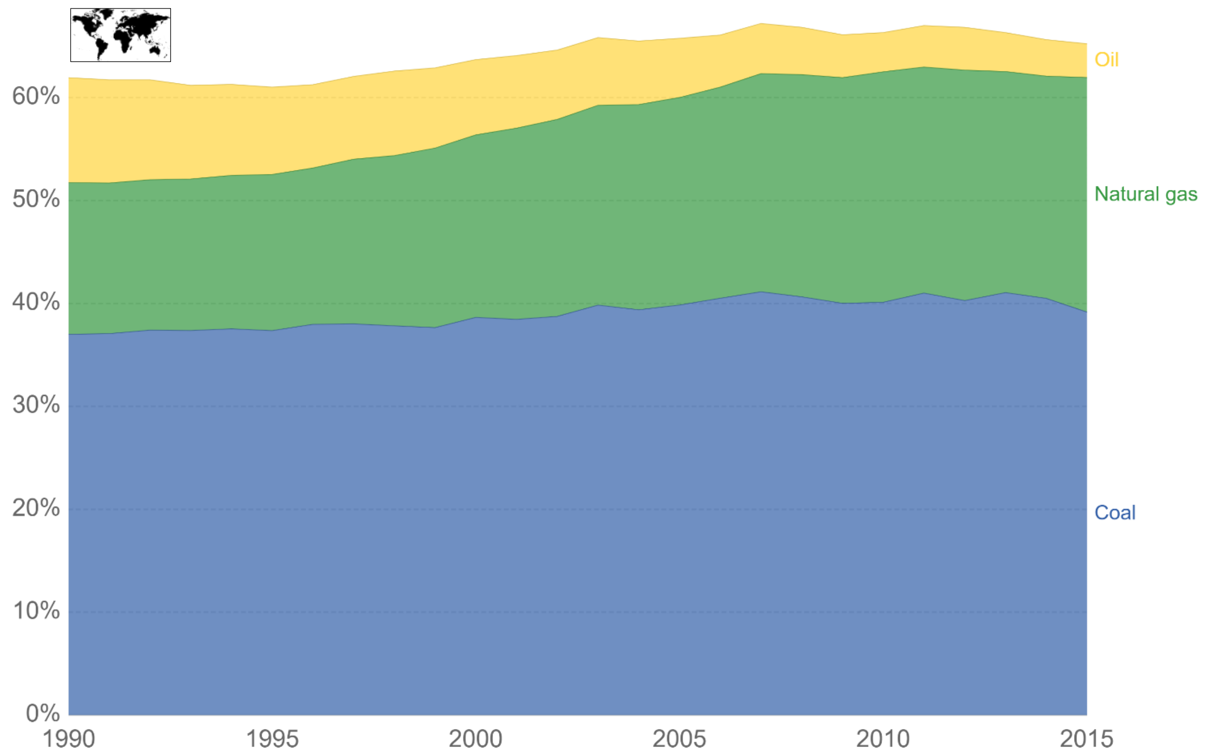


Figure 8.2. Global share of electricity production from fossil fuels
(Source: Our World in Data, International Energy Agency (IEA) via The World Bank)
(World Map Image by Clker-Free-Vector-Images from Pixabay)
(Copyright License: https://www.iea.org/media/copyright/Termsandconditions_2019update_FINAL.docx.pdf)

8.2 Electricity sourced using nuclear power generation

Figure 8.2 shows that global electricity production is still dominated by fossil fuels accounting for approximately 65%, where a large portion of what is left accounted for by nuclear power. Europe leads the world in context of proportion of electric power generation coming from renewable sources.

Nuclear technology uses the energy released by splitting the atoms of certain elements. It was first developed in the 1940s, and during the Second World War to 1945 research initially focused on producing bombs which released great energy by splitting the atoms of particular isotopes of either uranium or plutonium. In the 1950s attention turned to the peaceful purposes of nuclear fission, controlling it for power generation. Currently, the world produces as much electricity from nuclear energy as it did from all sources combined in the early years of nuclear power.

Nuclear Power Generation is the use of nuclear reactions that release nuclear energy to generate heat, which most frequently is then used in steam turbines to produce electricity in a nuclear power plant. The term includes nuclear fission, nuclear decay, and nuclear fusion. Presently, the nuclear fission of elements in the actinide series of the periodic table produce the vast majority of nuclear energy in the direct service electricity generation, with nuclear decay processes, primarily in the form of geothermal energy, and radioisotope thermoelectric generators, in niche applications making up the rest of industrial uses.

The civil nuclear power station fleet can now reference 17,000 reactor years of experience and supplies 11.5% of global electricity needs, from reactors in 31 countries through regional transmission grids. Many countries have also built research reactors to provide a source of neutron beams for scientific research and the production of medical and industrial isotopes. Figure 8.3 shows the global consumption of nuclear power generation.

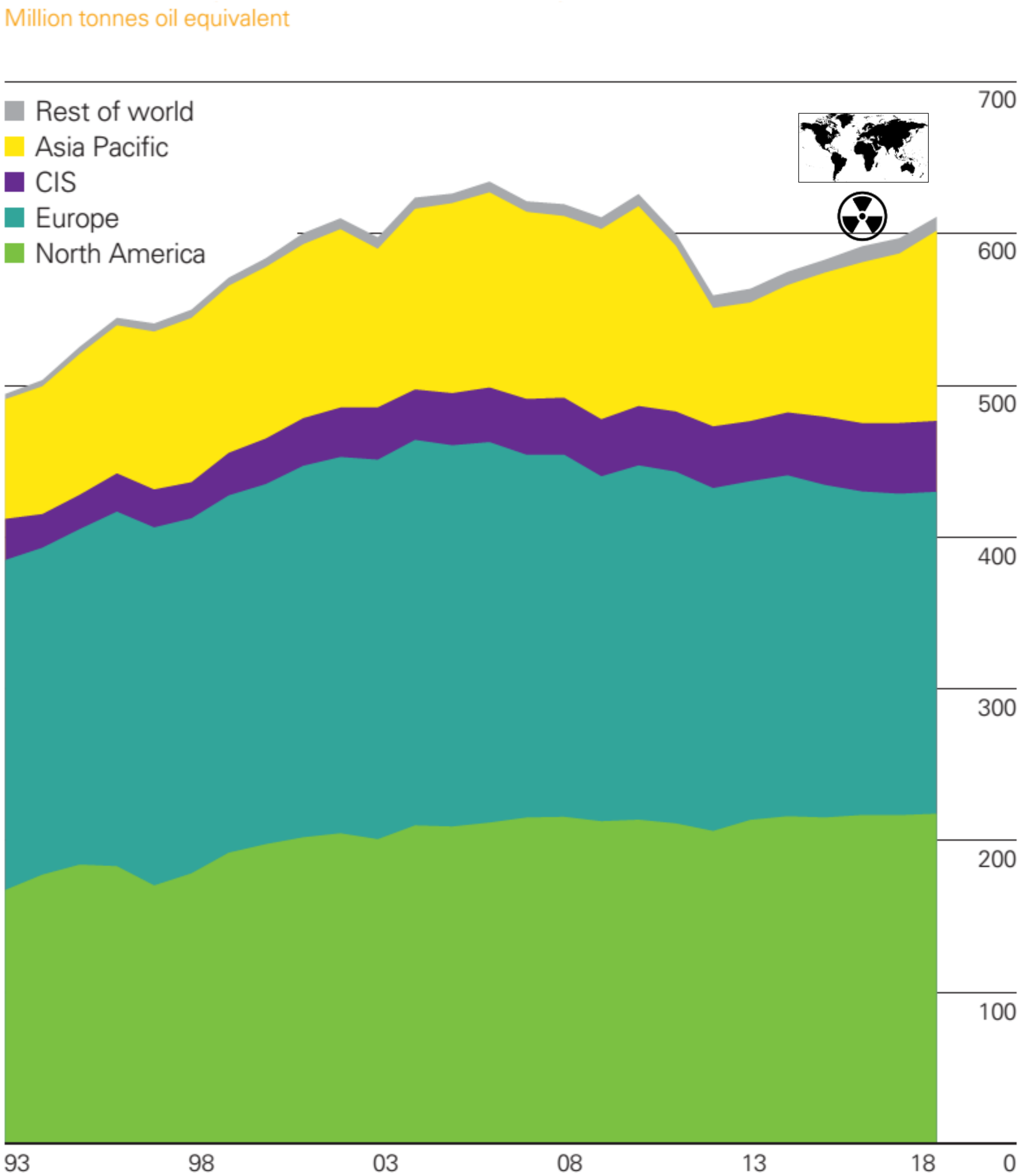


Figure 8.3. Global nuclear energy consumption by region
(Source: BP Statistical review of World Energy 2019) (World Map Image by Clker-Free-Vector-Images from Pixabay)

Figures 8.4 to 8.6 show the proportion of electricity generated with nuclear power for the major global economies, European Union economies and the Nordic country or Fennoscandic economies. Nuclear power is currently the only power source that has been engineered in a fashion to supply large quantities of power as an alternative to fossil fuels. All alternative energy sources at this time have not been able to be scaled up to be comparable.

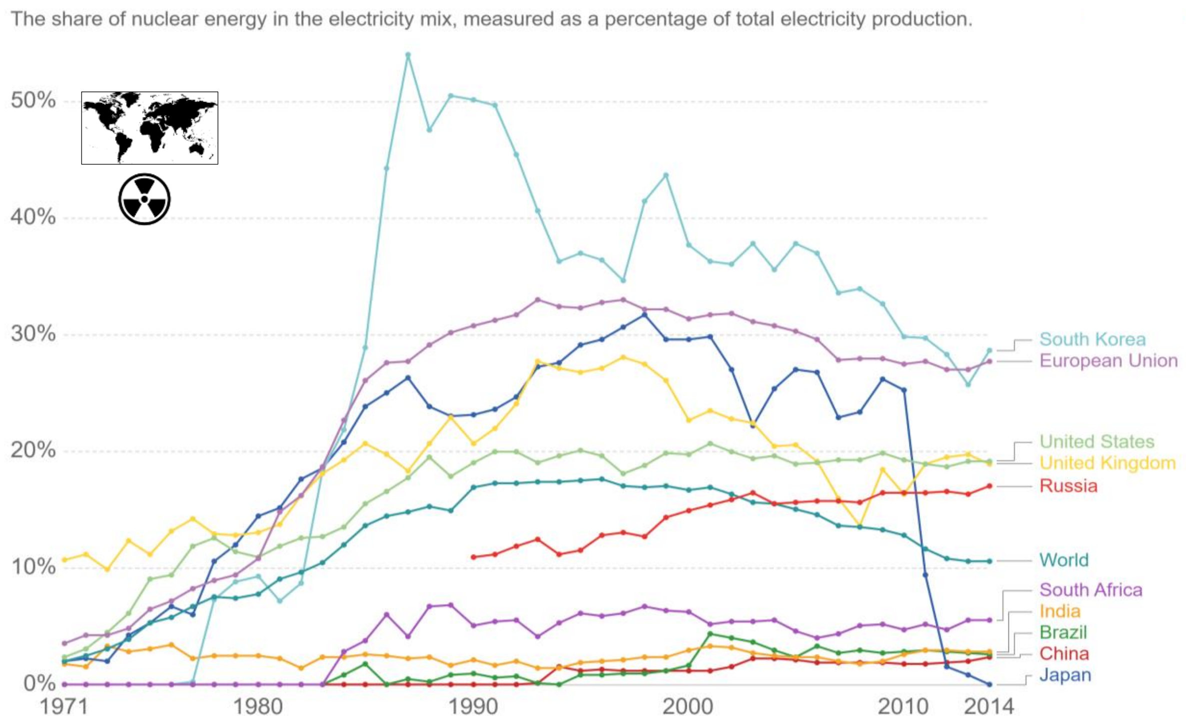


Figure 8.4. Nuclear energy as a share of electricity production in the major world economies
(Source: Our World In Data, IEA, World Bank) (World Map Image by Clker-Free-Vector-Images from Pixabay)
(http://data.worldbank.org/data-catalog/world-development-indicators)

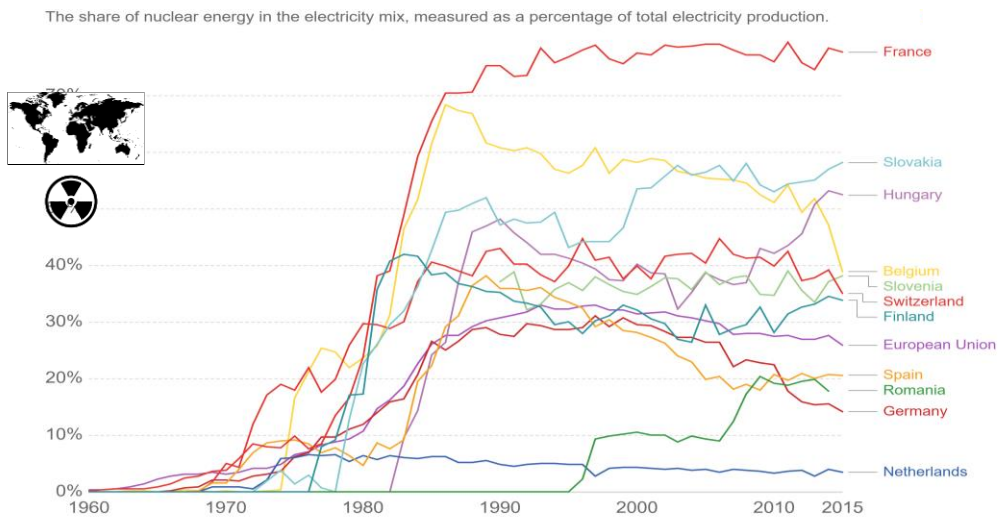


Figure 8.5. Nuclear energy as a share of electricity production in European Union EU-28
(Source: Our World In Data, IEA, World Bank) (World Map Image by Clker-Free-Vector-Images from Pixabay)

(http://data.worldbank.org/data-catalog/world-development-indicators)

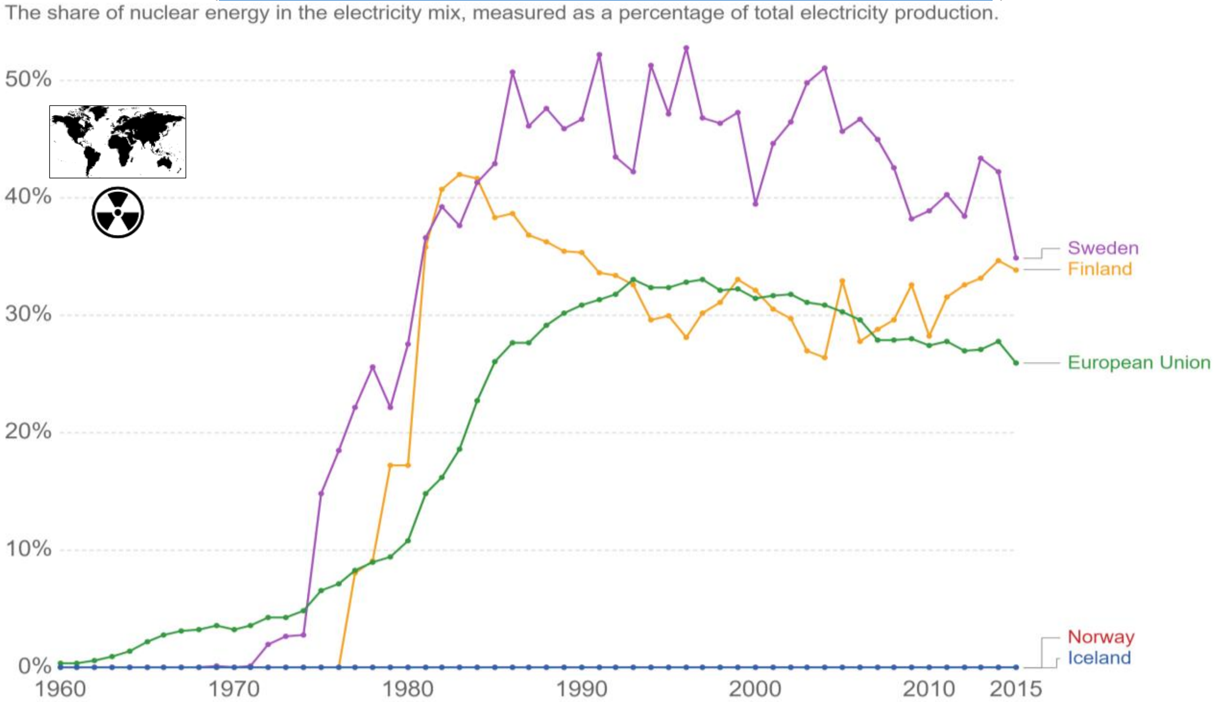
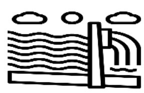


Figure 8.6. Nuclear energy as a share of electricity production in Nordic countries
(Source: Our World In Data, IEA, World Bank) (World Map Image by Clker-Free-Vector-Images from Pixabay)
(http://data.worldbank.org/data-catalog/world-development-indicators)

The relevance of this section is that if fossil fuels are to be phased out, then alternative energy systems would be required to supply and expand the existing electrical power generation grid.

8.3 Electricity sourced using wind, hydro and solar power generation

Renewable energy is energy that comes from sources that replenish themselves over short periods of time. For the most part, renewable energy sources also provide clean energy, or energy that emits few greenhouse gases or pollutants. For this reason, many policy experts and scientists advocate renewable energy sources over traditional fossil fuels. The difficulty is achieving the technology, and infrastructure to make this transition.


Hydroelectric energy is by far the most prevalent, accounting for 83% of the world's electricity generation from renewable sources. This is most likely because the requisite technology to generate electricity by harnessing the flow of water has been around the longest, dating back to the early 20th century. Wind energy is the next largest, at just over 7% of the electricity generated from renewable sources, followed by biowaste and biomass energy (7%), geothermal energy (2%), and solar, tidal, and wave energy (less than 1%).

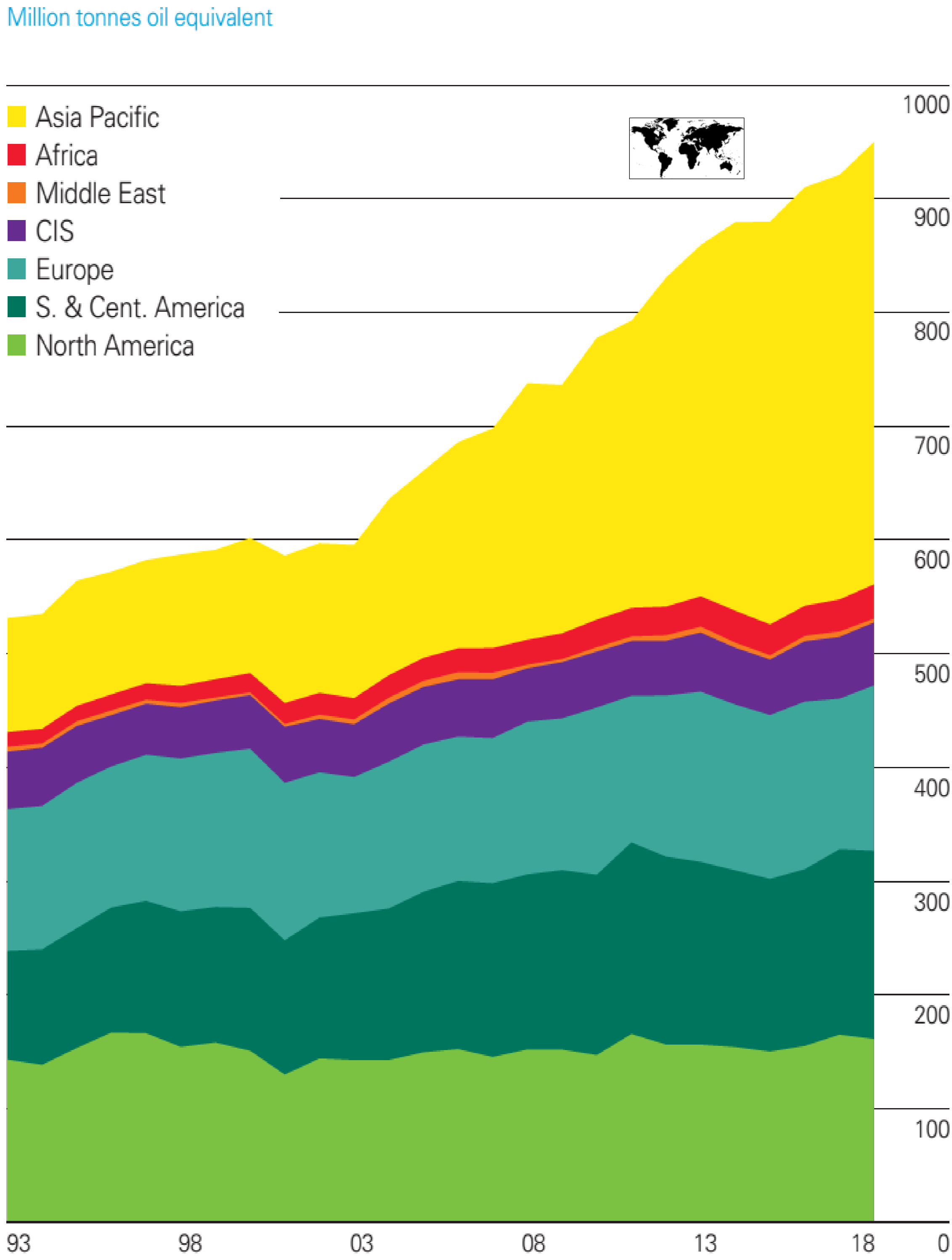


Figure 8.7. Global hydroelectric consumption by region
(Source: BP Statistical review of World Energy 2019) (World Map Image by Clker-Free-Vector-Images from Pixabay)

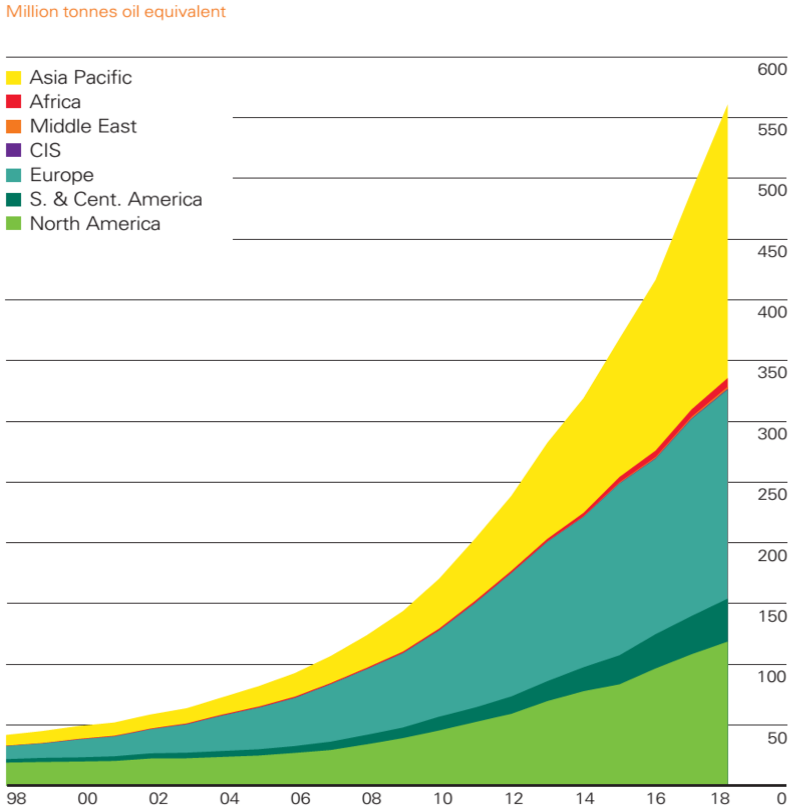


Figure 8.8. Global renewable energy consumption by region (mtoe)
(Source: BP Statistical review of World Energy 2019)

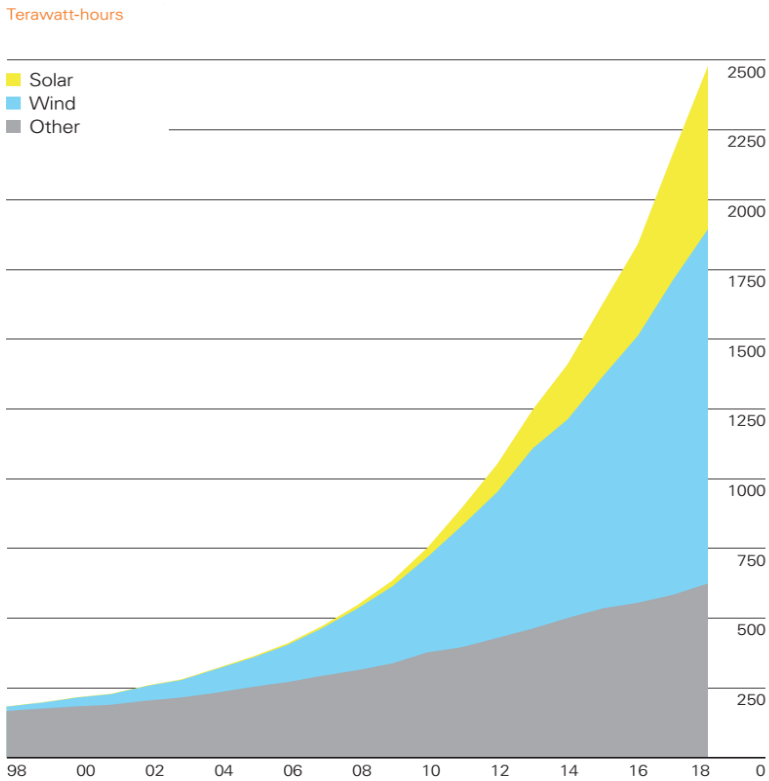


Figure 8.9. Global renewable energy generation by source (TWh)
(Source: BP Statistical review of World Energy 2019)

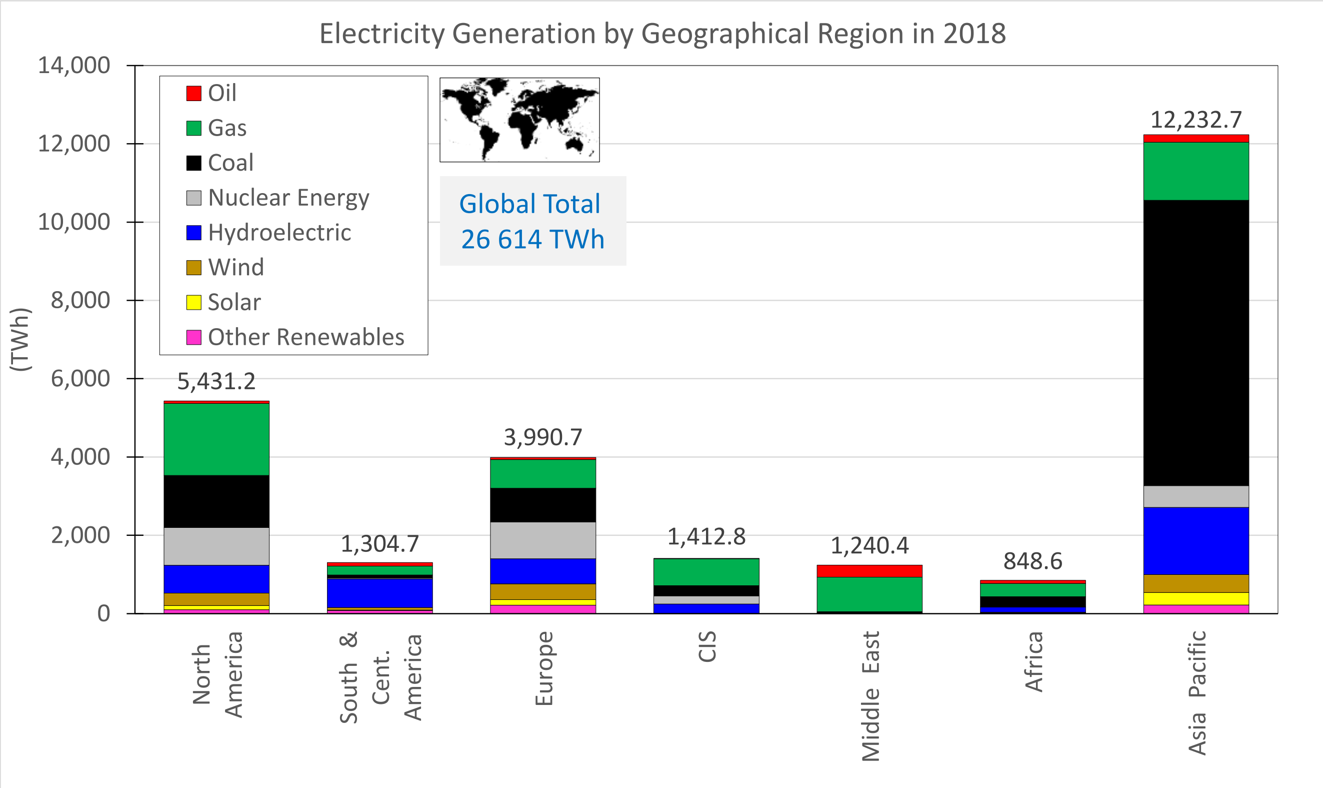


Figure 8.10. Electricity generation by geographical region (Source Data: BP Statistical Review of World Energy 2019) (World Map Image by Clker-Free-Vector-Images from Pixabay)

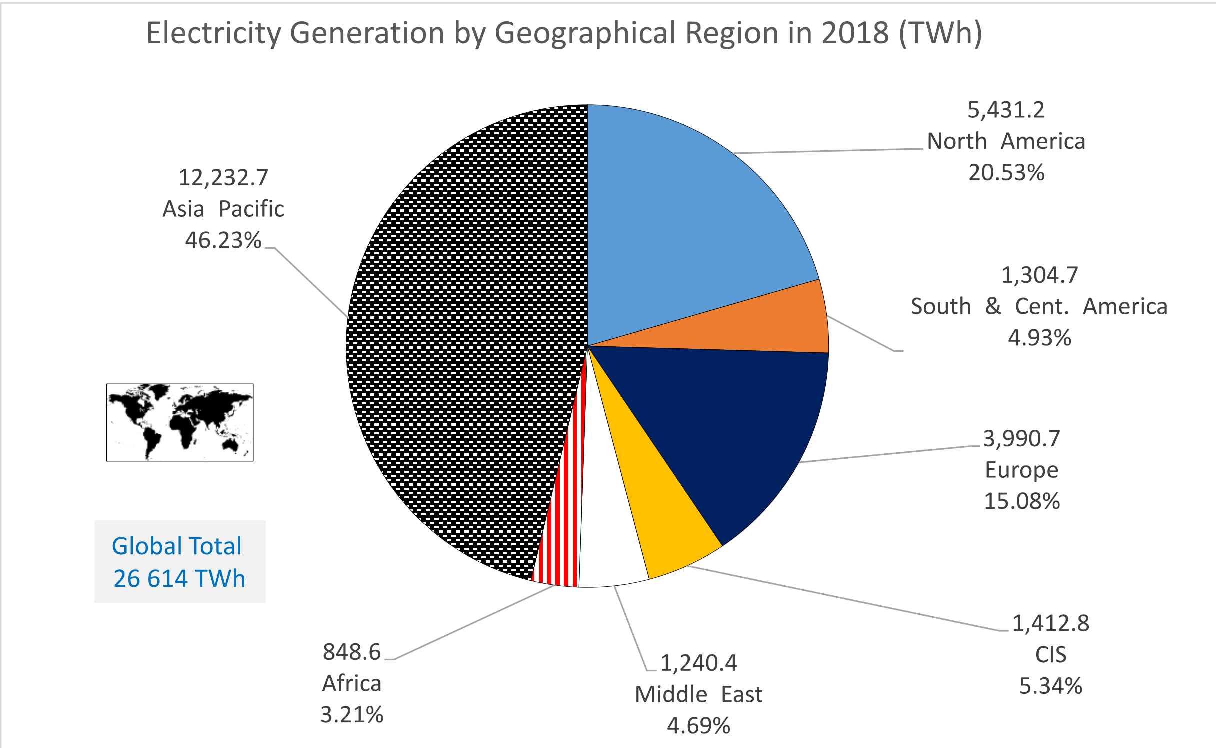


Figure 8.11. Electricity Generation by Geographical Region (Source Data: BP Statistical Review of World Energy 2019) (World Map Image by Clker-Free-Vector-Images from Pixabay)

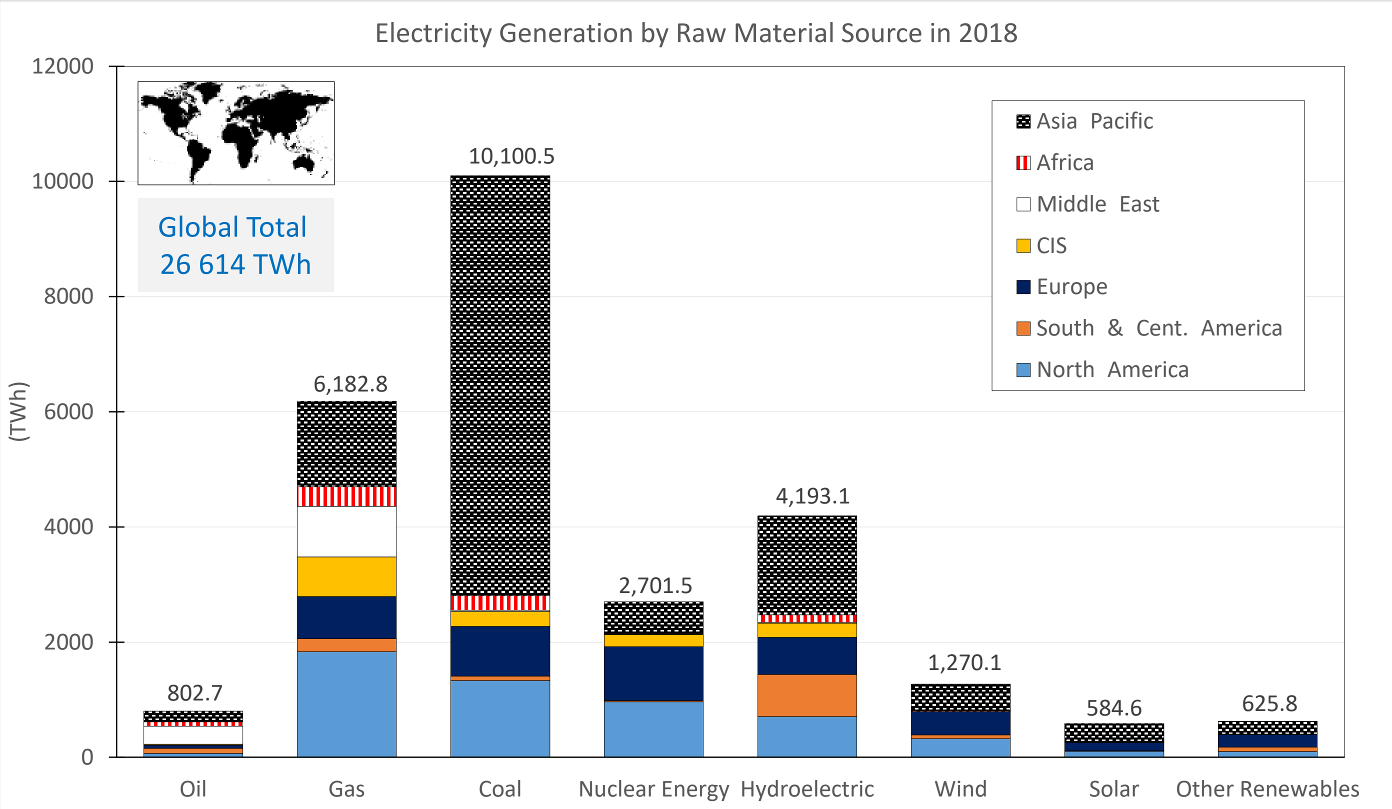


Figure 8.12. Electricity generation by raw material source (Source Data: BP Statistical Review of World Energy 2019) (World Map Image by Clker-Free-Vector-Images from Pixabay)

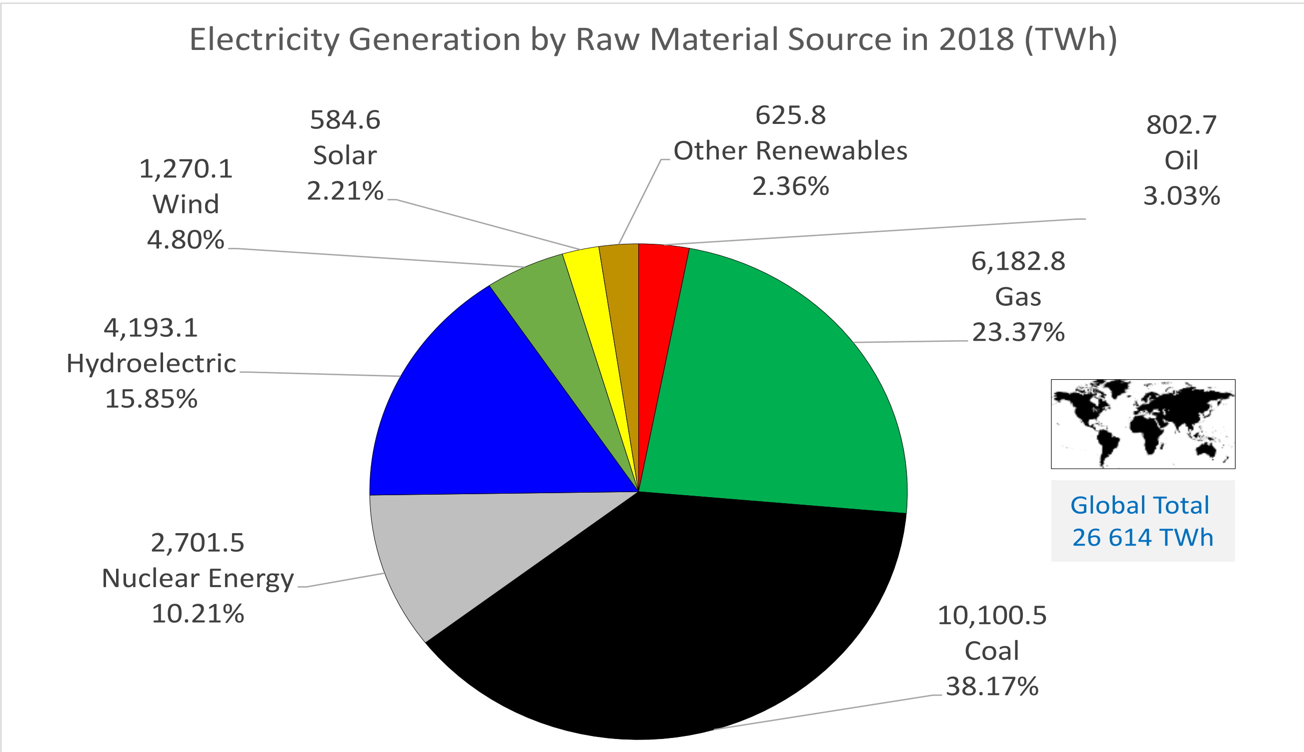


Figure 8.13. Electricity generation by raw material source (Source Data: BP Statistical Review of World Energy 2019) (World Map Image by Clker-Free-Vector-Images from Pixabay)

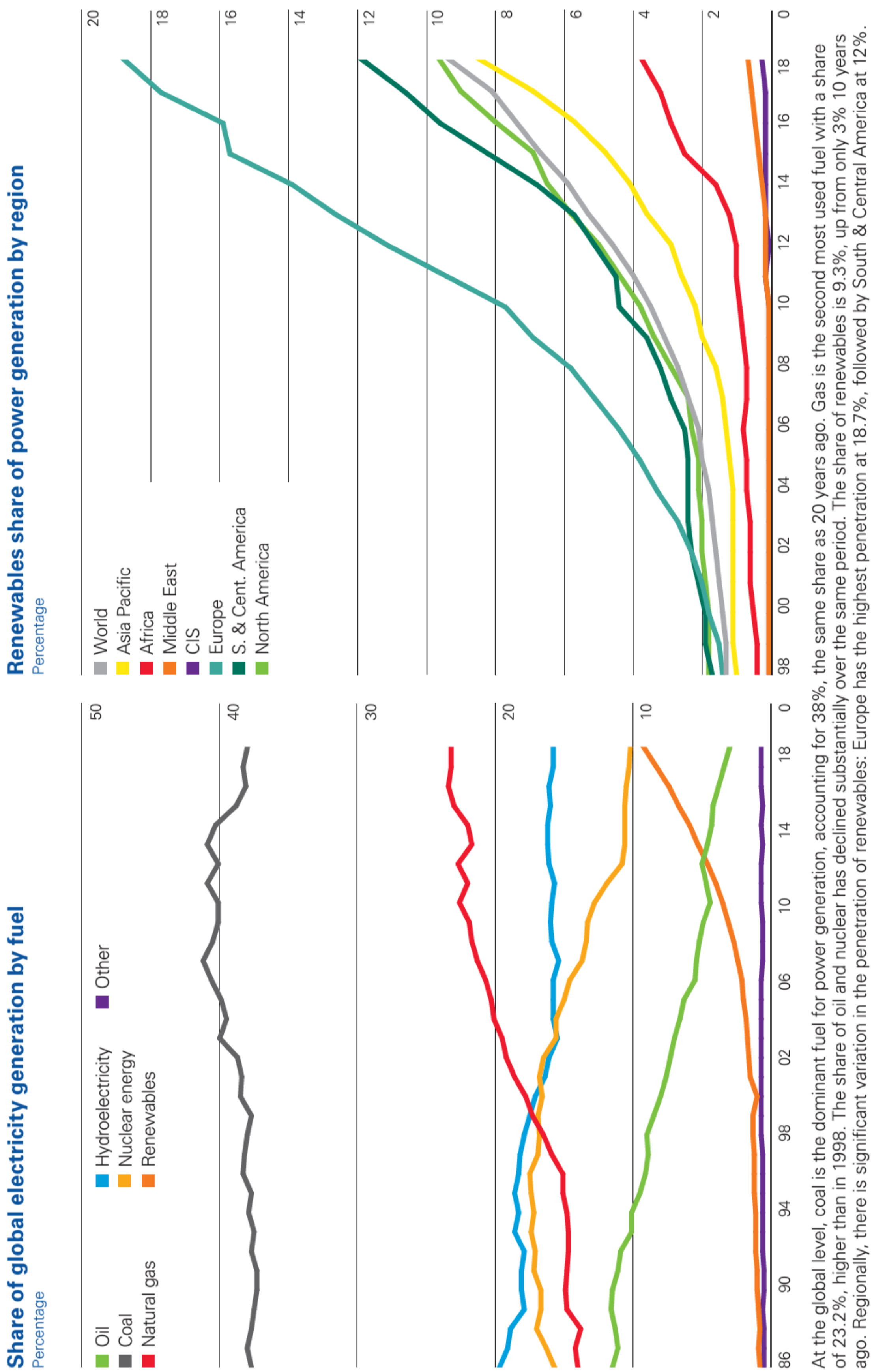


Figure 8.14. Global electricity generation by fuel in 2018
(Source: BP Statistical Review of World Energy 2019)

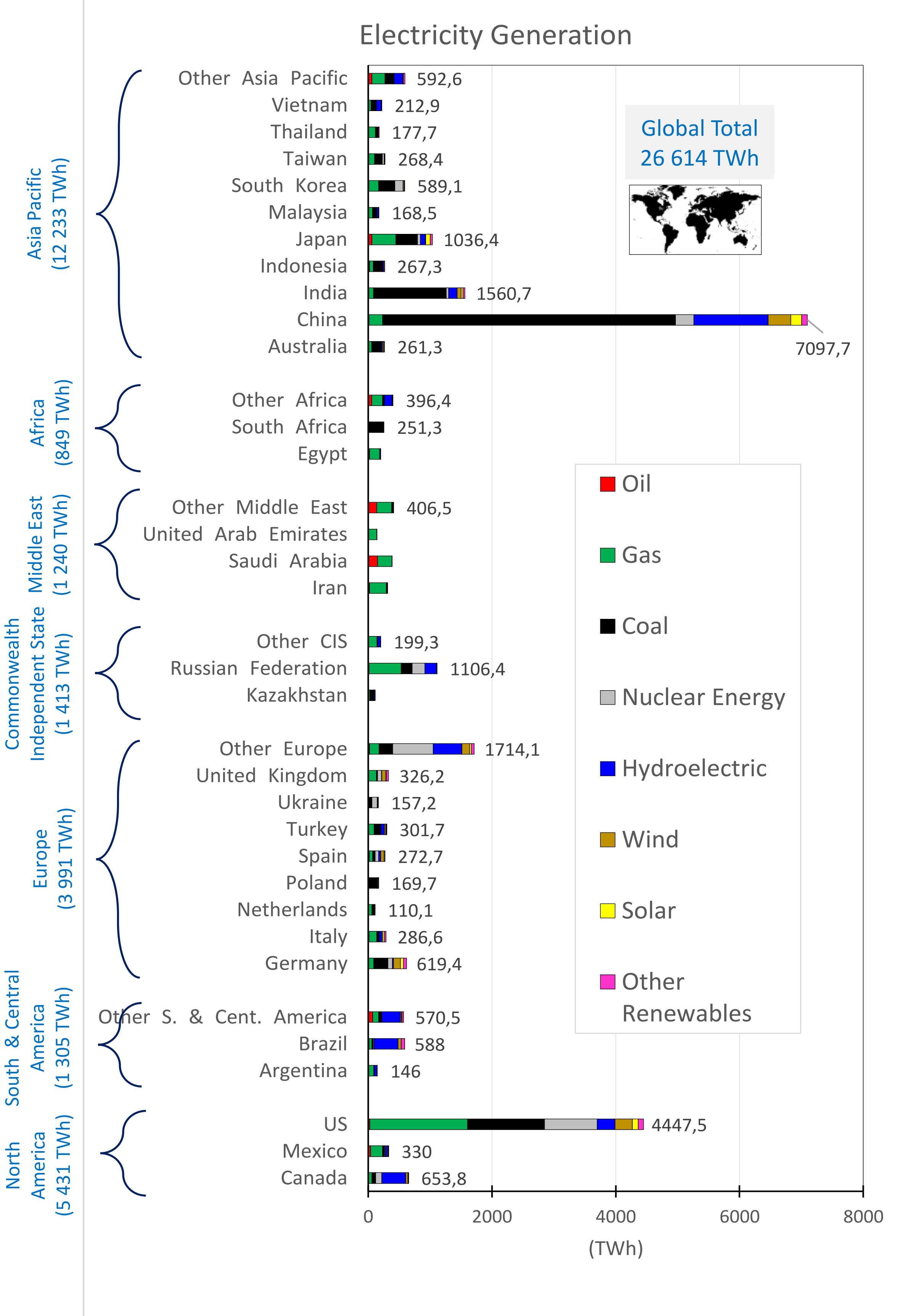


Figure 8.15. Electricity generation by source, country, and region
(Source: data from BP Statistical review of World Energy 2019) (World Map Image by Clker-Free-Vector-Images from Pixabay)

8.4 Electricity Generation by Geographical Region

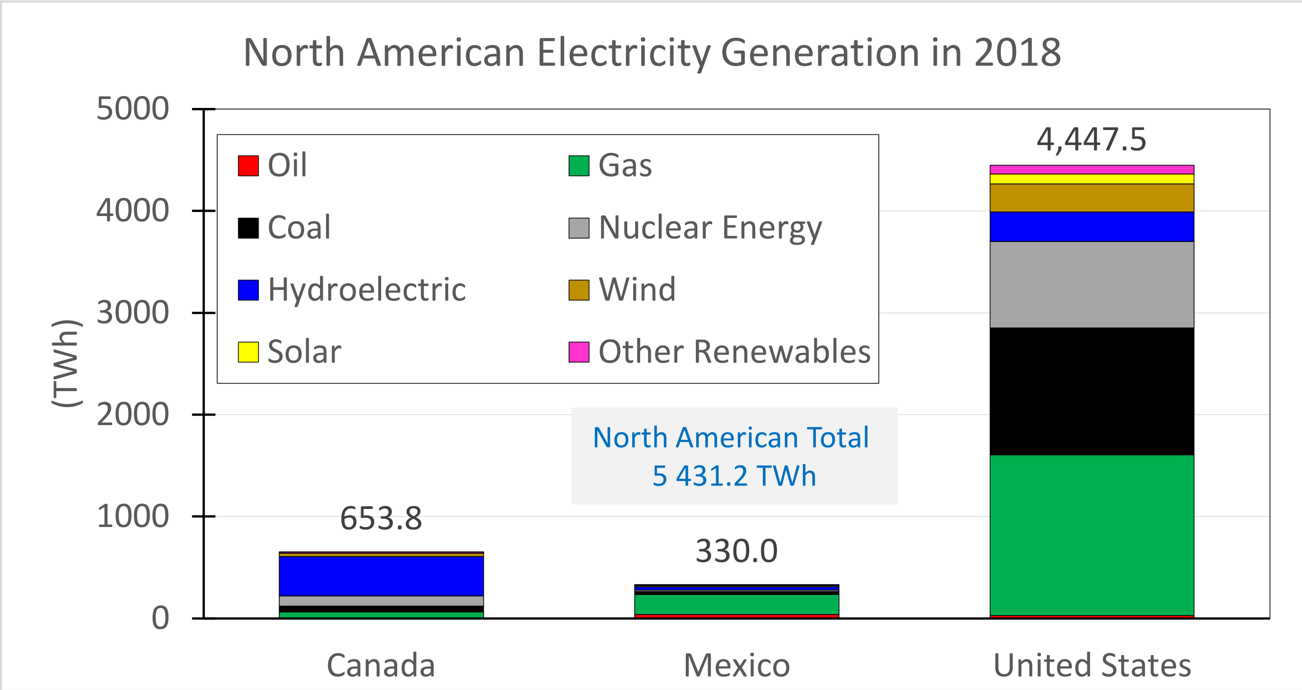


Figure 8.16. North American electricity generation by country and raw material source in 2018
(Source: BP Statistical Review of World Energy 2019)

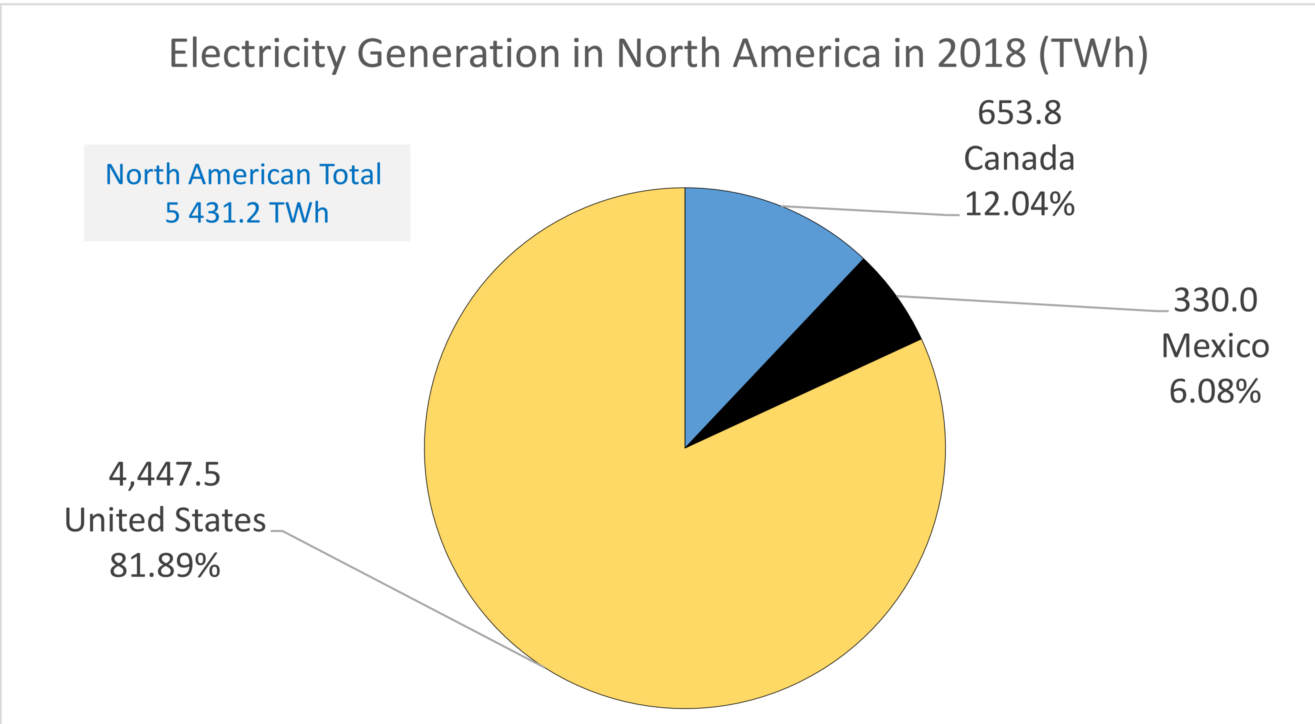


Figure 8.17. North American electricity generation by country in 2018
(Source: BP Statistical Review of World Energy 2019)

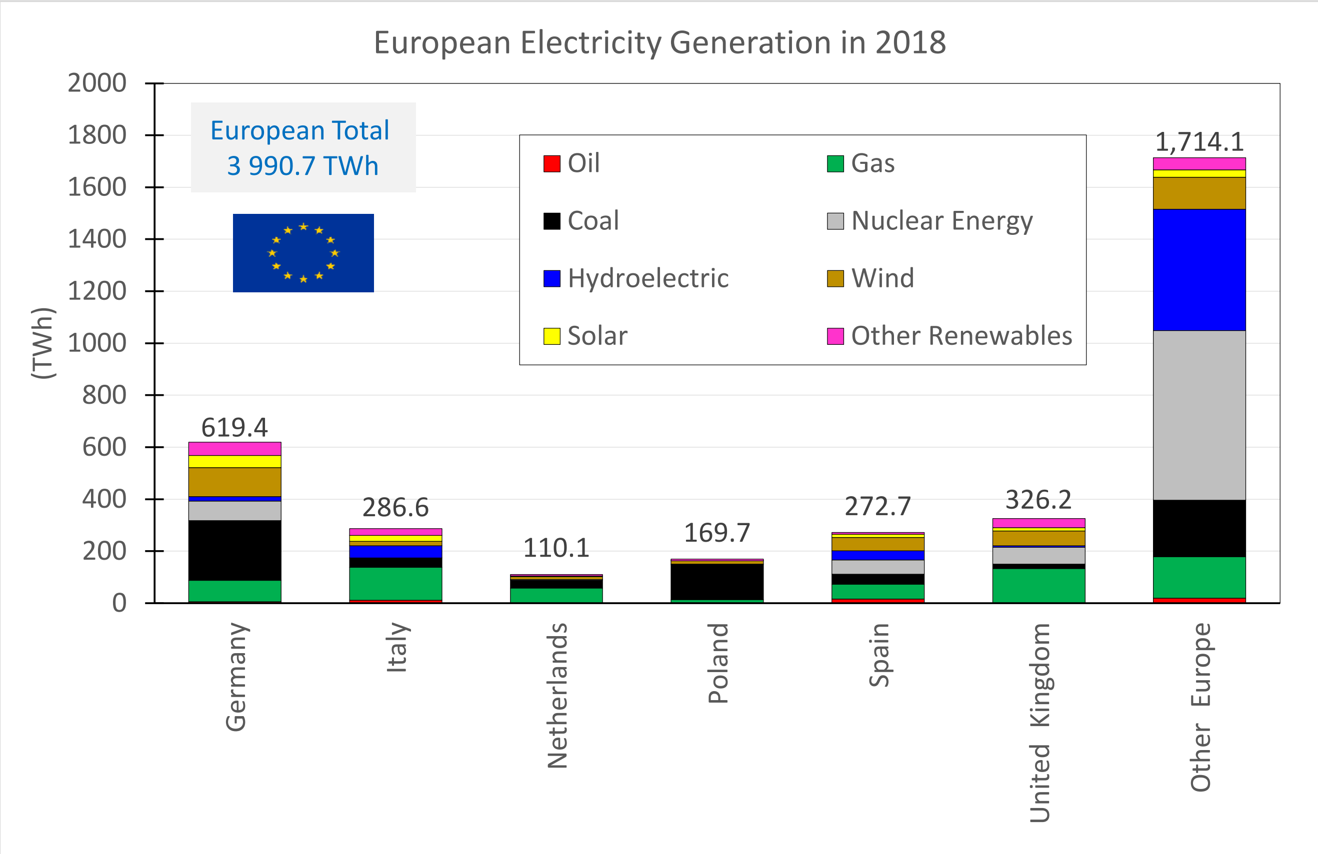


Figure 8.18. European electricity generation by country and raw material source in 2018
(Source: BP Statistical Review of World Energy 2019)

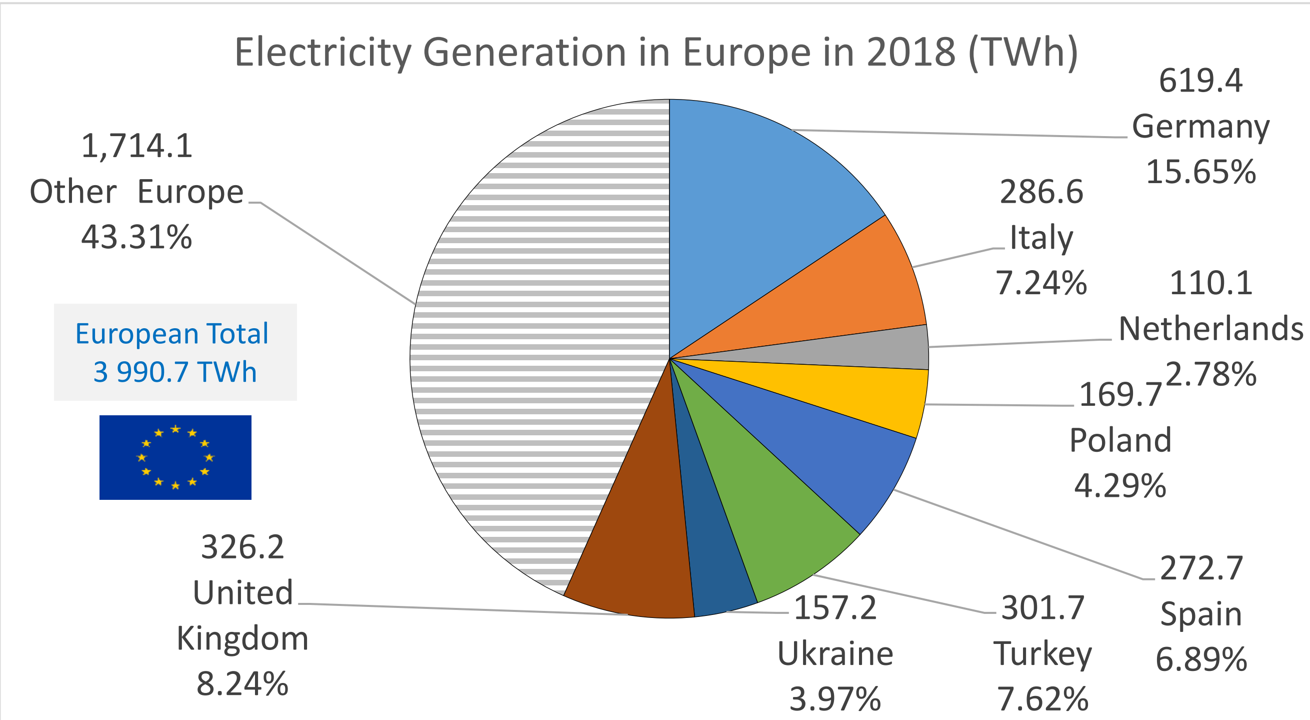


Figure 8.19. European electricity generation by country in 2018
(Source: BP Statistical Review of World Energy 2019)

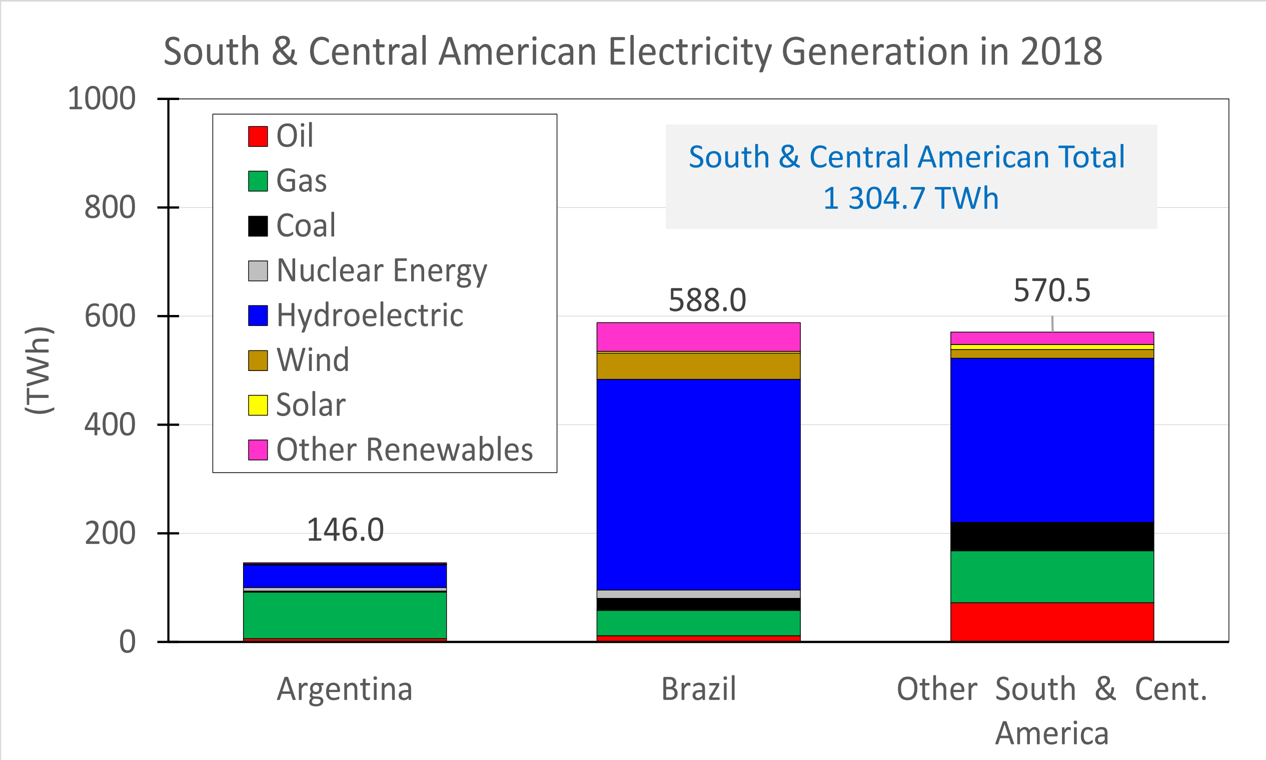


Figure 8.20. South & Central American electricity generation by country and raw material source in 2018 (Source: BP Statistical Review of World Energy 2019)

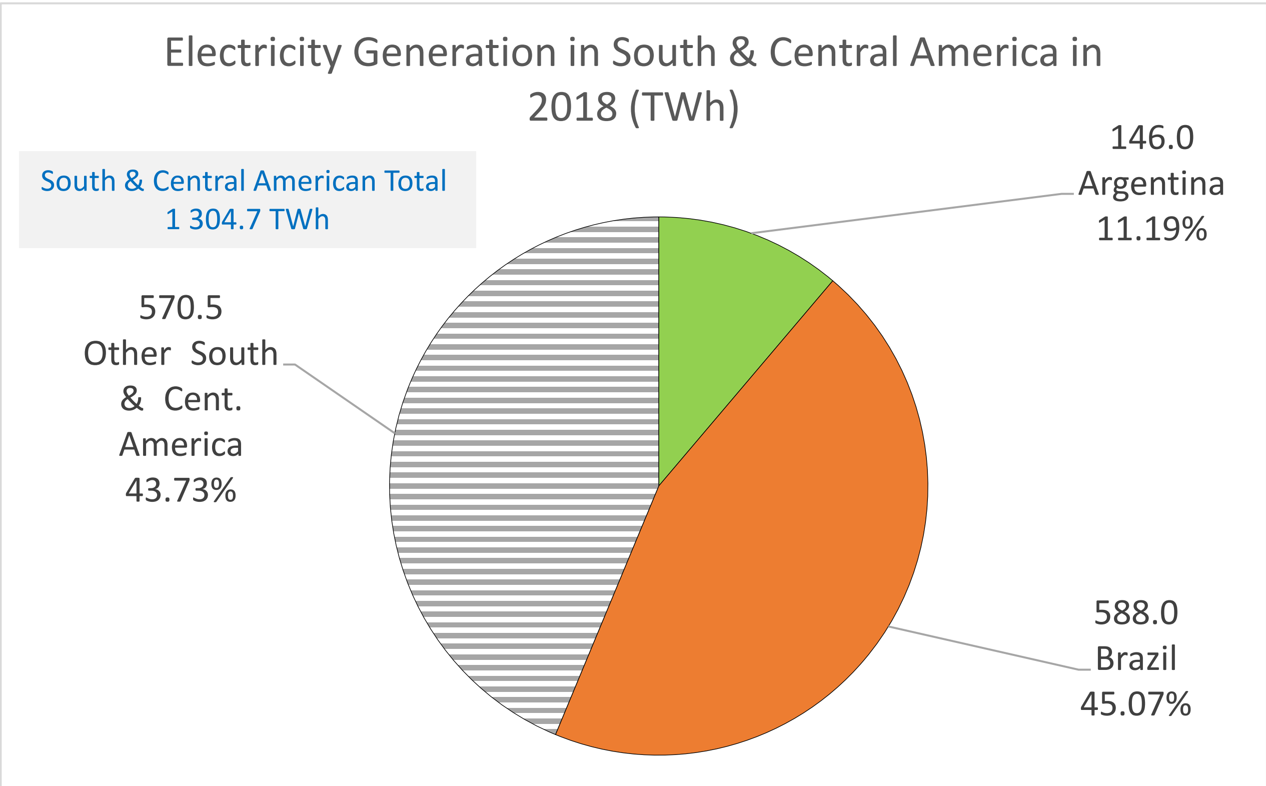


Figure 8.21. South & Central American electricity generation by country in 2018 (Source: BP Statistical Review of World Energy 2019)

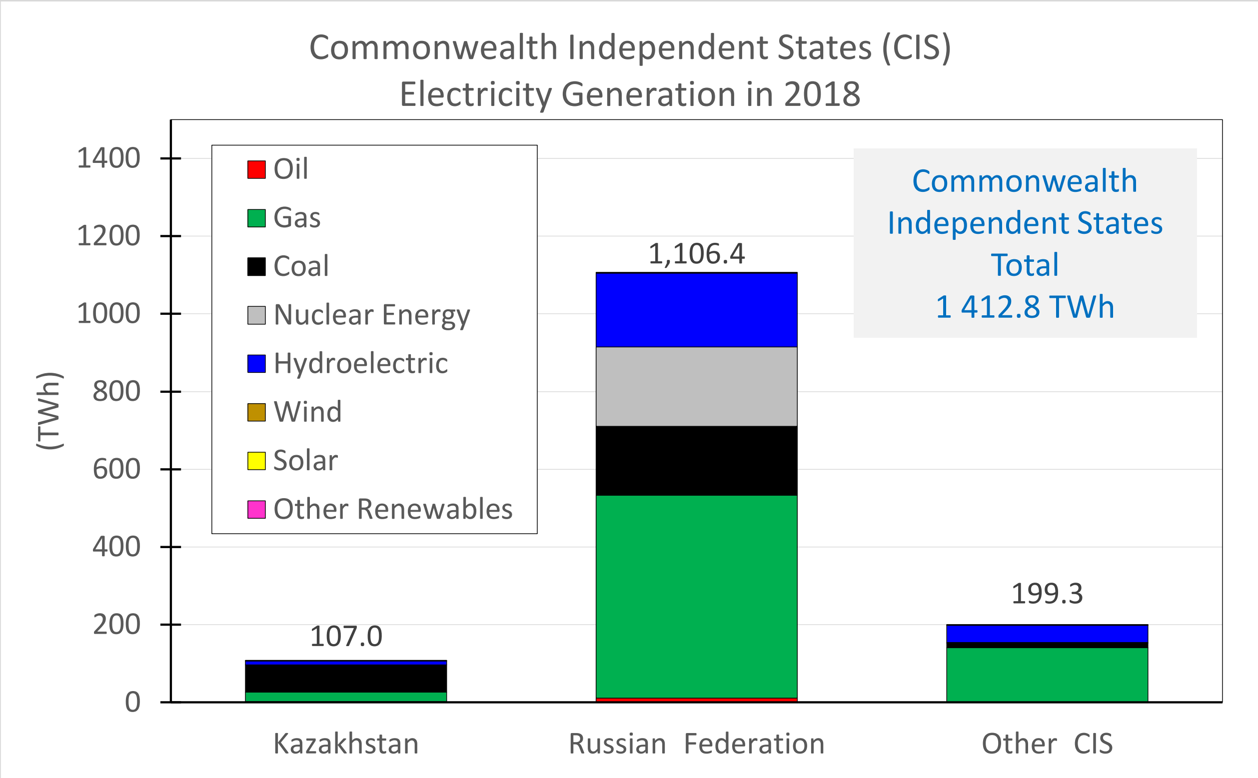


Figure 8.22. Commonwealth Independent States electricity generation by country and raw material source in 2018 (Source: BP Statistical Review of World Energy 2019)

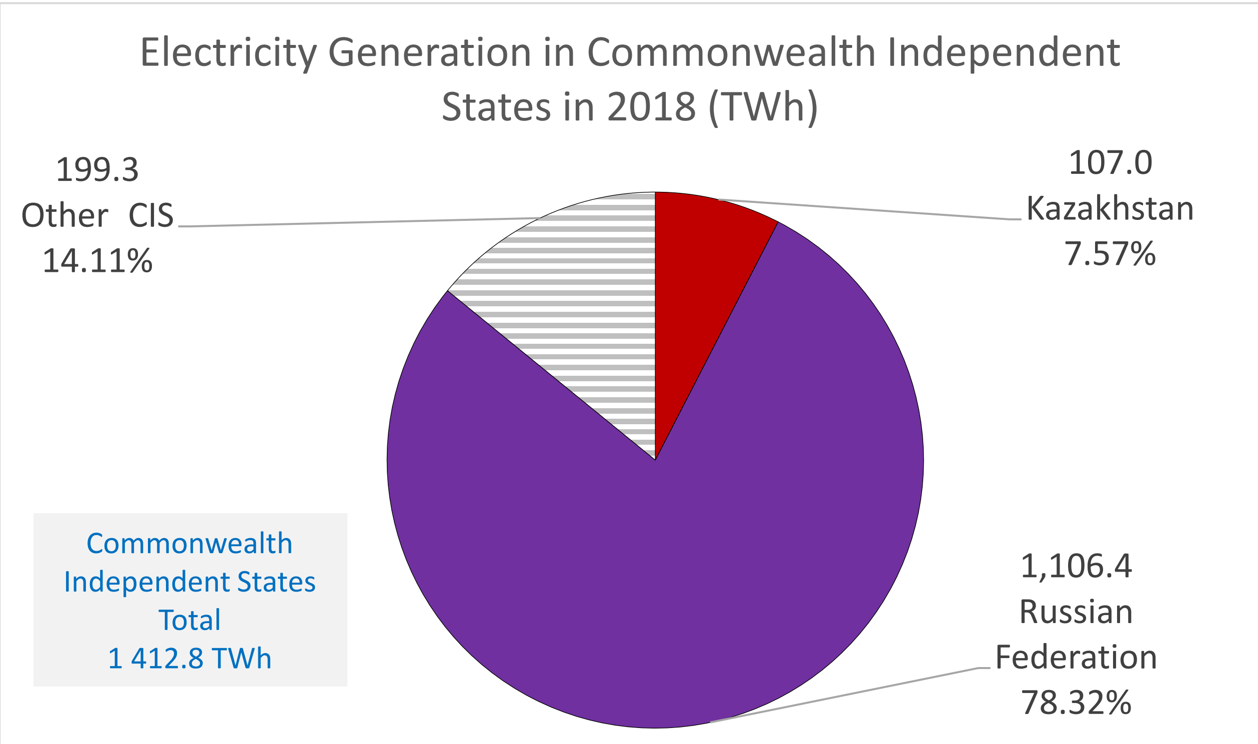


Figure 8.23. Commonwealth Independent States electricity generation by country in 2018 (Source: BP Statistical Review of World Energy 2019)

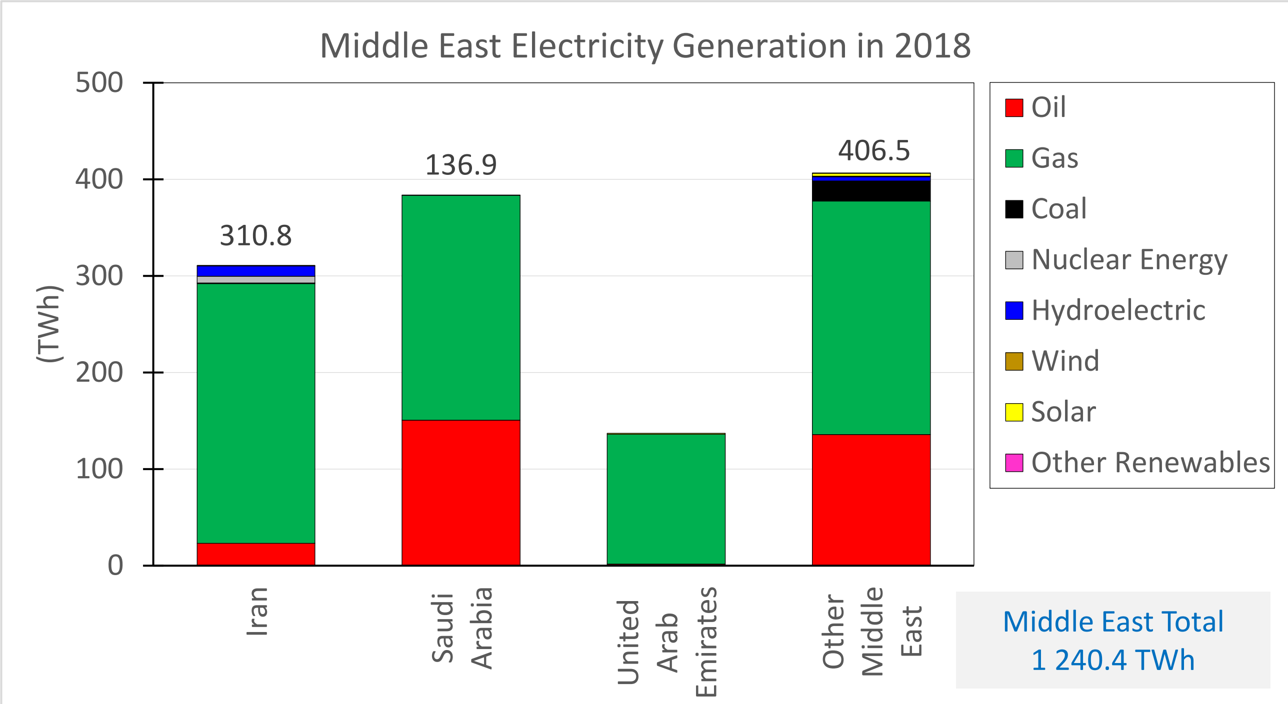


Figure 8.24. Middle East electricity generation by country and raw material source in 2018
(Source: BP Statistical Review of World Energy 2019)

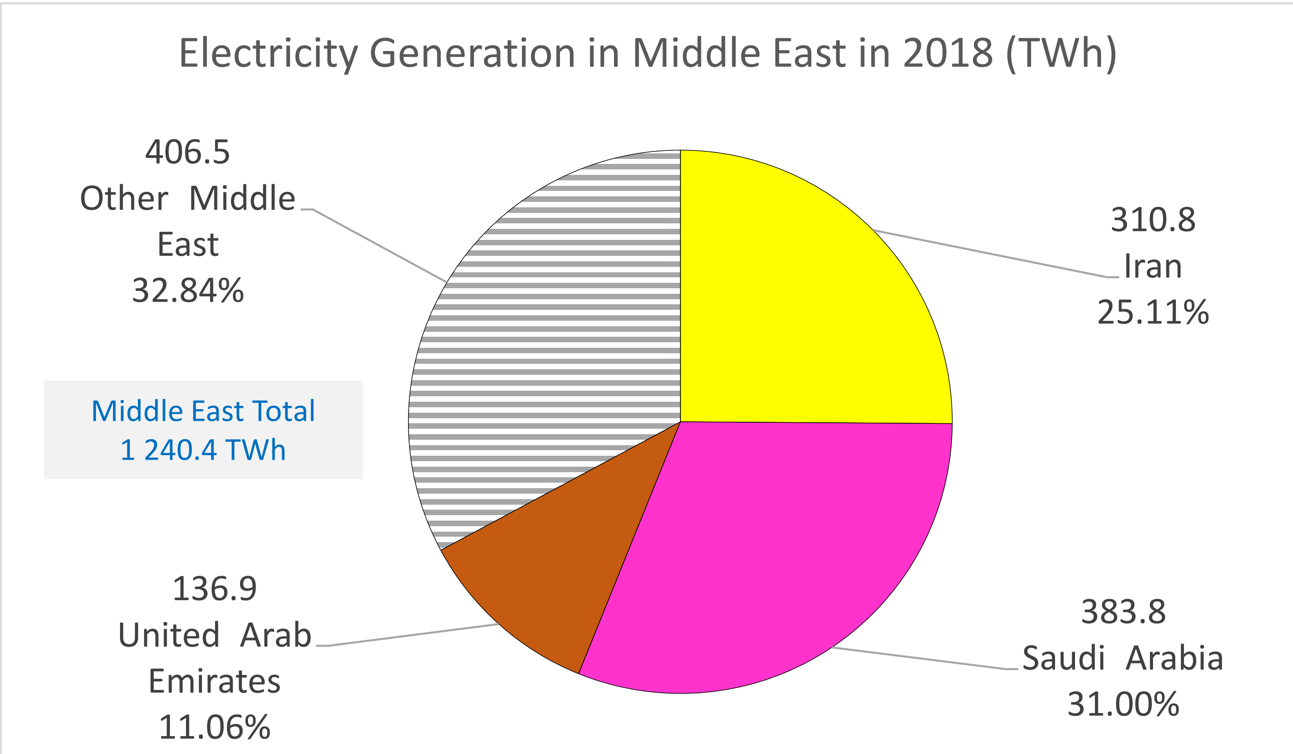


Figure 8.25. Middle East electricity generation by country in 2018
(Source: BP Statistical Review of World Energy 2019)

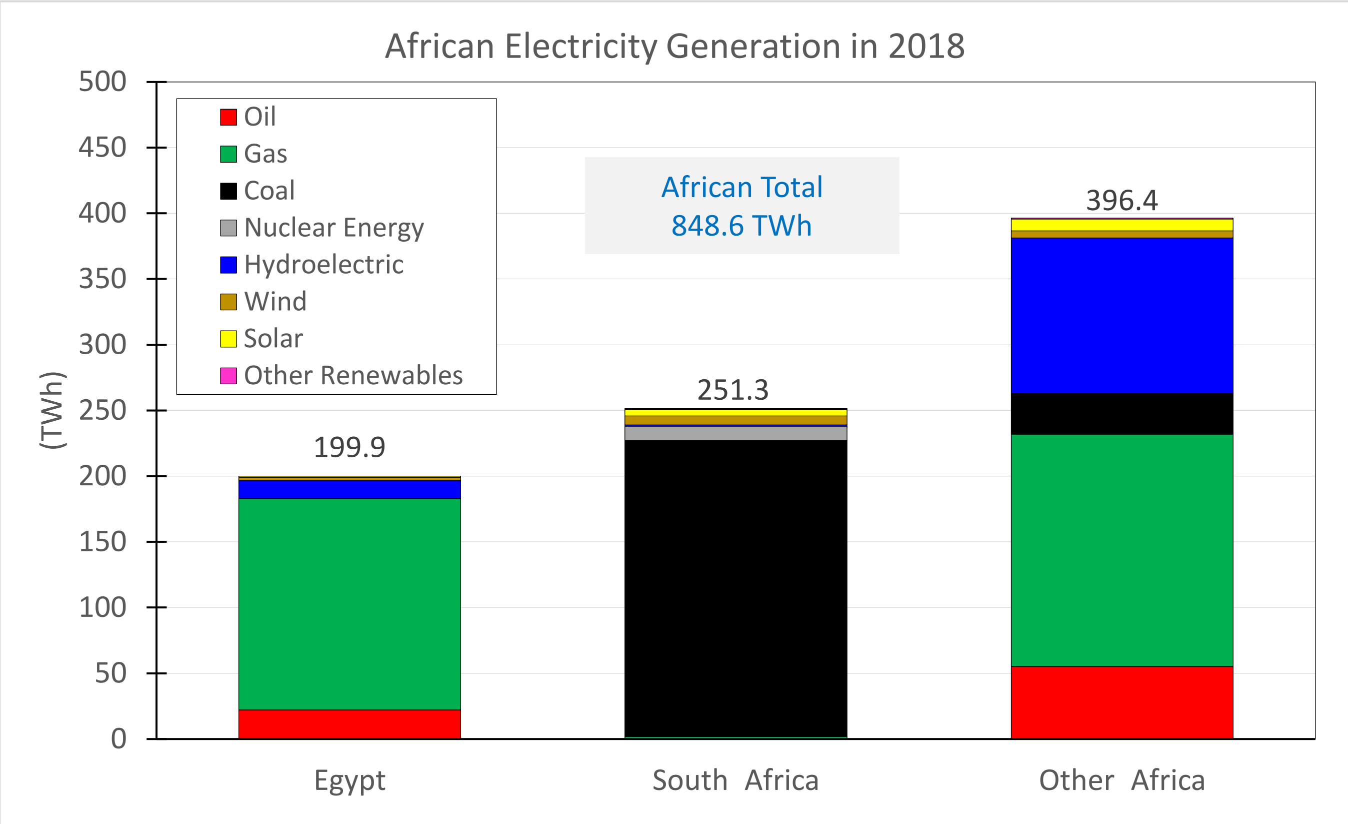


Figure 8.26. African electricity generation by country and raw material source in 2018
(Source: BP Statistical Review of World Energy 2019)

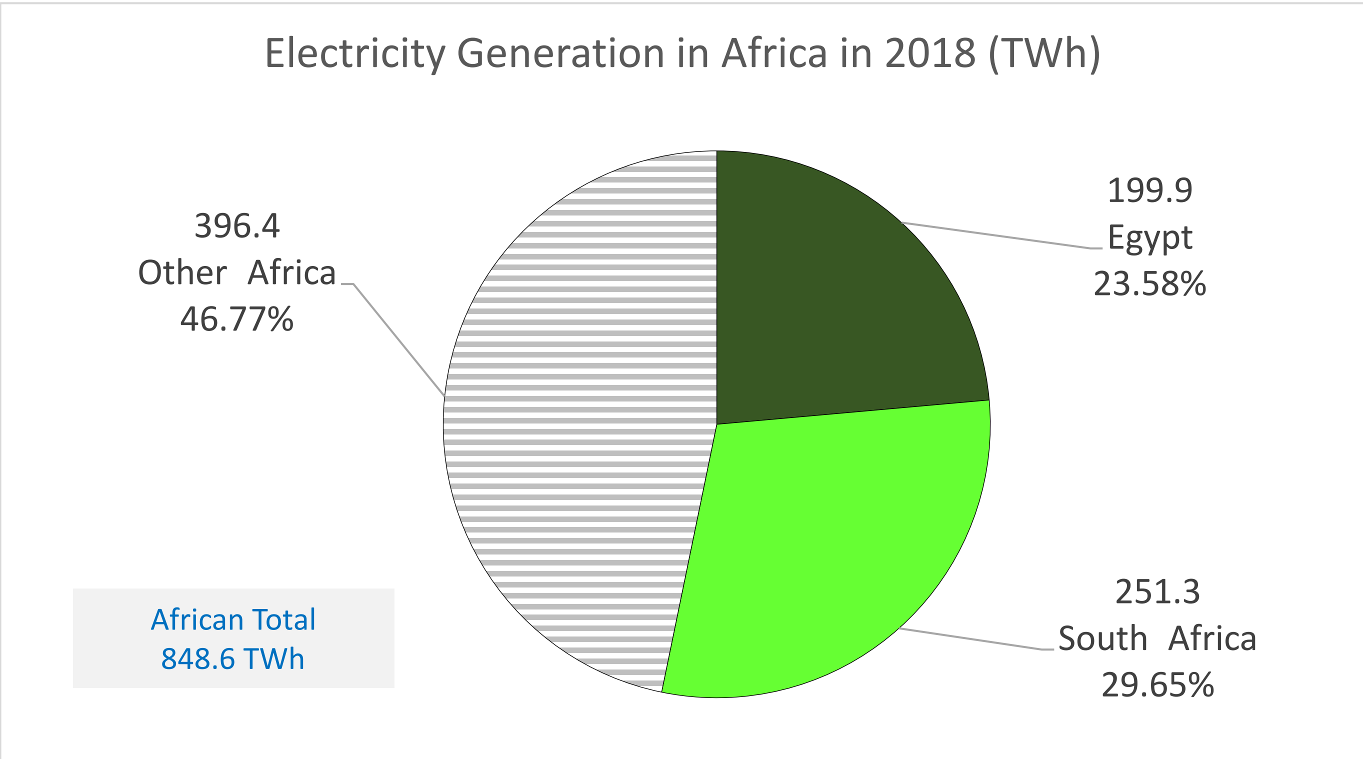


Figure 8.27. African electricity generation by country in 2018
(Source: BP Statistical Review of World Energy 2019)

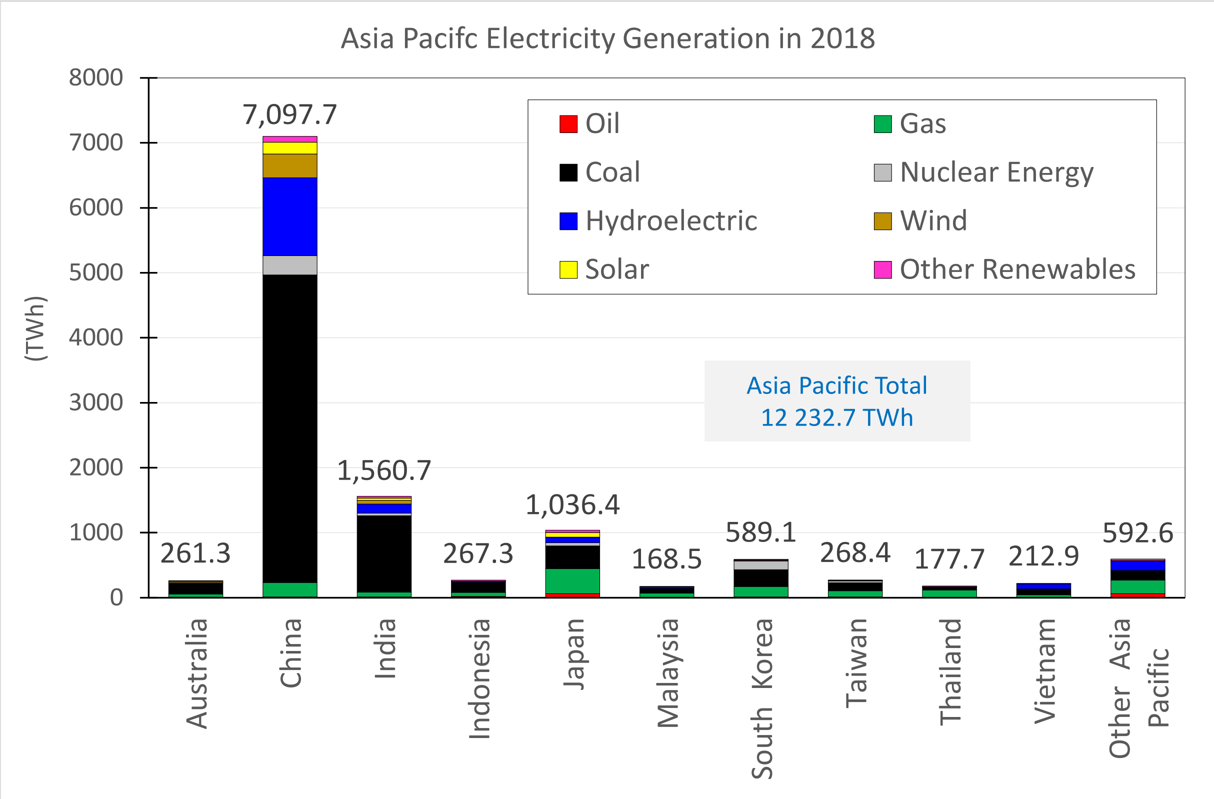


Figure 8.27. Asia Pacific electricity generation by country and raw material source in 2018 (Source: BP Statistical Review of World Energy 2019)

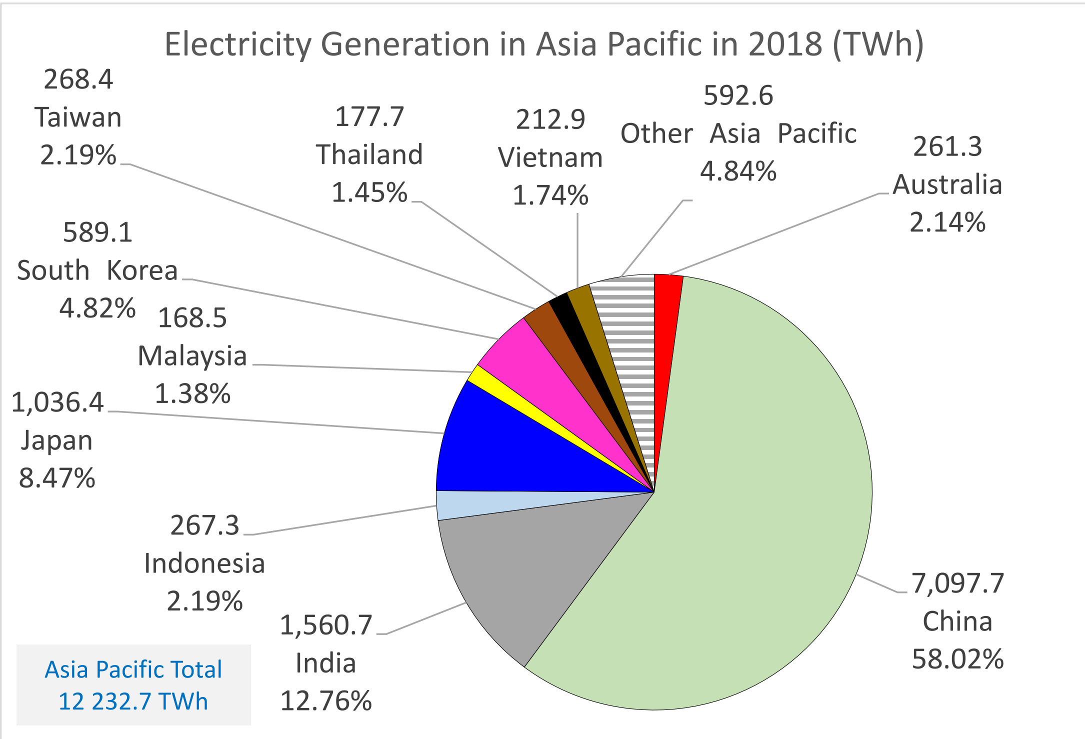


Figure 8.28. Asia Pacific electricity generation by country in 2018 (Source: BP Statistical Review of World Energy 2019)

8.5 Electricity Generation in Europe

Figures 8.29 to 8.33 and Table 8.2 show the electricity generation requirements and needs in the European Union.

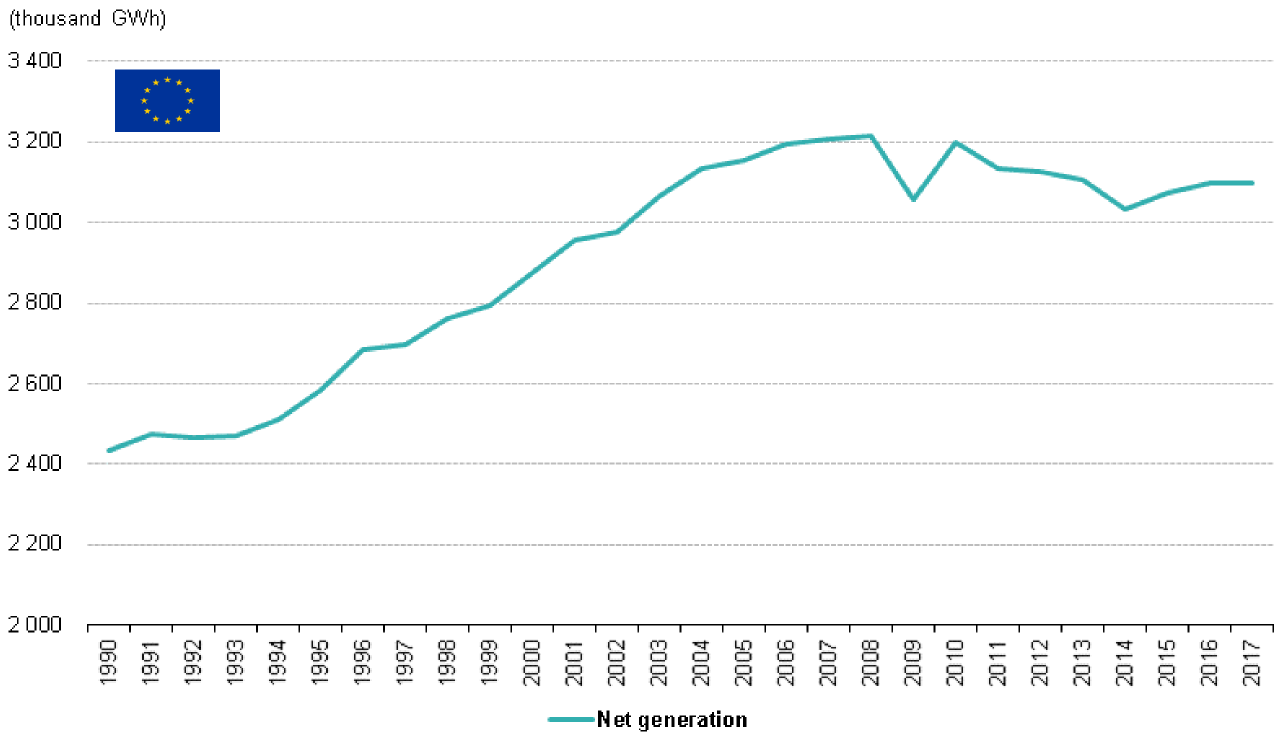


Figure 8.29. Net electricity generation, EU-28, between 1990 and 2017
(Source: Eurostat-online data code nrg_ind_peh)

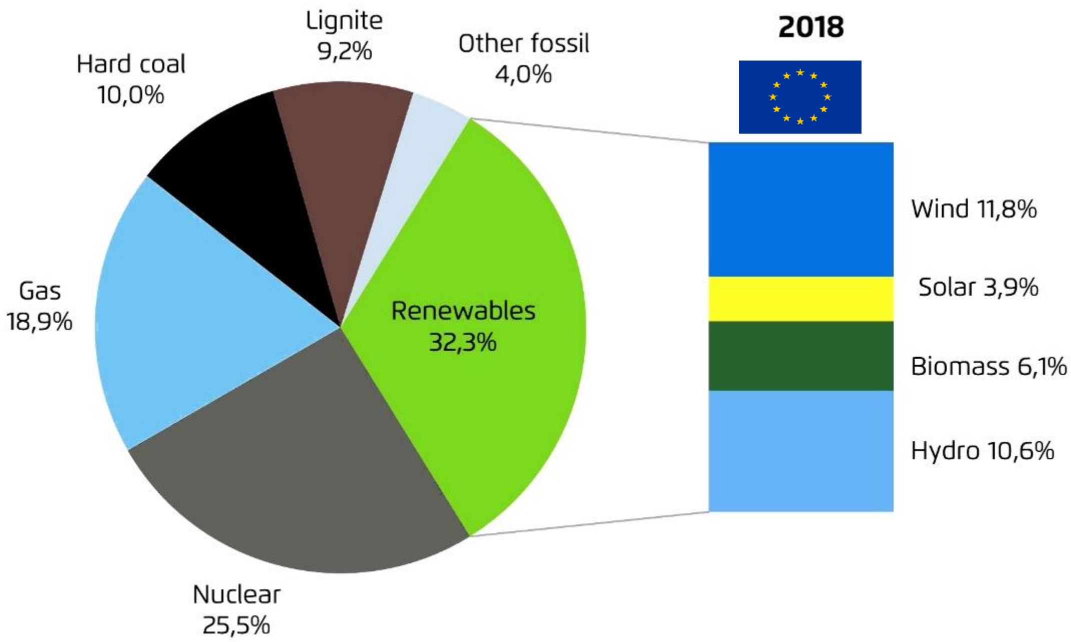


Figure 8.30. Electricity generation, EU-28, in 2018, (% of total based on GWh)
(Source: Eurostat-online data code nrg_ind_peh)

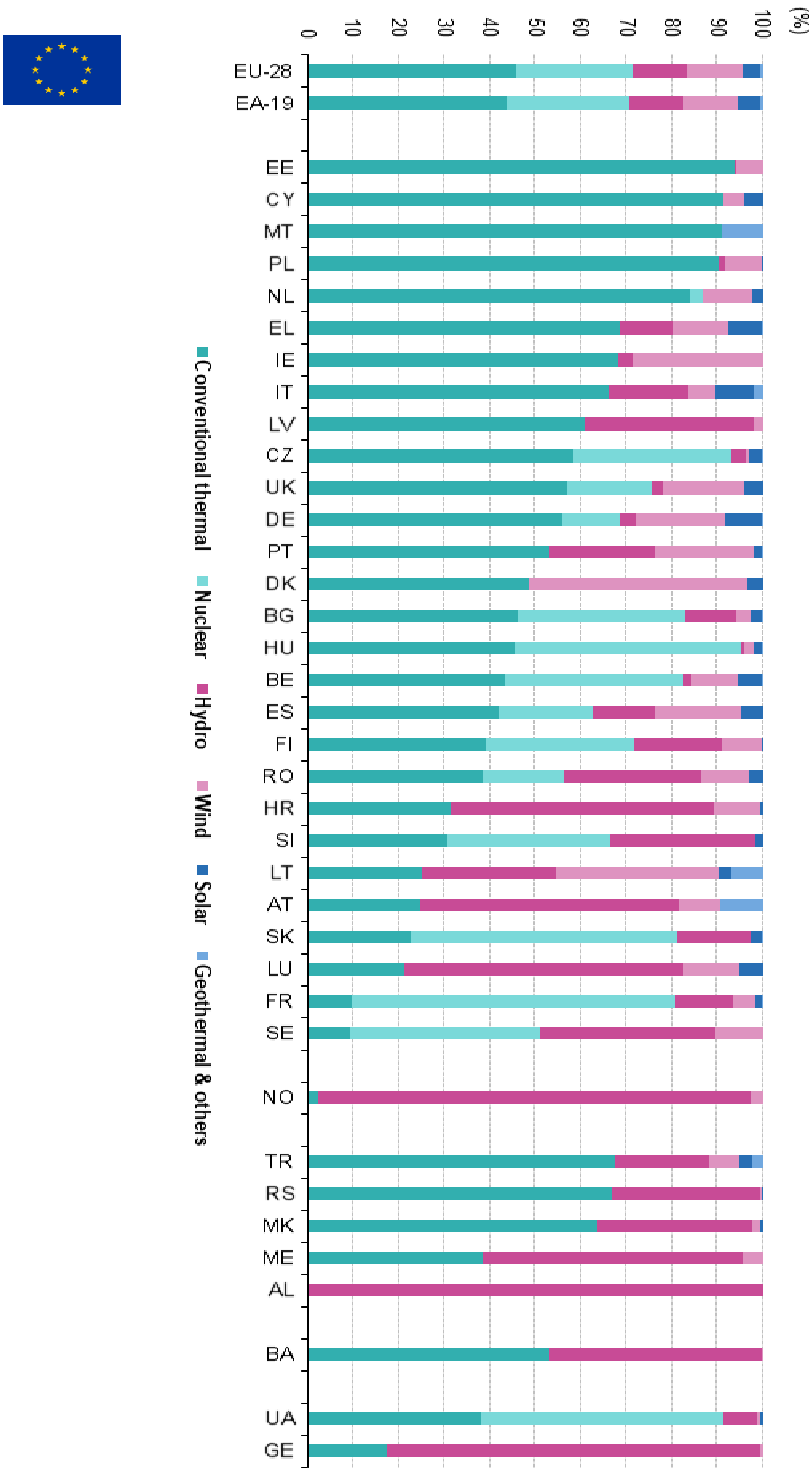


Figure 8.31. Breakdown of electricity by source in the European Union EU-28 in 2018
(Source: Eurostat – online data code: nrg_105m)

Table 8.2. Electric power generation in 2018, by fuel, by country in European Union, Units Terawatt hours (TWh) (Source: Agora Energiewende and Sandbag 2019)

TWh	Lignite	Hard Coal	Other fossil	Gas	Nuclear	Hydro	Solar	Wind	Biomass	Consumption	Imports	Production
EU28	**300**	**324**	**131**	**614**	**829**	**344**	**127**	**382**	**198**	**3276**	**26**	**3249**
Austria	0	2	4	9	0	37	2	6	5	72	9	64
Belgium	0	0	5	23	29	0	4	7	5	91	17	74
Bulgaria	19	1	0	2	16	5	1	1	0	38	-8	46
Cyprus	0	0	5	0	0	0	0	0	0	5	0	5
Czech	37	4	3	4	30	2	2	1	5	73	-14	87
Denmark	0	6	1	1	0	0	1	15	8	36	5	32
Estonia	0	0	10	0	0	0	0	1	1	10	-2	12
Finland	3	6	1	5	23	14	0	6	10	88	20	68
France	0	7	7	29	413	64	10	29	8	505	-63	568
Germany	146	83	26	84	76	17	46	112	52	595	-47	642
Greece	17	0	6	14	0	7	4	6	0	61	6	55
Hungary	5	0	0	7	16	0	0	1	2	46	14	32
Ireland	2	4	0	16	0	0	0	8	1	31	0	31
Italy	0	27	18	130	0	47	24	18	26	332	44	289
Latvia	0	0	0	3	0	2	0	0	1	8	1	7
Lithuania	0	0	1	0	0	0	0	1	1	13	10	3
Netherlands	0	34	6	55	2	0	3	9	5	121	6	114
Poland	49	80	5	11	0	2	0	13	8	175	6	169
Portugal	0	12	2	15	0	13	1	13	3	56	-3	59
Romania	16	0	1	10	11	18	2	6	0	62	-3	65
Slovakia	1	1	1	2	15	4	1	0	2	30	4	27
Slovenia	4	0	0	0	6	5	0	0	0	15	-1	16
Spain	0	38	19	57	57	33	13	52	6	284	10	274
Sweden	0	0	3	1	69	62	0	16	11	147	-17	164
United Kingdom	0	17	7	132	65	5	13	58	36	352	19	333
Luxembourg	0	0	0	0	0	0	0	0	0	7	6	1
Malta	0	0	1	0	0	0	0	0	0	2	2	1
Croatia	0	2	0	2	0	8	0	1	1	19	5	14

As can be observed, even though Europe leads the world in implementation in renewable power sources, it is still heavily dependent on fossil fuels for electric power generation.

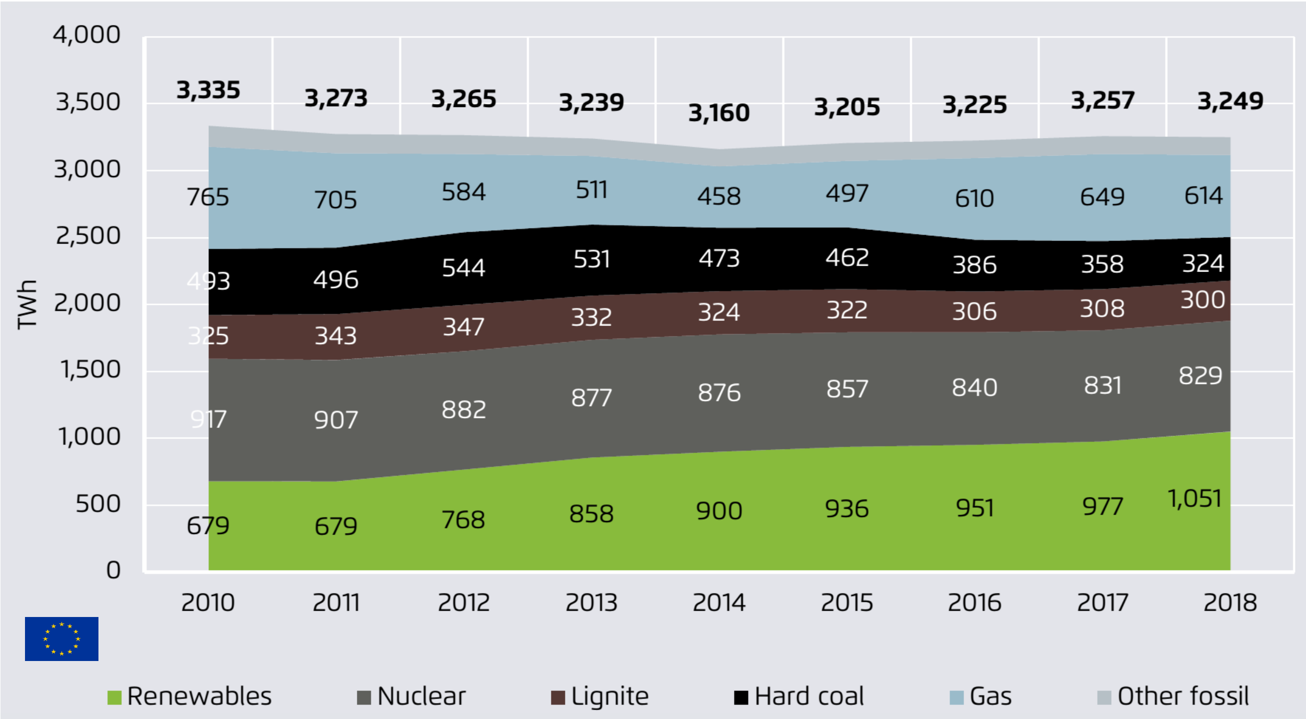


Figure 8.32. Electric power generation in 2018, by fuel, by country in European Union, 2010 to 2018
(Source: Agora Energiewende and Sandbag 2019)

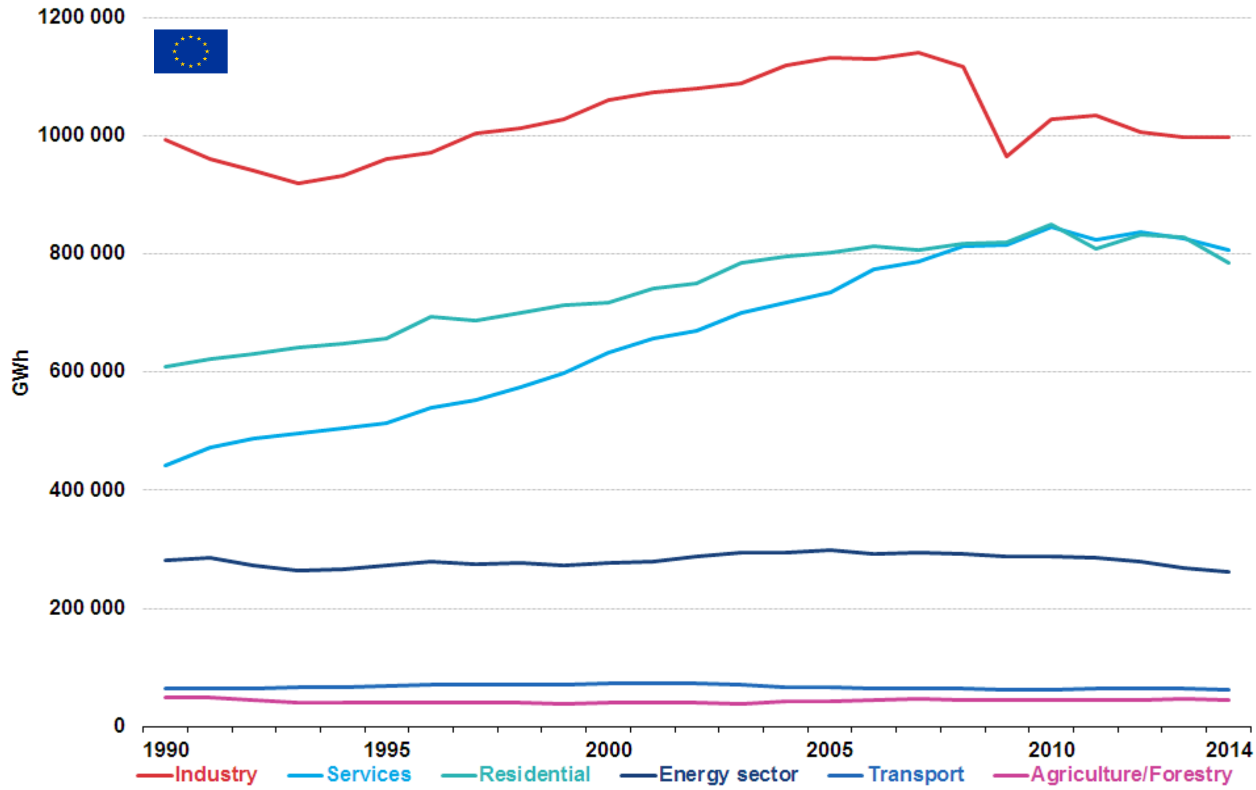


Figure 8.33: Consumption of electricity by sector, GWh, EU-28, 1990-2014
(Source: Eurostat) (Copyright License: https://creativecommons.org/licenses/by-nc-sa/4.0/)

8.6 Installed Power Capacity of Current Power Station Fleet

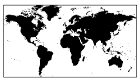
The purpose of this section is to quantify the size, scope, and capacity of the current global electrical power generation fleet of power stations. Table 8.3 and 8.4 show the power generation capacity by fuel system type. They also show the estimate operating hours (electric power generated kWh divided by installed capacity kW), where a full year has 8 760 hours (24 hours in a day x 365 days in a year). This shows in practice the relative efficiencies of each system.

Table 8.2. Number and capacity of electrical power systems by source in 2018

Power Generation System Source	Global Number Power Plants in 2018 (Global Energy Observatory) (number)	Maximum Installed Plant Capacity Found in Data for 2018 (Global Energy Observatory & Agora Energiewende and Sandbag 2019) (MW)	Power Produced by a **Single** Average Plant in 2018 (kWh)	Minimum Installed Plant Capacity Found in Data in 2018 (Global Energy Observatory) (MW)	Standard Deviation of Installed Plant Capacities for 2018 (Global Energy Observatory) (MW)
Coal	1 437	6 600 MW	7 028 812 030	0.9 MW	926.6
Gas	2 781	5 040 MW	2 223 247 834	1 MW	560.2
Nuclear	438	8 212 MW	12 803 184 576	20 MW	1339.4
Hydroelectric	3 163	22 500 MW	1 325 746 584	0.005 MW	703.5
Wind		610 MW	81 241 809		
Solar PV		850 MW	33 040 663		
Solar Thermal	52	392 MW	76 970 000	0.25 MW	73.78
Geothermal	108	1273 MW	603 226 027	0.05 MW	163
Biowaste to energy	3 800		34 581 818		
Fuel Oil Diesel	1 069	5 523 MW	850 797 343	0.7 MW	520.5

Table 8.3 shows the global consumption, efficiency of generation, installed capacity and electric power generated by the different types of electric power generation methods in 2018. Table 4.4 in Section 4.4 shows the efficiencies of each of the power generation systems.

Table 8.3. Global power generation and installed capacity by type
(World Map Image by Clker-Free-Vector-Images from Pixabay)

Power Generation System Source 	Installed Global Capacity in 2018 (Section 3.3 & Global Energy Observatory) (GW)	Global Electricty Production in 2018 (Appendix B & Agora Energiewende and Sandbag 2019) (TWh)	Operating hours in practice of existing installed capacity in 2018 (h)	Global Number Power Plants in 2018 (Global Energy Observatory) (number)	Average Installed Plant Capacity in 2018 (Global Energy Observatory) (MW)	Power Produced by a **Single** Average Plant in 2018 (kWh)
Coal	1237.7 GW	10,100.50	8,161	1,437	861.3	7,028,812,030
Gas	1207.5 GW	6,182.80	5,120	2,781	434	2,223,247,834
Nuclear	431.8 GW	2,701.40	6,256	438	2,046.5	12,803,184,576
Hydroelectric	712.9 GW	4,193.10	5,882	3,163	225	1,325,746,584
Wind	597 GW	1,303.80	2,184	16,048 (est)	37.2	81,241,809
Solar PV	580.14 GW	579.1	998	17,526 (est)	33.1	33,040,663
Solar Thermal	5.5 GW	5.5	1,000	52	77.0	76,970,000
Geothermal	14.6 GW	93	6,370	108	95	603,226,027
Biowaste to energy	55 GW	652.8	1,091	3,800	32	34,581,818
Fuel Oil Diesel	225.8 GW	802.8	3,555	1,069	239	850,797,343

Total (GW)	5067.94	2.66E+07		46,423		
Total(TWh)	5.07	26,614.80				

8.7 Summary Data for Electrical Power Generation

Table 8.4. Electrical power generation by country in year 2018 (Source: BP Statistical Review of World Energy 2019)

Country	Oil (TWh)	Gas (TWh)	Coal (TWh)	Nuclear Energy (TWh)	Hydroelectric (TWh)	Wind (TWh)	Solar (TWh)	Other Renewables (TWh)	Country Total (TWh)
Canada	3.2	58.7	59.3	100	387.3	32.20	3.50	9.6	653.8
Mexico	36.8	196.7	29.2	13.6	32.4	12.60	2.20	6.5	330.0
United States	26.4	1578.5	1245.8	849.6	288.7	277.70	97.10	83.7	4,447.5
Total North America	**66.3**	**1833.9**	**1334.3**	**963.2**	**708.4**	**322.50**	**102.90**	**99.7**	**5,431.2**
Argentina	6.4	85.3	2	6.9	41.6	1.40	0.10	2.3	146.0
Brazil	11.5	46.8	21.9	15.6	387.7	48.50	3.10	52.9	588.0
Other S. & Cent. America	72.2	95.8	52.6		302	16.00	9.10	22.8	570.5
Total S. & Cent. America	**90.2**	**227.9**	**76.5**	**22.5**	**731.3**	**65.90**	**12.40**	**78.0**	**1,304.7**
Germany	5.2	83	229	76.1	16.9	111.60	46.20	51.4	619.4
Italy	10.9	127.2	36.6		45.9	17.50	23.20	25.3	286.6
Netherlands	0.6	57.3	30	3.5	0.1	10.50	3.20	4.9	110.1
Poland	1.2	12.4	134.7		2	12.80	0.30	6.3	169.7
Spain	15.6	57.2	38.4	55.6	35.2	50.80	12.50	7.4	272.7
Turkey	0.6	92.2	111.7		59.5	19.80	7.90	10.0	301.7
Ukraine	0.5	12.1	47.7	84.4	9.9	1.10	1.30	0.2	157.2
United Kingdom	1.7	131.5	16.8	65.1	5.5	57.10	12.90	35.6	326.2
Other Europe	19.8	158.5	217.8	652.1	467.2	123.20	28.30	47.2	1,714.1
Total Europe	**56**	**731.3**	**862.7**	**937.5**	**642.1**	**404.40**	**139.10**	**217.6**	**3,990.7**
Kazakhstan	1.7	24.2	70.2		10.3	0.50	0.10		107.0
Russian Federation	11.4	521.5	177.5	204.5	190.2	0.20	0.60	0.50	1,106.4
Other CIS	0.5	140.4	11.3	2.1	44.3	0.30	0.20	0.20	199.3
Total CIS	**13.7**	**686.1**	**259**	**206.6**	**244.8**	**1.00**	**0.90**	**0.7**	**1,412.8**
Iran	23	269.1	0.5	7	10.8	0.40			310.8
Saudi Arabia	150.6	233					0.20		383.8
United Arab Emirates	1.6	134.4					0.90		136.9
Other Middle East	135.7	241.9	20.8		4.4	0.60	3.0	0.10	406.5
Total Middle East	**310.9**	**878.5**	**21.3**	**7**	**15.2**	**1.10**	**6.10**	**0.30**	**1,240.4**
Egypt	22.1	160.9			13.5	2.40	1.00		199.9
South Africa	0.1	1.9	225	11.1	0.9	6.90	4.90	0.50	251.3
Other Africa	55.3	176.6	31		118.4	5.4	8.9	0.8	396.4
Total Africa	**77.6**	**339.3**	**255.9**	**11.1**	**132.8**	**14.70**	**9.00**	**8.20**	**848.6**
Australia	5.3	50.2	156.6		17.3	16.30	12.1	3.50	261.3
China	10.7	223.6	4732.4	294.4	1202.4	366.00	177.5	90.7	7,097.7
India	10.1	74.3	1176.3	39.1	139.4	60.30	30.7	30.5	1,560.7
Indonesia	20.2	59.6	156.4		16.4	0.20		14.5	267.3
Japan	60	386.9	347.2	49.1	81	6.80	71.7	33.7	1,036.4
Malaysia	2.3	66.4	74.1		24.2		0.50	1.0	168.5
South Korea	9.1	160.4	261.3	133.5	2.9	2.40	9.30	10.2	589.1
Taiwan	8.4	94.8	126.6	27.7	4.5	1.70	2.70	2.0	268.4
Thailand	0.2	116.3	35.8		7.6	0.80	4.70	12.3	177.7
Vietnam	0.7	44.3	86.7		80.7	0.30	0.10	0.10	212.9
Other Asia Pacific	61	209	137.5	9.9	141.9	5.70	4.80	22.8	592.6
Total Asia Pacific	**188**	**1485.8**	**7290.8**	**553.6**	**1718.5**	**460.50**	**314.2**	**221.3**	**12,232.7**
Global Total	**802.8**	**6182.8**	**10100.5**	**2701.4**	**4193.1**	**1270.0**	**584.6**	**625.8**	**26,614.8**

8.8 Daily fluctuations of power demand and the capacity for off peak capacity

Peak demand is typically characterized as annual, daily, or seasonal and has the unit of power (Torriti 2016). Peak demand, peak load or on-peak are terms used in energy demand management describing a period in which electrical power is expected to be provided for a sustained period at a significantly higher than average supply level.

This happens all over the world and is a fundamental characteristic of how human society uses electrical power and this is related to how society uses electrical power during the day and then during the night, across the four seasons of the yearly cycle. Peak demand fluctuations may occur on daily, monthly, seasonal, and yearly cycles (Smil 2016b).

Different kinds of power demand each have different cycles. In industrialized regions of China or Germany, the peak demands mostly occur in daytime. In more service based economy such as Australia, the daily peak demands often occur in the late afternoon to early evening time (e.g. 4pm to 8pm) (Liu *et al* 2017). During the night there is a noticeable reduction in demand as most economic activity ceases (as shown in Figure 8.35). Residential and commercial electricity demand contributes a lot to this type of network peak demand (Liu *et al* 2017). Power demand also varies with the winter season, as more heating of buildings is required (Landsberg et al 1980), resulting in an increase in power demand across the winter months.

To keep the electrical generation grid delivery system stable, consumer demand and supply generation must be identical at every moment. The total power system generation must follow the same pattern as the demand. So as demand fluctuates, power generation and power demand must be in balance (Figure 34).

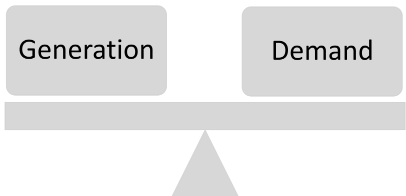


Figure 8.34. To keep the system stable, demand and generation must be identical a every moment, and in balance

Existing power systems currently rely on changing the generation of fossil fuel-based and hydro plants to cope with the fluctuations in the demand (Grigsby 2006). Intermittent power supply from wind and solar generation systems is also balanced up in the same manner, with most variation mitigation coming from gas power fired systems (shown in Figure 8.35).

Figure 8.35 shows the electrical power generation portfolio of various technologies in Ontario, Canada for the time period February 17-22, 2021. As can be seen demand follows a well-established peak and trough pattern, of variable amplitudes. What is interesting to note, was how the different power generation systems changed production to meet those changes. Nuclear power provided a stable base load that did not really change. This is appropriate as nuclear power stations are quite inflexible in regard to the quantity of power they deliver (UK Parliament 2014, Feb). Coal fired power station are also not very flexible in changing the quantity of power they deliver. Wind and solar power were highly variable over the whole time period. The maximum wind generation happen to occur in a demand valley on the 22nd of 2021. Solar did not deliver power at all for several days. Canada has a strong capacity for hydroelectricity. In the time period shown in Figure 8.35, hydroelectrical power supply was able to vary with demand, but only within a relatively narrow amplitude range (about half of the range needed). Hydroelectricity can vary power output but is heavily influenced by the volume of water in in its associated reservoir, which makes it vulnerable to changes in weather patterns. So, hydro can only be part of the fluctuating variability mitigation to ensure balance of supply to demand.

Figure 8.35 shows that gas powered electricity generation was highly flexible in what it was able to deliver. Gas power formed a buffer between changing demand across the day/night cycle and contributions of wind and solar. Without gas power generation as a source, keeping the power grid stable in context of supply and demand would be challenging. This is something to consider as gas power generation is being phased out. The extra power generation capacity also must be non-fossil fuel in operation. This excludes the use of oil, gas or coal fired power stations. Solar power cannot operate at night. Wind power is too intermitent and variable in operation to be reliable enough as a buffer system. Hydroelectric power generation can vary in output but only in a limited range. Biofuel power systems could form a buffer to replace gas systems if they were optimized to do so and operating plants were commissioned in large enough numbers.

It is suggested that to replace gas as a variable mitigation system, extra systems of wind (buffered by power storage banks), biofuel/biomass power generation, geothermal, tidal, and hydro systems (where possible) be constructed. Due to the difference in flexibility, these systems will have to be larger in capability, where some capacity is simply idle for periods of time.

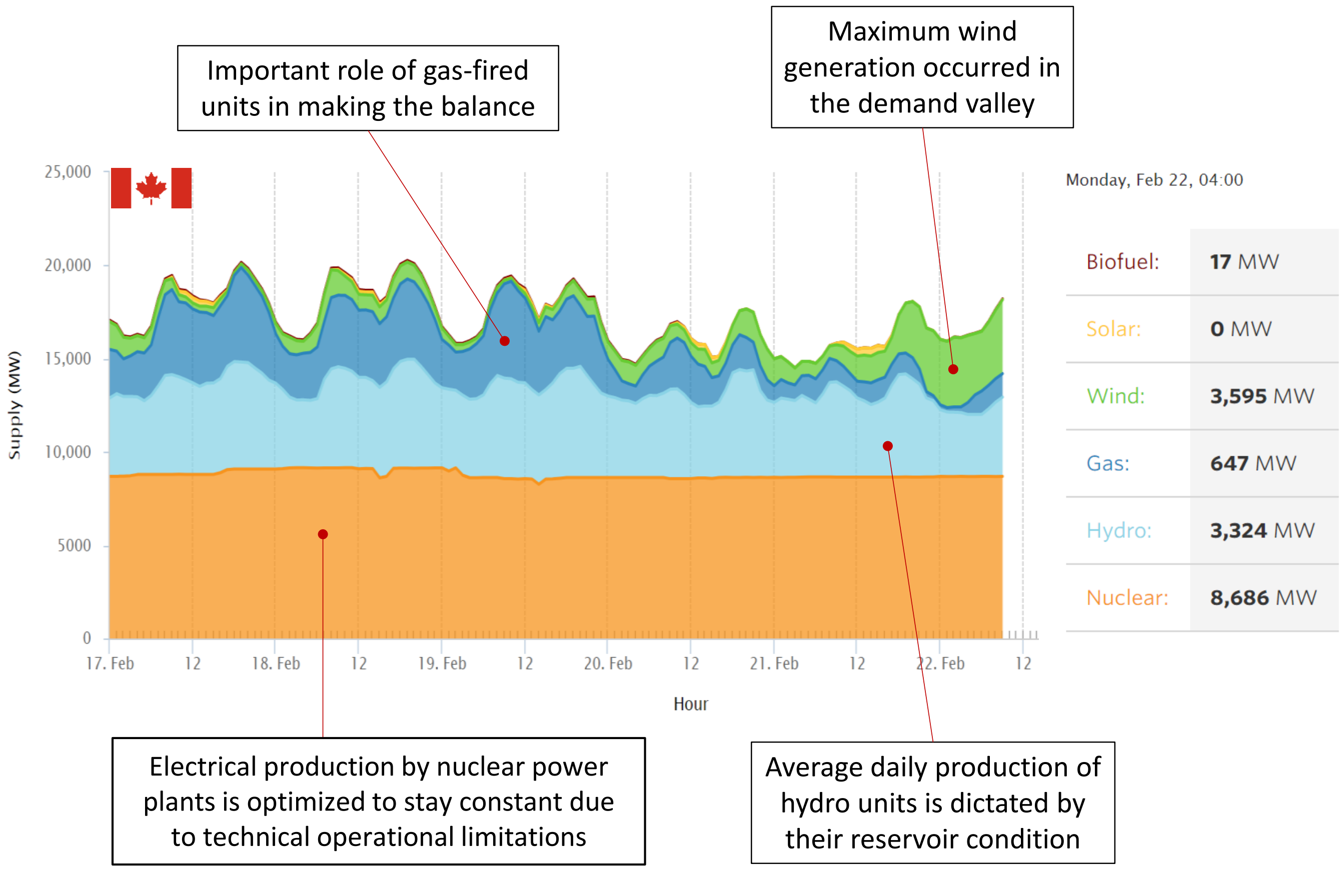


Figure 8.35. Electrical power generation portfolio of various technologies in Ontario, Canada (February 17-22, 2021)

One of the strategies for future energy management of the incoming electric vehicle fleet, was to charge EV batteries only in off peak electricity production (off-peak hours when power demand is usually low). That is charge EV batteries only at night. Figure 8.35 shows an approximate variation of power demand/supply between 15 000 MW and 20 000 MW, or a range of 5 000 MW. This was just an approximate 25 % variation across the day/night cycle. The required extra capacity of power generation required to phase out fossil fueled ICE vehicles is estimated in Section 18, or Scenario A. This estimate shows that the power grid will have to expand much more than 25 %. Thus, it is concluded that the plan of charging EV batteries off peak will not be a practical solution beyond an optimization measure.

8.9 System reliability and intermittent power supply challenges

Sources of electricity that exhibit uncontrolled increases or decreases in output are often referred to as intermittent. All existing electrical power generation systems have down time and intermittent supply profiles (UK Parliament 2014, May). Some systems are more reliable than others (Torriti 2016).

Table 8.5. Contribution of technologies to electricity system reliability at times of annual peak demand (Source: UK Parliament 2014 May)

Technology	Reliable capacity as a % of maximum capacity	2013 UK max capacity, (GW)
Wind	7-25%	11.0
Solar †	0%	2.7
Hydro	79-92%	1.7
Tidal *	35%	<0.001
Wave *	35%	<0.001
Fossil Fuel	77-95%	
Nuclear	77-95%	78

* There was little data available on the contribution of tidal & wave

† Peak demand happens after sunset, solar not operational

All forms of electricity generation exhibit uncontrolled increases or decreases in output (intermittency). For example, conventional (fossil-fuelled and nuclear) power plants break down, causing larger instantaneous losses of capacity than renewables. However, the term intermittency is typically associated with the renewables: wind, solar, wave and tidal. Intermittency from these sources is characterised by very large variations in the amount of electricity they can provide at the national level. Although these variations are not normally controlled, they can be predicted with some accuracy. Wind power is dependent on the weather; thus, prediction of reliability is related to the accuracy of weather predictions (EIA 2015). Solar is also intermittent but can be predicted more reliably. Tidal power generation systems are reliant on the regional coastal tides, which are reliably predictable.

8.10 Power storage stations

The intermittent nature of renewable energy can be mitigated with measures like connecting lots of renewable power stations together and optimizing their power delivery through one system (Droste-Franke 2015). Power storage systems are mostly required to ensure consistent supply to the grid during the long periods of reduced sunlight hours and reduced wind where it is needed, for solar and wind systems (Mulder 2014). With some organized integration and effective data management, a combination of storage and power sharing over a wide geographical area could provide an optimal solution.

A secure electrical power system needs adequate levels of both system strength and inertia, which to date have been provided by synchronous power generation. System strength relates to the ability of a power system to manage fluctuations in supply or demand while maintaining stable voltage levels. Inertia relates to the ability of a power system to manage fluctuations in supply or demand while maintaining stable system frequency.

There is a distinction between intermittency and predictability. Solar and tidal systems are relatively predictable. It's important to understand that while solar is intermittent, it does not have a random generation pattern. Solar resource for power generation is very predictable, which makes grid integration less of an issue. Additionally, forecasting solar resource on a day-ahead and hour-ahead basis has a high accuracy factor. For example, sourcing 1000 MW of Photo Voltaic power on one transmission line will clearly be more difficult to integrate than 1000 MW of Photo Voltaic power spread across multiple distribution and transmission lines and across a broader geographical area.

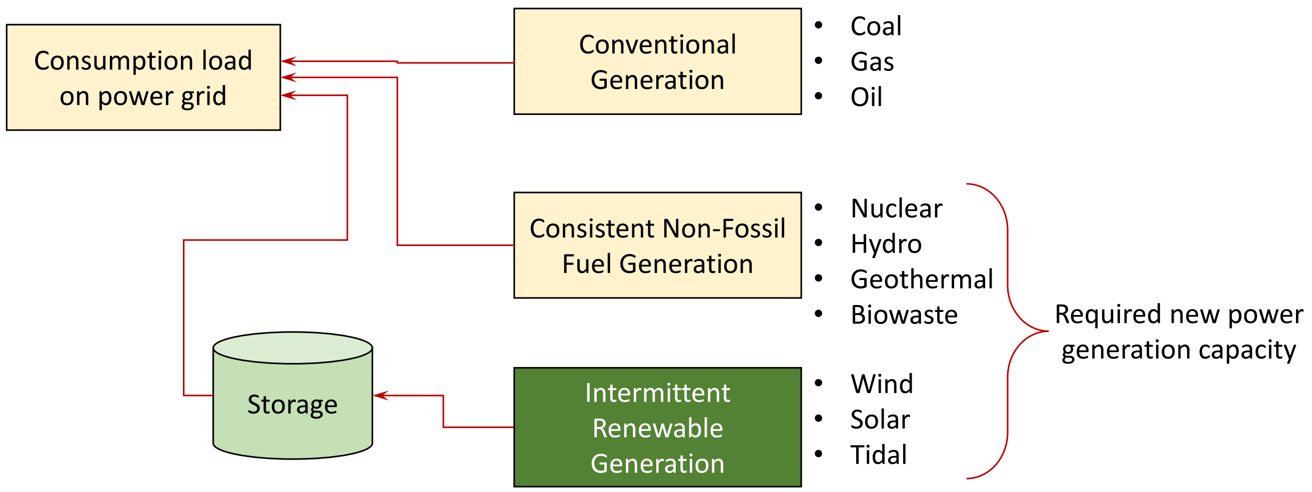


Figure 8.36. Energy storage to mitigate fluctuations of power supply from intermittent generation

Wind power is much more intermittent (EIA 2015, Huang 2014, Ren *et al* 2017, Ren *et al* 2018 and UK Parliament 2014). The output from a single wind farm located in any particular geographical region is highly variable on time scales ranging from minutes to days. This creates difficulties for incorporating relevant outputs into an integrated power system. The high frequency (shorter than once per day) variability of contributions from individual wind farms is determined mainly by locally generated small scale meteorological weather boundary in the atmosphere.

The difficulty associated with integrating variable sources of electricity stems from the fact that the modern power grid was designed around the concept of large, controllable electric generators (gas, coal or nuclear powered). To manage the system used in 2020, the grid operator uses a three-phase planning process to ensure power plants produce the right amount of electricity at the right time, in a manner to meet electric demand consistently and reliably. Because the grid currently has very little storage capacity, the balance between electricity supply and demand must be maintained at all times to avoid a blackout or other cascading problem. This issue will have to be addressed in some form to meet the variable nature of renewable power if it is to work (Fares 2015). Currently, most wind and solar power is delivered to the grid in a highly intermitent form (see Figure 8.35 in Section 8.7), without any buffer power storage station. As shown in Figure 8.35, gas powered electricity generation was used to match supply to demand as both varied.

While the volume of electrical power from renewable sources is relatively small this is a manageable issue. Once renewable power becomes a larger share of power generation, then infrastructure will be needed in electrical power storage (Friedemann 2021).

Energy storage is useful when energy is harvested at a different time from when it's used. For example, electricity must be used very quickly after it's been made (within milliseconds). Energy storage would be needed if the electrical grid starts relying on large amounts of intermittent electricity sources like wind power.

Table 8.6. Technology options for energy storage (Source: J.M.K.C. Donev *et al* (2018)

Storage Type	Form of energy stored	Technology
Mechanical	Potential	Compressed air energy storage (CAES) Pumped storage
	Kinetic	Flywheels
Electrical	Electrostatic	Capacitors Super capacitors
	Magnetic	Superconducting magnetic energy storage (SMES)
Chemical	Chemical	Batteries
	Electrochemical	Fuel cells
	Thermochemical	Fuels from solar power
Thermal	High temperature thermal	Sensible heat storage Latent heat storage

Using a combination of interconnection integration management measures in conjunction with a number of storage power stations could make renewable energy power systems more practical to scale up. As the degree of variability varies greatly across a 24 hour cycle for solar, wind, and tidal power, but in some cases is predictable, the size of the needed storage is related to the number of power sources networked and how efficient that network can be managed to transfer power to one place to another when needed. Another issue will be that many EV systems will be charged at night or overnight. Solar power in particular is only efficient during the day.

Steinke *et al* 2012 put forward the recommendation for a fully renewable powered Europe to have 2 days of power storage, plus 10%. This study was to examine all power requirements for Europe to be 100% renewable. Another study (Droste-Franke 2015) examined the possibility of a 'supergrid' across the European Union, North Africa, and the Mediterranean. This study found that there would still need to be 1 month of energy storage to keep the grid up during seasonal variations (Droste-Franke 2015). Palmer (2020) proposed that up to 7 weeks of storage would be required as well as large amounts of renewable capacity overbuild.

Pumped-storage hydropower (PSH) is a type of hydroelectric energy storage. In terms of energy storage, PHS provides 98% of all the existing electrical energy stored in the world (Mongird *et al* 2019). PSH is a configuration of two water reservoirs at different elevations that can generate power (discharge) as water moves down through a turbine; this draws power as it pumps water (recharge) to the upper reservoir (U.S. DoE). The method stores energy in the form of gravitational potential energy of water, pumped from a lower elevation reservoir to a higher elevation. Low-cost surplus off-peak electric power is typically used to run the pumps. During periods of high electrical demand, the stored water is released through turbines to produce electric power. Although the losses of the pumping process make the plant a net consumer of energy overall, the system increases revenue by selling more electricity during periods of peak demand, when electricity prices are highest. If the upper lake collects significant rainfall or is fed by a river then the plant may be a net energy producer in the manner of a traditional hydroelectric plant.

PSH capabilities can be characterized as open loop—where there is an ongoing hydrologic connection to a natural body of water—or closed loop, where the reservoirs are not connected to an outside body of water (Figure 8.37).

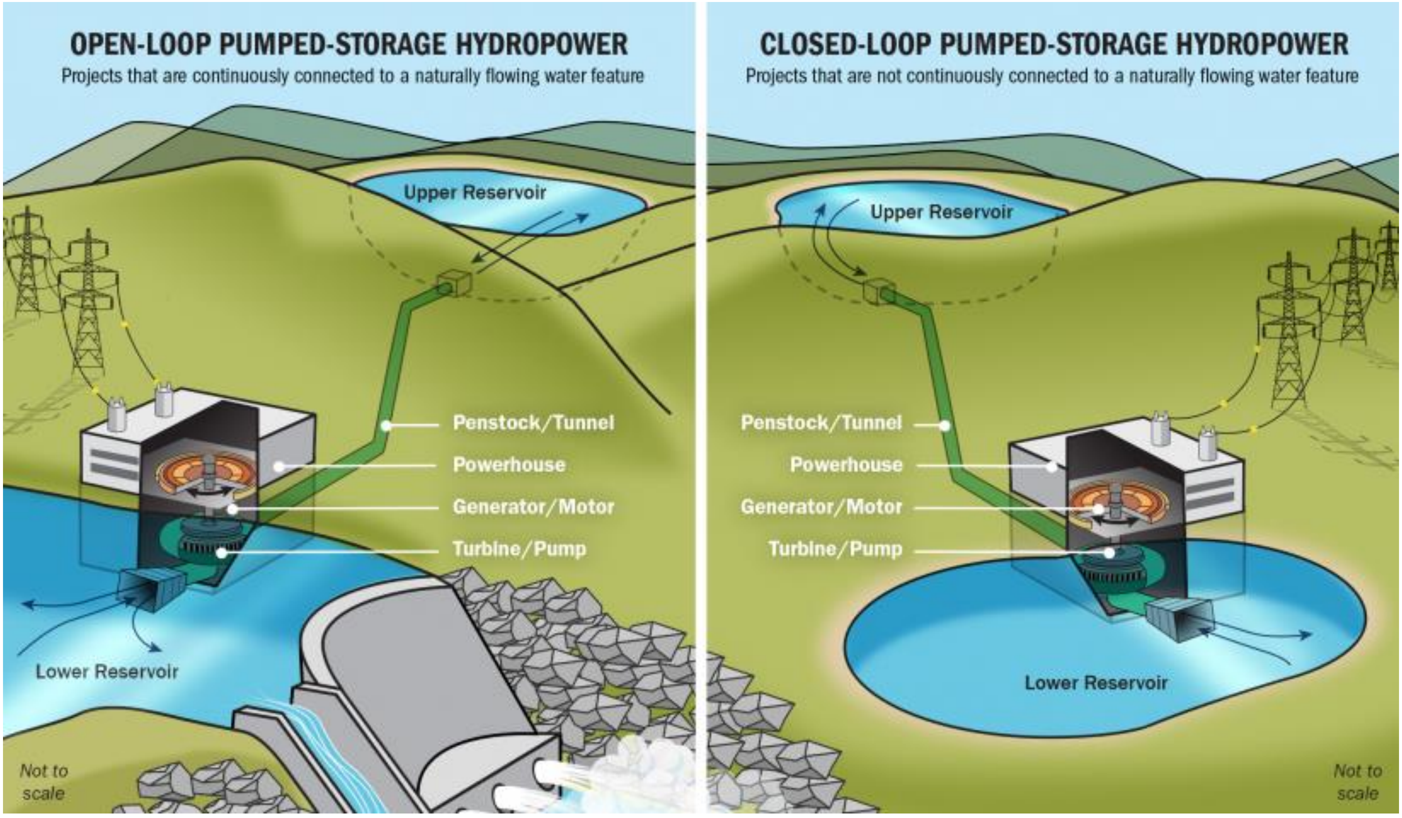


Figure 8.37. Pumped-Storage Hydropower (Source: United States Department of Energy) (Copyright License: https://www.energy.gov/about-us/web-policies)

In the United States, there is 43 pumped storage supported hydroelectricity plants (Friedemann 2021 and U.S. Department of Energy 2016). Over a 12 month cycle, those 43 plants produced the equivalent of 2 days of energy storage for the US national power grid (combined local grids). This was just 23 TWh (U.S. Department of Energy 2016). If PHS was the selected power storage method used for the United States, then the capacity for a 4 week period, plus 10 % (Steinke *et al* 2012) would be required. The equivalent of 4 weeks of power consumption requirements in the United States grid (4 447.5 TWh, Table 8.4), was estimated to be 370.6 TWh. An additional 10 % would result in a needed 407.7 TWh of required power storage for just the United States. If the average PHS station stored 534.9 GWh over a 365 day cycle (23 TWh ÷ 43 stations), to store the needed 407.7 TWh, 762 PHS stations will be required to be operating.

The energy density of PHS storage is quite low compared to fossil fuel sources. To store the energy contained in just 3.78 liters (one gallon) of petroleum gasoline (oil), in a PHS system, it requires 208 197 liters of water pumped 221 meters high (Greenblatt et al. 2012), which could then be released back into the hydroelectric turbine.

Establishing an operating PHS station with an elevated supporting dam is logistically difficult. It cannot be positioned just anywhere. Very specific requirements are needed for the site if the hydroelectric system is to function. This limits the viability of PHS stations to very few geographical locations.

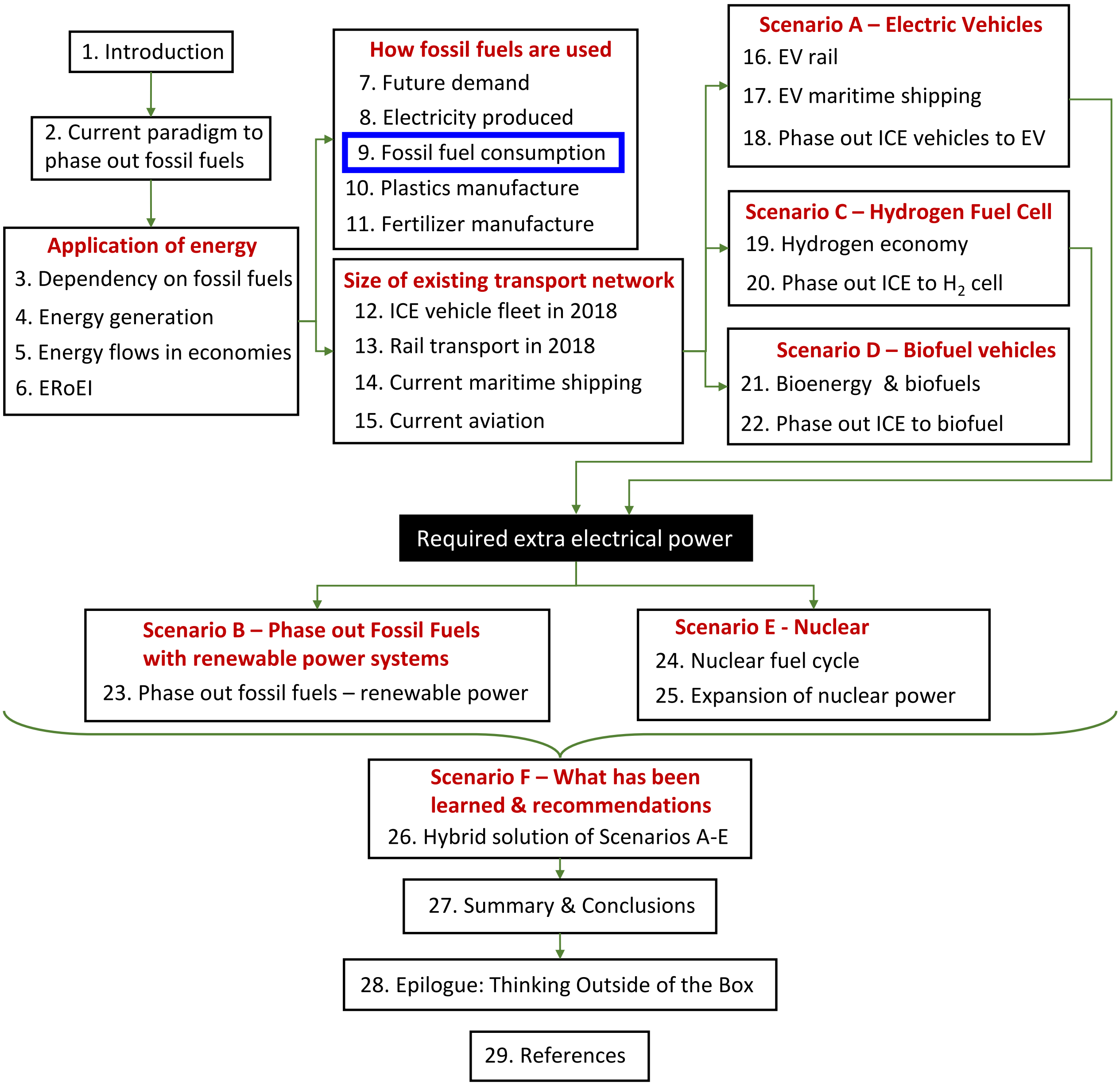
A power storage system that is more flexible in application and is not as limited by geographical location, is a large battery storage power station. This is a type of energy storage power station that uses a group of batteries to store electrical energy. As of 2020, the maximum power of battery storage power plants is an order of magnitude less than pumped storage power plants, the most common form of grid energy storage.

A secure electrical power system needs adequate levels of both system strength and inertia, which to date have been provided by synchronous power generation. System strength relates to the ability of a power system to manage fluctuations in supply or demand while maintaining stable voltage levels (Smil 2016a). Inertia relates to the ability of a power system to manage fluctuations in supply or demand while maintaining stable system frequency.

As of 2020, the largest battery storage power station in the world was the Australian Hornsdale Power Reserve, adjacent to the Hornsdale wind farm, built by Tesla (Parkinson 2017a). The plant is operated by Tesla and provides a total of 129 megawatt-hours (460 GJ) of storage capable of discharge at 100 MW into the power grid. Its 100 MW output capacity is contractually divided into two sections: 70 MW running for 10 minutes and 30 MW with a 3-hour capacity (Weatherill 2017). In construction of the EV batteries themselves, Samsung 21–70-size cells were used (Parkinson 2017b).

9 FOSSIL FUEL CONSUMPTION

Section 9 will examine how the different fossil fuels (oil, gas, and coal) are consumed. This will be done for the United States, Europe (EU-28), China and for the Global ecosystems.



Assessment of the Extra Capacity Required of Alternative Energy Electrical Power Systems to Completely Replace Fossil Fuels

Most energy currently generated is derived from a nonrenewable natural resource as a fuel. We are in essence, a petroleum dominated society (Martenson 2011, Ruppert 2007, Tainter 1988), with a heavy dependency on other fossil fuels like gas and coal. Nuclear power is no different. It requires uranium to be mined then refined. This is a finite resource like any other and has a limit (Zittel *et al* 2013). Renewable power sources like photovoltaic solar require minerals to manufacture solar panels in vast numbers. These minerals are also nonrenewable natural resources.

The different sources of energy are not equal in calorific content. Nor are they used in the same applications. Transfer of energy source to power technology from one resource to another is often not possible. With the exception of oil and to a lesser extent gas, once these energy resources are used to generate power, those power stations have to run at a consistent supply to grid level or suffer degradation in their infrastructure. Oil and gas are flexible in use, coal and nuclear are not.

The global resources consumed to produce energy are shown since the beginning of the industrial revolution in Figure 9.1 and since 1993 in Figure 9.2. Note the majority proportion has always been fossil fuels and still is. Also note that the demand for the all of the energy resources has been increasing consistently in an exponential fashion (as opposed to society becoming more efficient and reducing fossil fuel resources). Note the radical increase in global energy consumption since 1950.

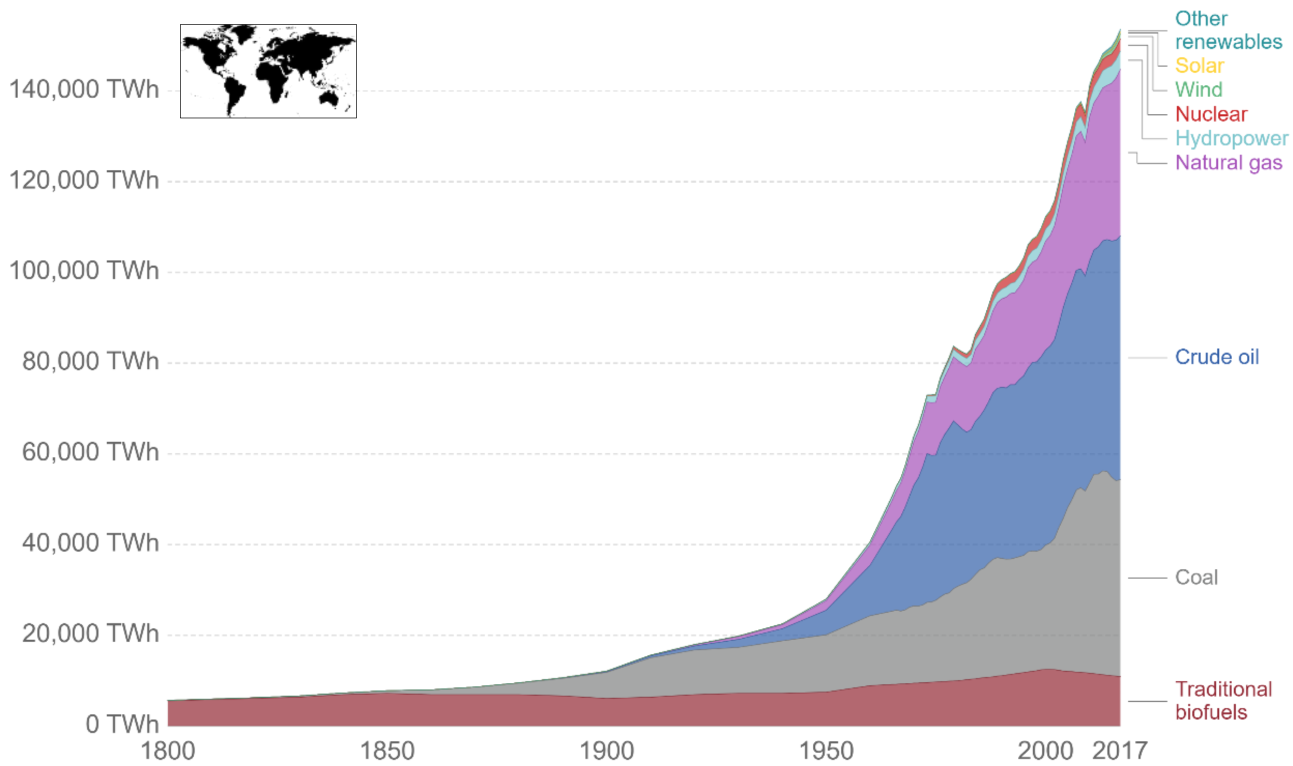


Figure 9.1. Global Primary energy consumption. Units measured in terawatt-hours (TWh) per year. Classification 'other renewables' are renewable technologies not including solar, wind, hydropower and traditional biofuels.
(Source: Our World in Data, BP Statistical review of World Energy 2018)
(World Map Image by Clker-Free-Vector-Images from Pixabay)
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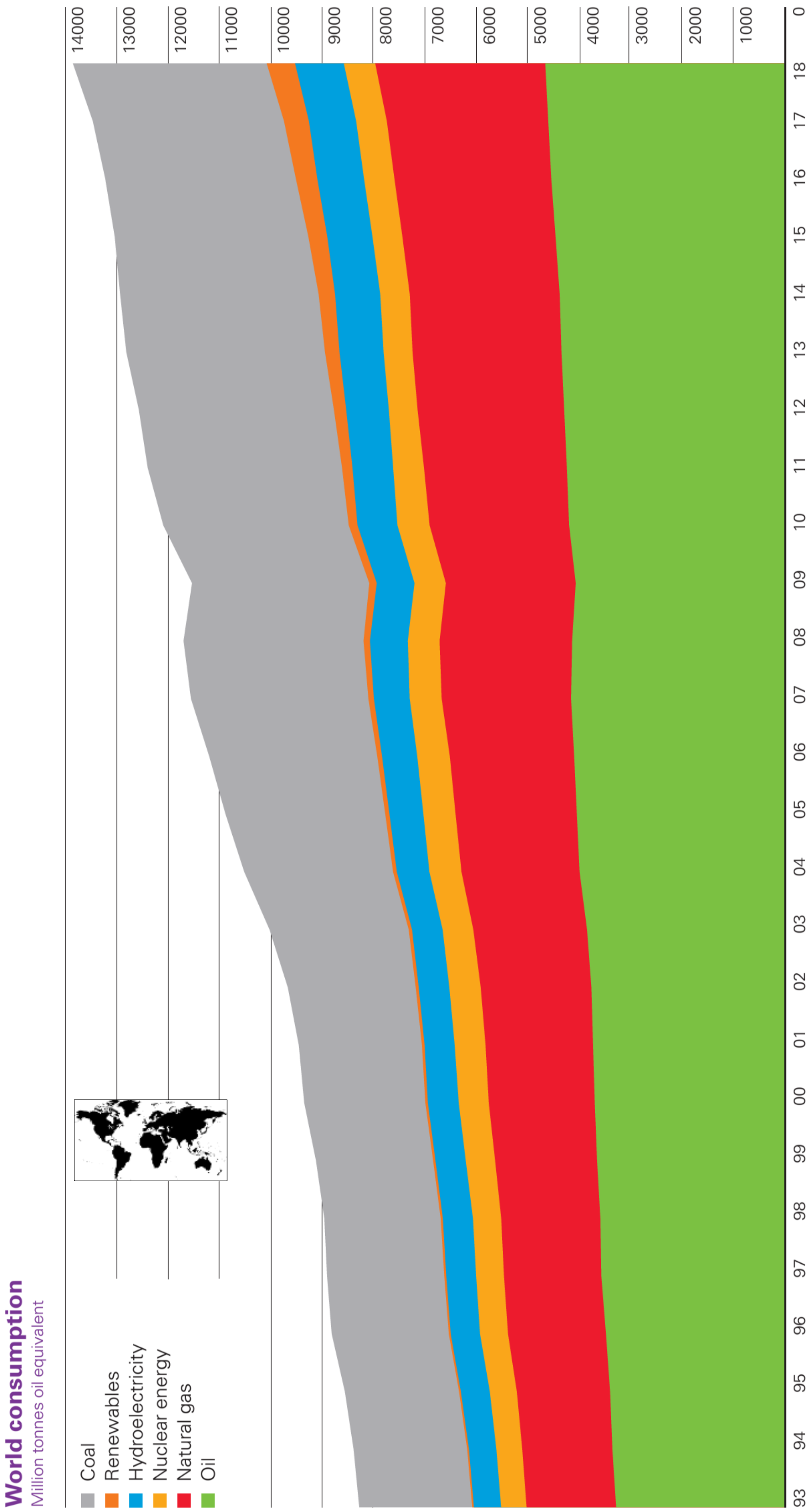


Figure 9.2. World consumption of energy (million tonnes of oil equivalent)
(Source: BP Statistical review of World Energy 2019) (World Map Image by Clker-Free-Vector-Images from Pixabay)

Global energy consumption increased by 2.9% in 2018. Growth was the strongest since 2010 and almost double the 10 year average. The demand for all fuels increased but growth was particularly strong in the case of gas (168 mtoe, accounting for 43% of the global increase) and renewables (71 mtoe, 18% of the global increase) (BP Statistical review of World Energy 2019).

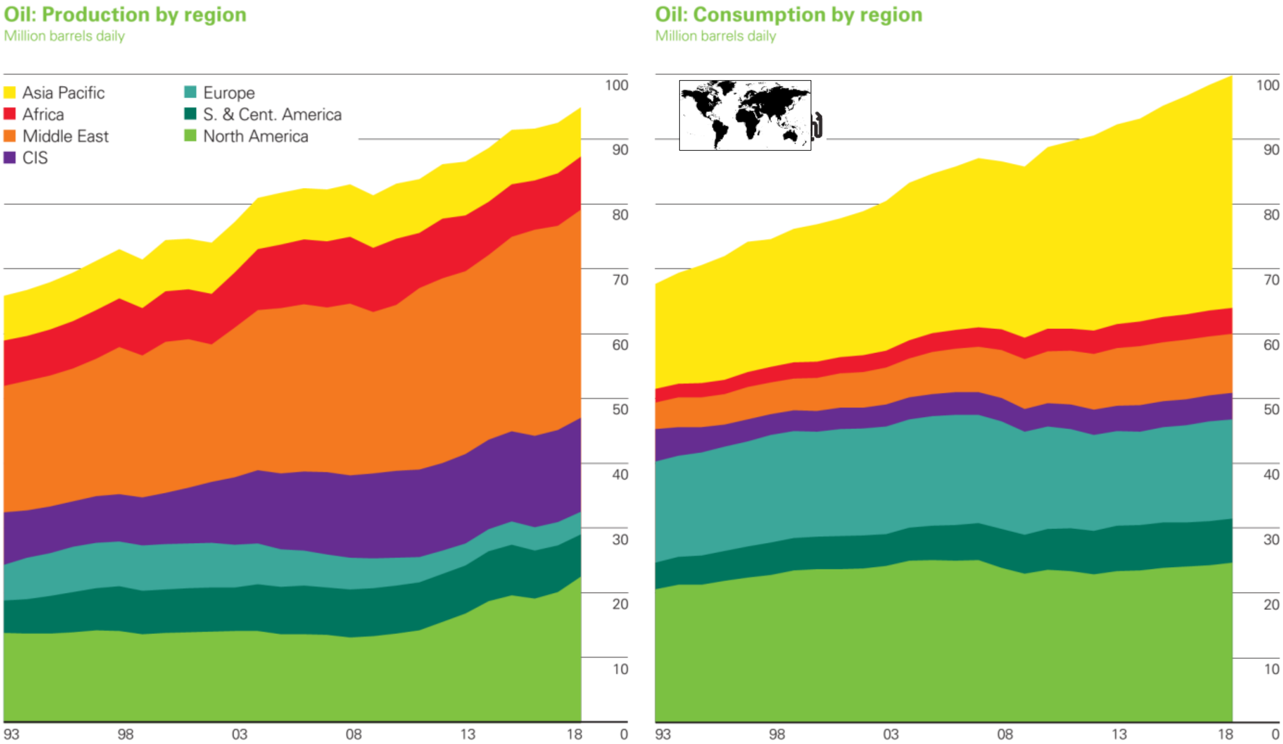
9.1 Oil as a natural resource

Crude oil is a mixture of hydrocarbons that formed from plants and animals that lived millions of years ago. Crude oil is a fossil fuel, and it exists in liquid form in underground pools or reservoirs, in tiny spaces within sedimentary rocks, and near the surface in tar (or oil) sands. Petroleum products are fuels made from crude oil and other hydrocarbons contained in natural gas. Petroleum products can also be made from coal, natural gas, and biomass. Table 9.1 shows the global consumption and production of oil, by geographic region and also by major economy.

Table 9.1. Global oil reserves, production, and consumption
(Source: Appendix C, BP Statistical review of World Energy 2019)

Geographic Region	Proven Reserves (Thousand Million Barrels)	Proven Reserves (Thousand Million Tonnes)	Production (Thousand Barrels a Day)	Production (Million Tonnes)	Consumption (Thousand Barrels a Day)	Consumption (Million Tonnes of Oil Equivalent)
Global	1 729,8	244,1	94 718	4 474,2	99 843	4 662,1
Total North America	236,7	35,4	22 587	1 027,1	24 714	1 112,5
Total Central & South America	325,1	51,1	6 537	335,1	6 795	315,3
Total Europe	14,3	1,9	3 523	162,9	15 276	742,0
Commonwealth of Independant States	144,7	19,6	14 483	709,1	4 099	193,5
Middle East	836,1	113,2	31 762	1 489,7	9 136	412,1
Total Africa	125,3	16,6	8 193	388,7	3 959	191,3
Total Asia Pacific	47,6	6,3	7 633	361,6	35 863	1 695,4
Nations						
United States	61,2	7,3	15 311	669,4	20 456	919,7
China	25,9	3,5	3 798	189,1	13 525	641,2
European Union	4,8	0,6	1 533	72,7	13 302	646,8
Russian Federation	106,2	14,6	11 438	563,3	3 228	152,3

Since the comparatively modest beginnings of the oil industry in the mid-19th century, petroleum has risen to global prominence. The first oil had actually been discovered by the Chinese in 600 B.C. and transported in pipelines made from bamboo (Clark 2016). The start of the industrial use of oil in context of how it is used currently happened in 1859 with the discovery of oil in Pennsylvania (United States) and the Spindletop discovery in Texas in 1901 (Tarbell 2015). Petroleum as an energy resource soon proved much more adaptable and flexible than coal. Additionally, the kerosene that was refined originally from crude oil provided a reliable and relatively inexpensive alternative to “coal-oils” and whale oil for fueling lamps. Most of the other products were discarded.



Global oil production increased by 2.2 million b/d in 2018. Growth was heavily concentrated in the US (2.2 million b/d), Canada (410,000 b/d) and Saudi Arabia (390,000 b/d) while oil production declined sharply in Venezuela (-580,000 b/d) and Iran (-310,000 b/d). OPEC production declined by 330,000 b/d while non-OPEC production increased by 2.6 million b/d. Oil consumption in 2018 grew by an above average 1.4 million b/d. China (680,000 b/d) and the US (500,000 b/d) accounted for the majority of this year's growth.

Figure 9.3. Global oil production and consumption by region
(Source: BP Statistical Review of World Energy 2019) (World Map Image by Clker-Free-Vector-Images from Pixabay)

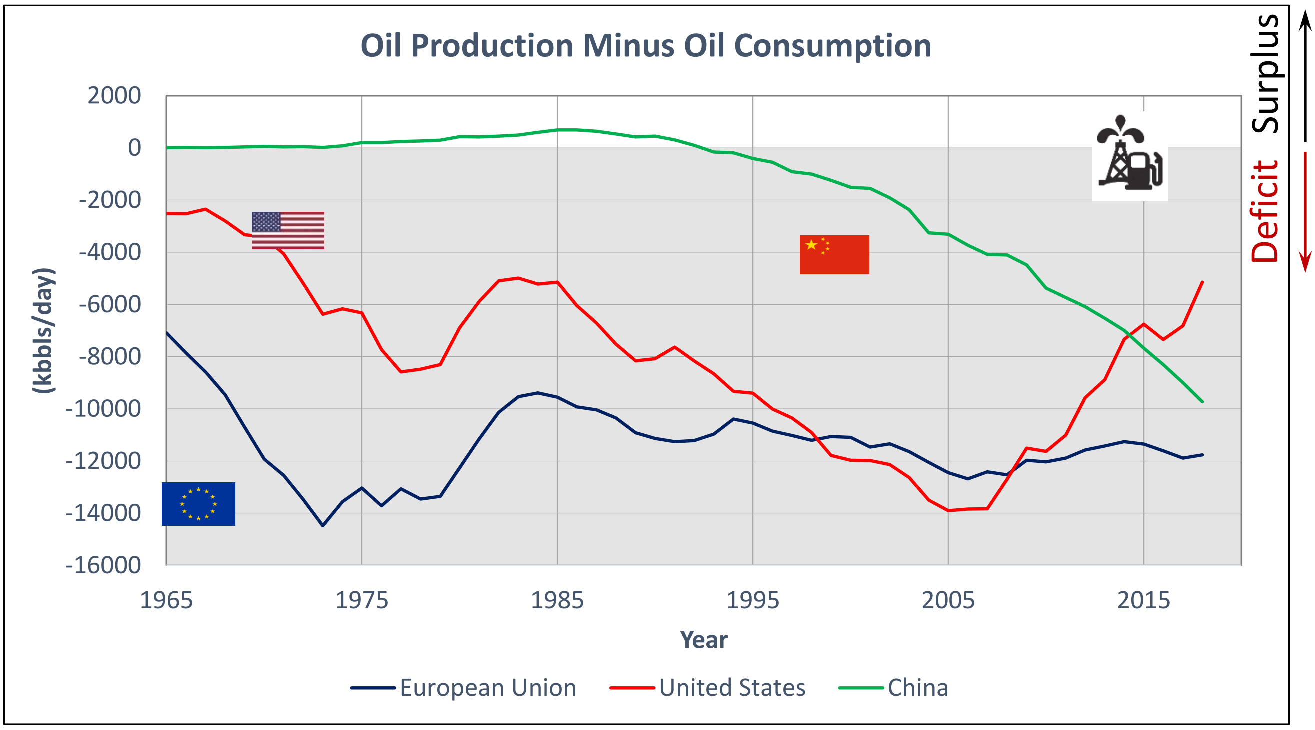


Figure 9.4. The net dependency of EU, US and China on oil imports
(Source: data from BP Statistical Review of World Energy 2019 and BP Statistical Review of World Energy 2011)

Figure 9.4 shows the yearly consumption of oil subtracted from the production of oil for the three largest economies, the United States, European Union and China. Europe is heavily dependent on crude oil imports (a deficit of 11 769 kbbls/day in 2018 or 88.5% of EU demand). The United States is a net importer of crude oil, in spite of the success of the tight oil plays being developed since 2006 (shown as the sharp upward movement from 2006 in Figure 9.4). The United States deficit of crude oil in 2018 was of 5 145 kbbls/day in 2018 or 25.2% of U.S. demand. China was a net exporter of crude oil and was self-sufficient until 1993. Since then, China has become heavily dependent on crude oil imports (a deficit in 2018 of 9 727 kbbls/day, or 72% of Chinese demand). This is highly relevant for the discussion in this report. On one hand, China now represents the bulk of the real economy (similar to the US position in 1944 when the Bretton-Woods agreement was signed). Oil has can be seen correlates with the ability for an economy to do useful physical work (the real economy). The data for Figure 9.4 is shown in Appendix C.

The three economies shown in Figure 9.4 represent 65% of the global GDP in 2018 (Global GDP in 2018 was 85.8 trillion, where the European Union's GDP was estimated to be $18.8 trillion (nominal) in 2018, representing ~22% of global economy (Nominal global GDP), United States GDP: $21.4 trillion, or 25% of global, China GDP: $15.5 trillion, or 18.1% of Nominal global GDP. Source: World Bank). This means that the stability of economies for 65% of world GDP is dependent on oil imports. This shows how fragile the energy system is and how close to inelastic in oil supply the global system could become.

With the technological breakthroughs of the 20th century, oil emerged as the preferred energy source. The key drivers of that transformation were the electric light bulb and the automobile. Automobile ownership and demand for electricity grew exponentially and, with them, the demand for oil.

The internal combustion (IC) engine has been the dominant prime mover in our society since its invention in the last quarter of the 19th century (Heywood 1988). Its purpose is to generate mechanical power from the chemical energy contained in the fuel and released through combustion of the fuel inside the engine. It is this specific point, that fuel is burned inside the work-producing part of the engine.

Internal combustion engines are used in applications ranging from marine propulsion and power generating sets with capacity exceeding 100 MW to hand-held tools where the power delivered is less than 100 W (Heywood 1988). This implies that the size and characteristics of today's engines vary widely between large diesels having cylinder bores exceeding 1,000 mm and reciprocating at speeds as low as 100 rpm to small gasoline two-stroke engines with cylinder bores around 20 mm. Within these two extremes lie medium-speed diesel engines, heavy-duty automotive diesels, truck and passenger car engines, aircraft engines, motorcycle engines and small industrial engines. From all these types, the passenger car gasoline and diesel engines have a prominent position since they represent, by far, the largest volume of produced engines in the world; as such, their influence on social and economic life is of paramount importance.

Figure 9.5. Internal combustion engines power most trucks and automobiles
(Source: Image by Monika Neumann LHS and Jan-Marco Gessinger RHS from Pixabay)

Initially, kerosene, used for lighting and heating, was the principal product derived from petroleum. However, the development of drilling technology for oil wells in mid-19th century America put the petroleum industry on a new footing, leading to mass-consumption of petroleum as a highly versatile fuel powering transportation in the form of automobiles, ships, airplanes and so on, applied to generate electricity, used for heating and to provide hot water supplies. By 1919, gasoline sales exceeded those of kerosene. Oil-powered ships, trucks and tanks, and military airplanes in World War One proved the role of oil as not only a strategic energy source, but also a critical military asset.

After crude oil is removed from the ground, it is sent to a refinery where different parts of the crude oil are separated into useable petroleum products (Figure 9.6). These petroleum products include gasoline, distillates such as diesel fuel and heating oil, jet fuel, petrochemical feedstocks, waxes, lubricating oils, and asphalt. On average, 44.4% of petroleum becomes gasoline (Source: EIA). There really are no waste products from petroleum. The lighter chemicals are natural gas, liquefied petroleum gas (LPG), jet fuel, and kerosene. The heavier products are used for the manufacture of lubricants, plastics, and asphalt. In addition, many less valuable products can be chemically converted into more saleable compounds.

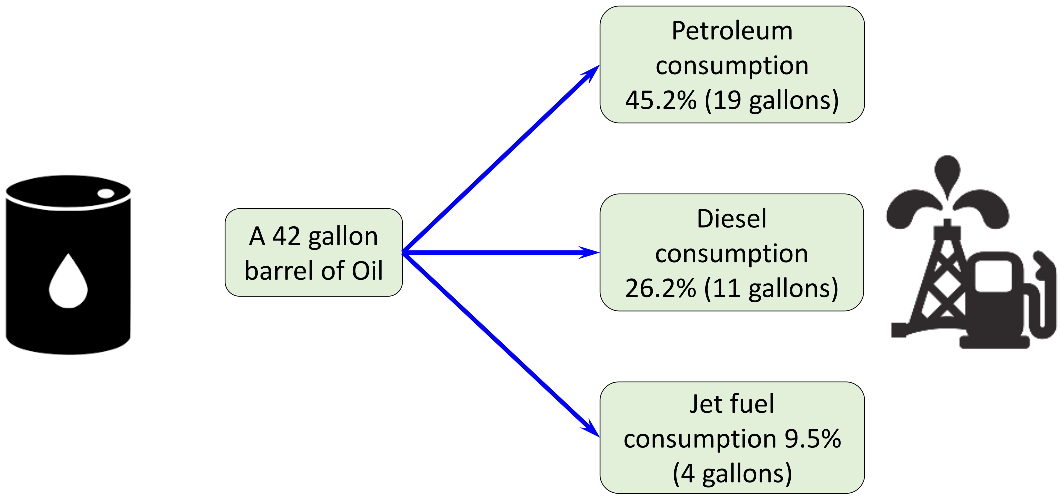


Figure 9.6. Refining oil into industrially useful products (Source: data from EIA –Refining of crude oil)

The most common use of petroleum now is in the internal combustion engine, used across all industries, especially transport. Petroleum products are used to propel vehicles, to heat buildings, and to produce electricity. In the industrial sector, the petrochemical industry uses petroleum as a raw material (a feedstock) to make products such as plastics, polyurethane, solvents, and hundreds of other intermediate and end-user goods. Not all fuels are equal in terms of energy density. Oil based products are the most calorifically dense fuel currently used in the transport sector.

Petroleum products are made from crude oil and from natural gas processing, including gasoline, distillate fuels (mostly diesel fuel), jet fuel, residual fuel oil, and propane. Biofuels refer to ethanol and biodiesel. The form these uses take are:

- Gasoline is used in cars, motorcycles, light trucks, and boats. Aviation gasoline is used in many types of airplanes.
- Distillate fuels (diesel) are used mainly by trucks, buses, and trains and in boats and ships.
- Jet fuel is used in jet airplanes and some types of helicopters.
- Residual fuel oil is used in ships.
- Biofuels are added to gasoline and diesel fuel.
- Natural gas, as compressed natural gas and liquefied natural gas, is used in cars, buses, trucks, and ships. Most of the vehicles that use natural gas are in government and private vehicle fleets.
- Natural gas is also used to operate compressors to move natural gas in pipelines.
- Propane (a hydrocarbon gas liquid) is used in cars, buses, and trucks. Most of the vehicles that use propane are in government and private vehicle fleets.
- Electricity is used by public mass transit systems and by electric vehicles.

Figure 9.7 shows the thermal chemical energy in petroleum products.

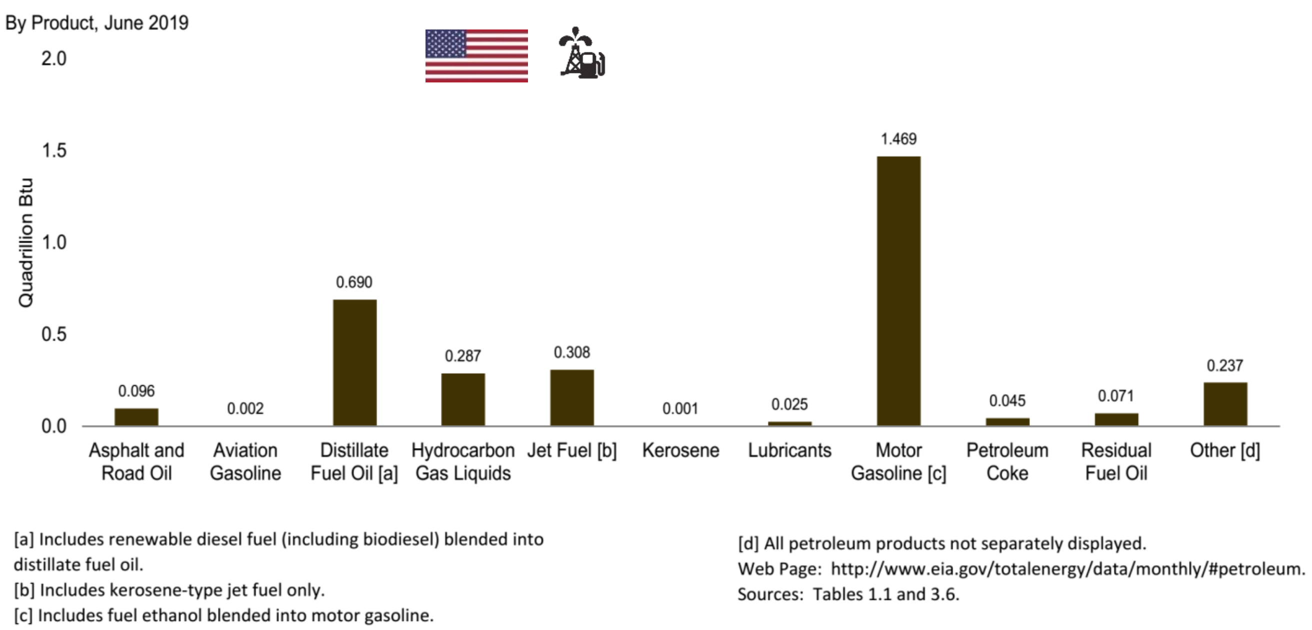


Figure 9.7. The thermal heat content of different petroleum products in the United States
(Source: EIA Monthly Energy Review, Tables 1.1 and 3.6)

Table 9.2. Refined Petroleum Products (Source: OECD Data Statistics Database, Table 4 and Table 5)

Fuel	Global Consumption in year 2018	Energy Content of Fuel	ICE Technology	Energy Efficiency of ICE Technology
Crude Oil	4662.1 Mtoe	41.87 MJ/kg	N/A	
Diesel Fuel Oil	10 439 million barrels	45.6 MJ/kg	Diesel Engine	35-42%
Heavy Fuel Oil (Maritime)	194 499 kt	41.8 MJ/kg	Diesel Engine	35-42%
Petrol (Gasoline)	9 307.5 million barrels	46.4 MJ/kg	Petrol Engine	25-50%
Jet Fuel	2 260 million barrels	43.0 MJ/kg	Jet Turbine	36-48%

9.2 Petroleum products in Europe

The European Union relied on net imports (imports minus exports) for 86.7 % of the oil products consumed in 2017. The dependency on foreign petroleum in the last few years is at its peak, the highest rate being recorded in 2015 (89.2 %). The lowest import dependency for oil was observed in 1995, namely a rate of 73.9 %.

Table 9.3. Net imports pf selected petroleum products, EU-28, years 1990-2017
(Source: Eurostat, online data code nrg_bal_c)

(million tonnes of oil equivalent)

	1990	1995	2000	2005	2010	2015	2016	2017
Crude oil & Natural gas liquids (NGL)	469.1	470.2	499.7	569.9	527.2	534.2	525.5	541.2
Refinery feedstocks	33.0	21.6	11.2	13.7	13.2	15.9	15.3	14.1
Liquified petroleum gas (LPG)	6.0	5.9	5.6	6.6	9.0	13.5	13.5	12.9
Naphtha	13.6	12.9	10.4	12.3	13.7	12.7	11.9	15.8
Motor gasoline	-8.8	-14.7	-16.8	-39.1	-45.2	-55.8	-55.6	-57.9
Kerosene-type jet fuel	-2.8	-2.2	4.8	13.8	16.0	17.4	18.3	18.3
Gas oil and diesel oil	13.4	-0.1	8.0	25.0	27.7	25.4	28.3	24.1
Fuel oil	6.2	13.1	1.3	-8.8	-3.0	-16.6	-15.3	-15.7
All other products	0.2	3.3	8.1	10.3	2.9	-5.8	-6.9	-9.5

Import dependency on oil is calculated as the ratio of net imports (imports minus exports) to gross inland energy consumption (but including international maritime bunkers) of crude oil and petroleum products. Positive values over 100 % indicate a stock build, while negative dependency rates indicate a net exporter country.

To determine the industrial sectors that are dependent on petroleum product imports, Eurostat developed the concept of Sectorial oil dependency rate. Sectoral oil dependency refers to the ratio of oil consumption in a specific sector to the total fuel consumption of that sector. The dependence on oil for transport and for fishing is the highest of all sectors, although both decreased in 2017 compared with 1990 (see Table 9.4). However, the industry sector, residential and services have decreasing dependency rates towards 11-10 % dependency on oil. Note in Table 9.4 that there is approximately a 50% in residential oil dependency between 1995 and 2017.

Table 9.4. Sectoral oil dependency, EU-28, years 1990-2017 (Source: Eurostat, online data code nrg_bal_c)

(%)

	1990	1995	2000	2005	2010	2015	2016	2017
Consumption in Energy Sector	45.2	46.2	45.2	45.0	40.6	38.8	38.9	38.0
Final Non-energy Consumption	82.6	85.3	85.2	86.0	85.1	83.4	83.6	83.5
Industry sector	17.7	18.1	16.9	15.1	13.3	11.2	10.9	10.3
Transport sector	97.7	97.7	97.6	96.5	93.6	92.9	93.1	92.7
Residential	22.1	21.7	19.8	17.7	13.6	12.2	11.5	11.2
Fishing	99.7	99.9	96.3	94.3	88.9	88.8	87.5	86.8
Agriculture/Forestry	59.9	62.3	62.0	60.3	54.7	54.1	52.5	53.0
Services	24.6	21.5	18.6	16.2	12.0	10.6	10.6	10.4

Imports of crude oil are by far the most important component of trade in oil statistics. The imports of crude oil are complemented by imports of already domestically manufactured petroleum products such as:

- Gas/diesel oil (24.1 million tonnes in 2017)
- Kerosene type jet fuel (18.3 million tonnes)
- Naphtha (15.8 million tonnes)
- Liquefied petroleum gas (12.9 million tonnes)

The EU-28 also exports manufactured petroleum products to third countries. In 2017, EU-28 exported 57.9 million tonnes of motor gasoline and 15.7 million tonnes of fuel oil. Trade of other petroleum products (lubricants, bitumen, other hydrocarbons, etc.) is of a smaller magnitude and in 2017 resulted in net exports of 9.5 million tonnes (Source: Eurostat). Figures 9.8 to 9.14 show the petroleum product import, use and consumption in Europe.

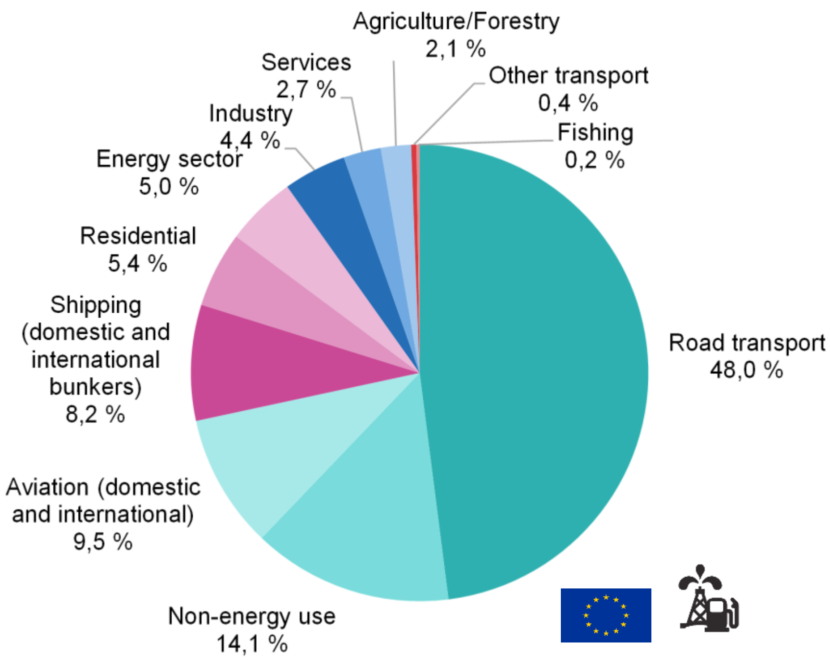


Figure 9.8. Consumption of oil in selected sector, EU-28, 2017
(Source: Eurostat) (Copyright License: https://creativecommons.org/licenses/by-nc-sa/4.0/)

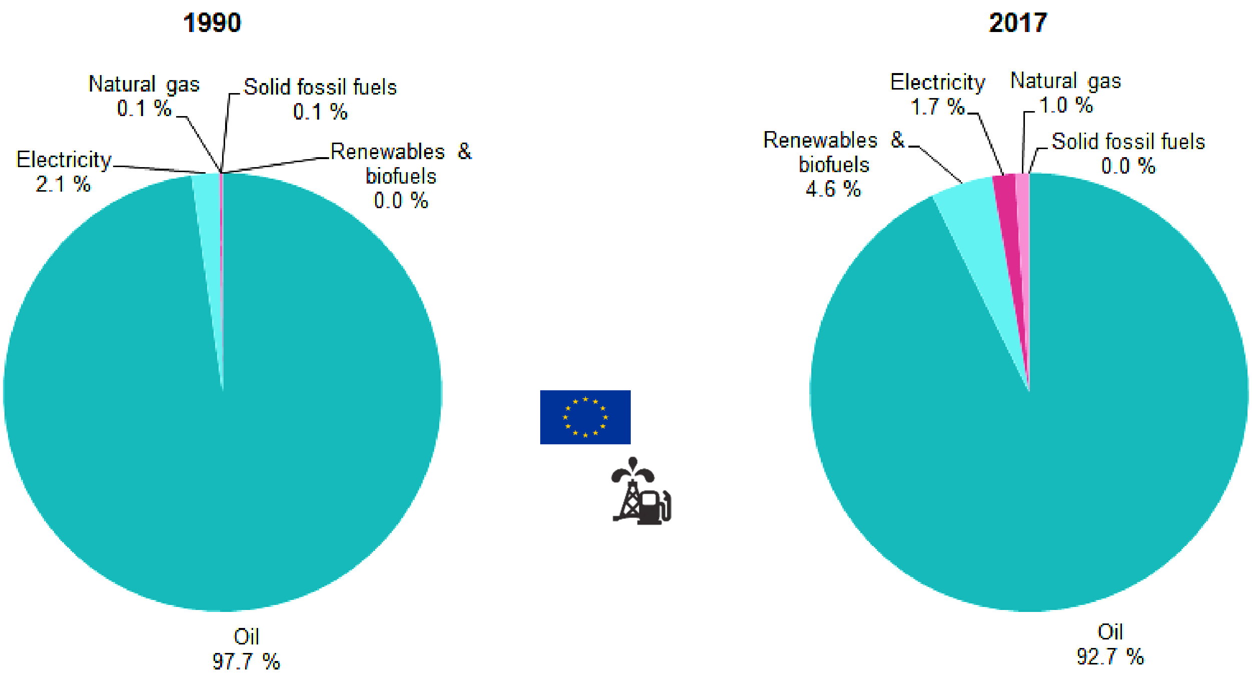


Figure 9.9. Use of fuels in transport, EU-28, 1990 and 2017
(Source: Eurostat – online data code: nrg_bal_c)

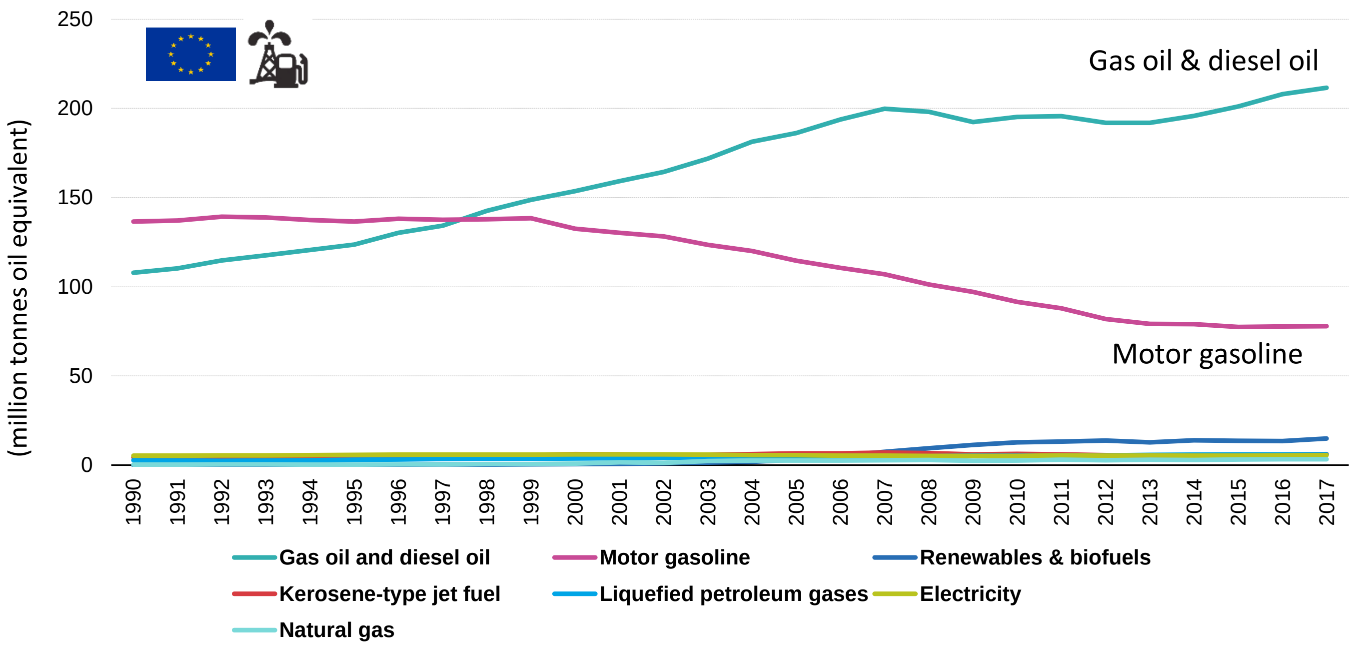


Figure 9.10: Use of fuels in transport, EU-28, 1990-2017
(Source: Eurostat) (Copyright License: https://creativecommons.org/licenses/by-nc-sa/4.0/)

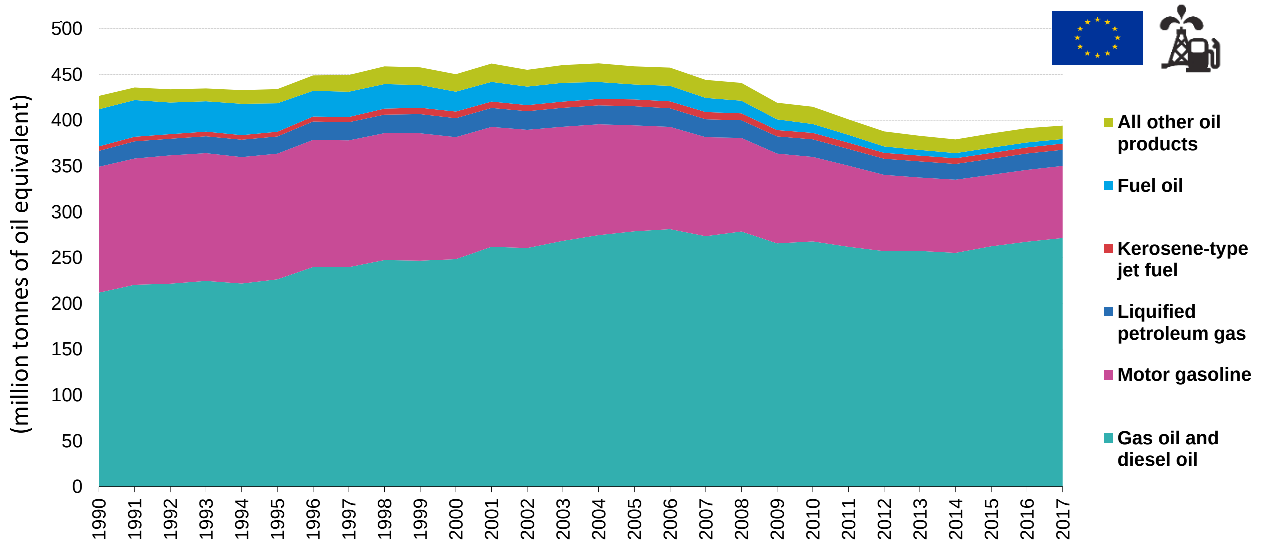


Figure 9.11. Final energy consumption of petroleum products, EU-28, 1990-2017
(Source: Eurostat – online data code: nrg_bal_c) (Copyright License: https://creativecommons.org/licenses/by-nc-sa/4.0/)

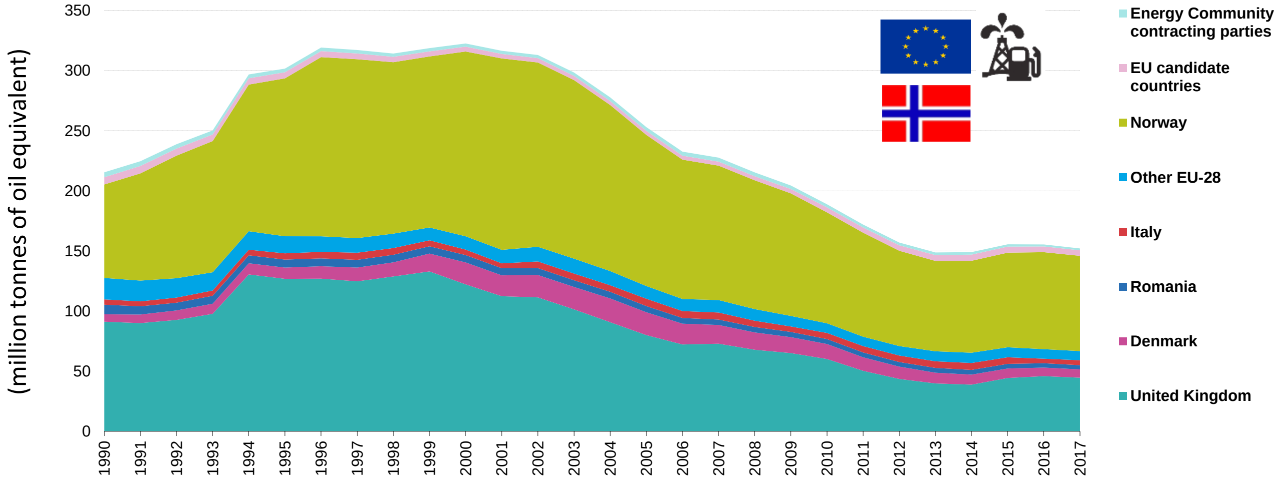


Figure 9.12. Primary production of crude oil EU-28, 1990-2017
(Source: Eurostat – online data code: nrg_bal_c) (Copyright License: https://creativecommons.org/licenses/by-nc-sa/4.0/)

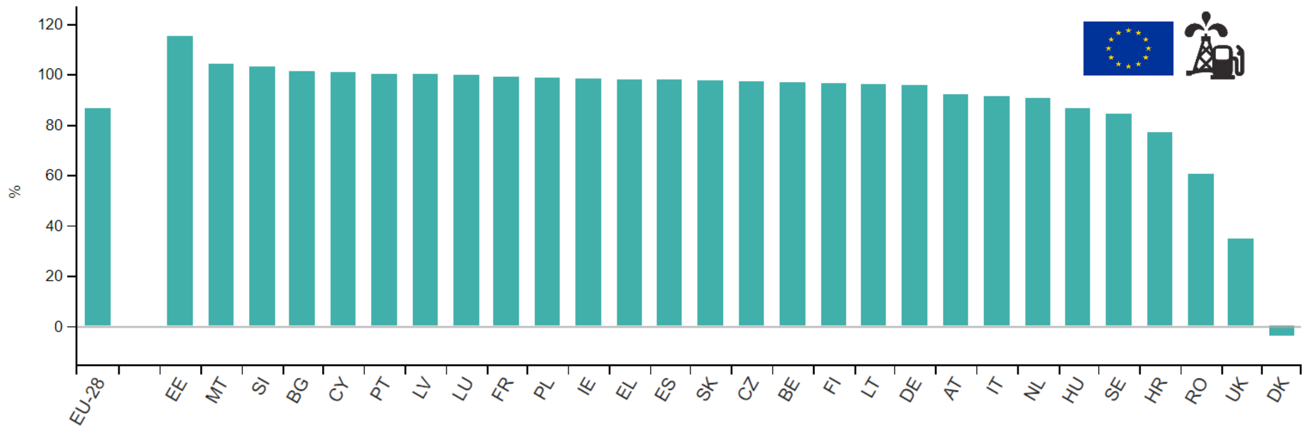


Figure 9.13. EU-28 Oil import dependency in 2017 (% of net imports in gross available energy based on tonnes of oil equivalent)
(Source: Eurostat – online data code: nrg_ind_id) (Copyright License: https://creativecommons.org/licenses/by-nc-sa/4.0/)

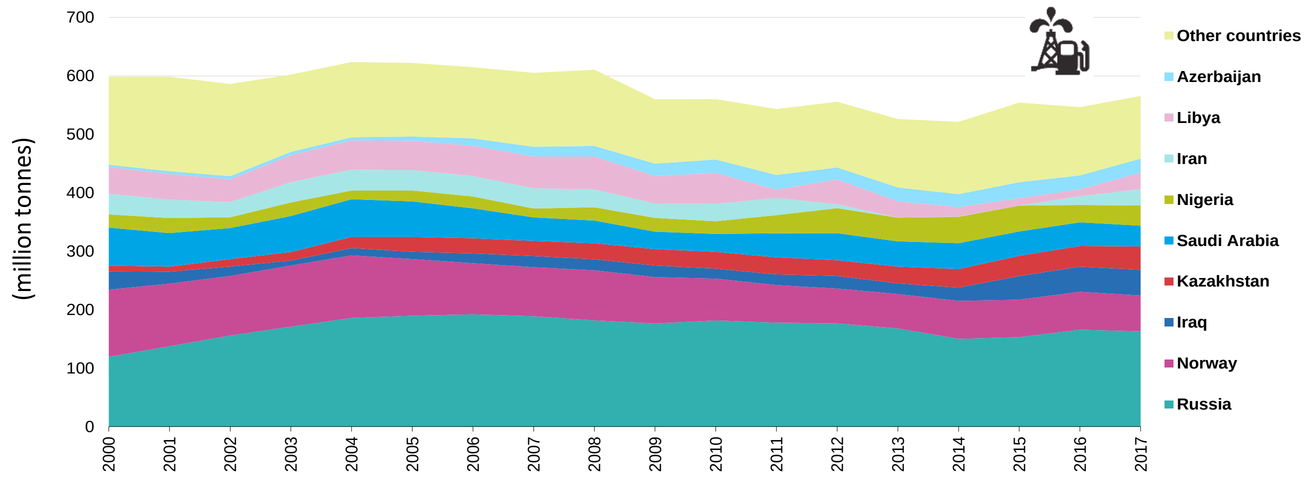


Figure 9.14. Crude oil imports by country of origin, EU-28, 2000-2017
(Source: Eurostat – online data code: nrg_bal_c) (Copyright License: https://creativecommons.org/licenses/by-nc-sa/4.0/)

9.3 Petroleum products in the United States

For decades, the United States was the primary global consumer of oil and petroleum products. Currently the U.S. accounts for 16.6% of world oil consumption, where China accounts for 23.6% (BP World Energy Statistical Review 2019). The U.S. is used as an example because the American institutions EIA and IEA collect excellent quality data that is public domain. This can be used as a proxy for the rest of the world in context of all developing countries that are assumed to want to evolve into something like current Western Culture with a corresponding economic complexity.

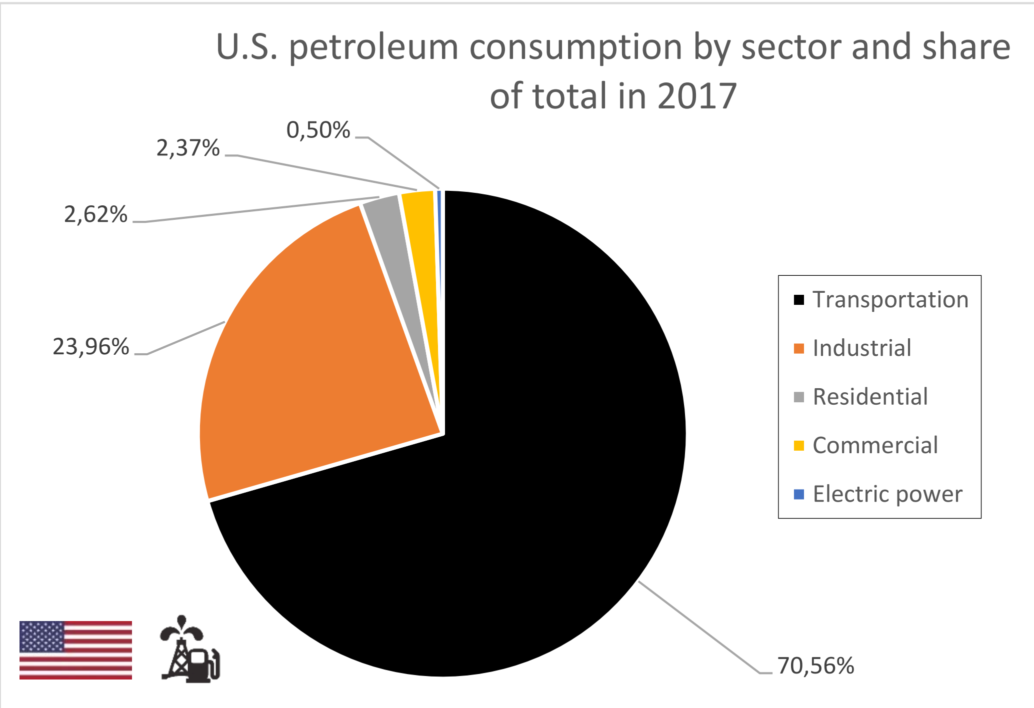


Figure 9.15. U.S. petroleum consumption by sector and share of total in 2017
(Source: EIA – Crude Oil and Petroleum products)
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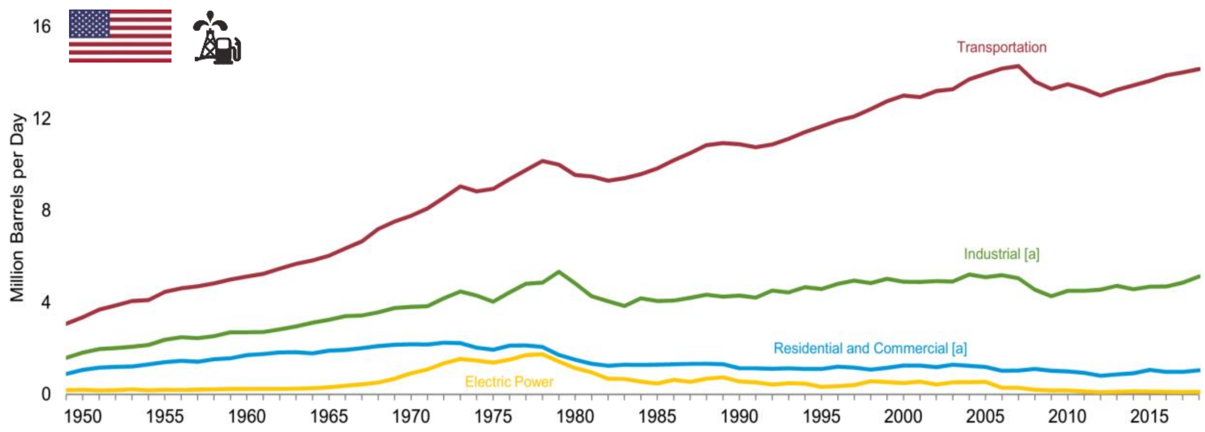

Figure 9.16. Petroleum product consumption by sector in the United States 1949 -2018
(Source: U.S. Energy Information Administration – monthly energy review July 2019)
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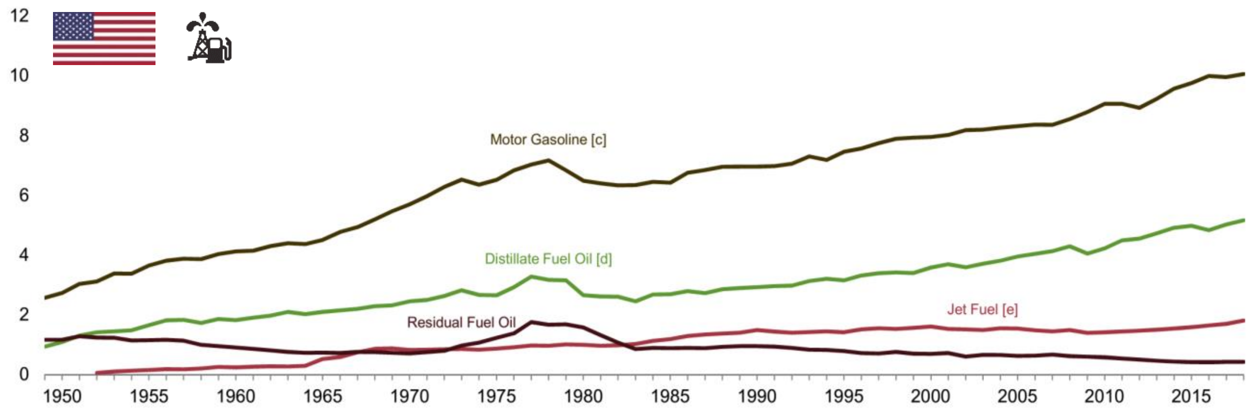

Figure 9.17. Petroleum net production for selected products in the United States
(Source: U.S. Energy Information Administration – monthly energy review July 2019)
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In 2018, of the approximately 7.5 billion barrels of total U.S. petroleum consumption, 46% was motor gasoline (includes fuel ethanol), 20% was distillate fuel (heating oil and diesel fuel), and 8% was jet fuel (Source: EIA- Petroleum products and their applications). These petroleum products accounted for about 92% of the total U.S. transportation sector energy use. Biofuels, such as ethanol and biodiesel, contributed about 5%. Natural gas accounted for about 3%, most of which was used in natural gas pipeline compressors. Electricity provided less than 1% of total transportation sector energy use and nearly all of that in mass transit systems. Distillate fuels, mostly diesel, accounted for 23%, and jet fuel for 12%. Where:

- In 2018, gasoline was the dominant transportation fuel in the United States, followed by distillate fuels (mostly diesel fuel) and jet fuel.
- Gasoline includes aviation gasoline and motor gasoline.
- Motor gasoline includes petroleum gasoline and fuel ethanol added to petroleum gasoline.
- Fuel ethanol includes ethanol (a biofuel) and petroleum denaturants.
- The petroleum component of gasoline (excluding ethanol) accounted for 54% of total U.S. transportation energy use in 2018.

9.4 Gas as a natural resource

Natural gas is a versatile fuel - as well as being used as an efficient energy source in its own right, for heating, cooking, and hot water, it is also a means for electricity production. Gas power stations convert the heat energy from the combustion of natural gas into electricity, which can be used in homes and businesses. Figure 9.18 shows approximate proportions of how gas is used in a developed economy. Figure 9.19 is based on data drawn from the U.S. EIA website. Substitutions for the services other than electric power generation, are not economically viable and would involve more power draw on the electrical grid. Table 9.5 shows the global consumption and production of natural gas.

Table 9.5. Global gas reserves, production, and consumption
(Source: Appendix E, BP Statistical review of World Energy 2019)

Geographic Region	Proven Reserves (Trillion cubic metres)	Annual Production (billion cubic metres)	Production (Million Tonnes of Oil Equivalent)	Annual Consumption (billion cubic metres)	Annual Consumption (Million Tonnes of Oil Equivalent)
Global	196.9	3868.0	3325.7	3848.8	3309.5
Total North America	13.9	1053.9	906.2	1022.3	879.1
Total Central & South America	8.2	176.7	151.9	168.3	144.8
Total Europe	3.9	250.7	215.5	549	472
Commonwealth of Independant States	62.8	831.1	714.6	580.8	499.4
Middle East	75.5	687.3	590.9	553.1	475.6
Total Africa	14.4	236.6	203.4	150	129
Total Asia Pacific	18.1	631.7	543.2	825.3	709.6
Nations					
United States	11.9	831.8	715.2	817.1	702.6
China	6.1	161.5	138.9	283	243.3
European Union	1.1	109.2	93.9	458.5	394.2
Russian Federation	38.9	669.5	575.6	454.5	390.8

Gas is the primary energy resource by heavy industry, especially in areas away from large populations. A gas pipeline would supply gas to a small gas fired power station, which would in turn supply electrical power to an industrial site. Often primary raw material extraction has this profile. Often a mine site, with a smelter or refinery would be sited together to draw power from a single power station, which was built for that purpose.

There are two main types of power stations used to convert natural gas into electricity - open cycle and combined cycle. The most common of the two is open cycle, in which natural gas is burned to produce pressurized gas. This powers a turbine, which is connected to a generator, causing the generator's magnets to spin and create an electrical current.

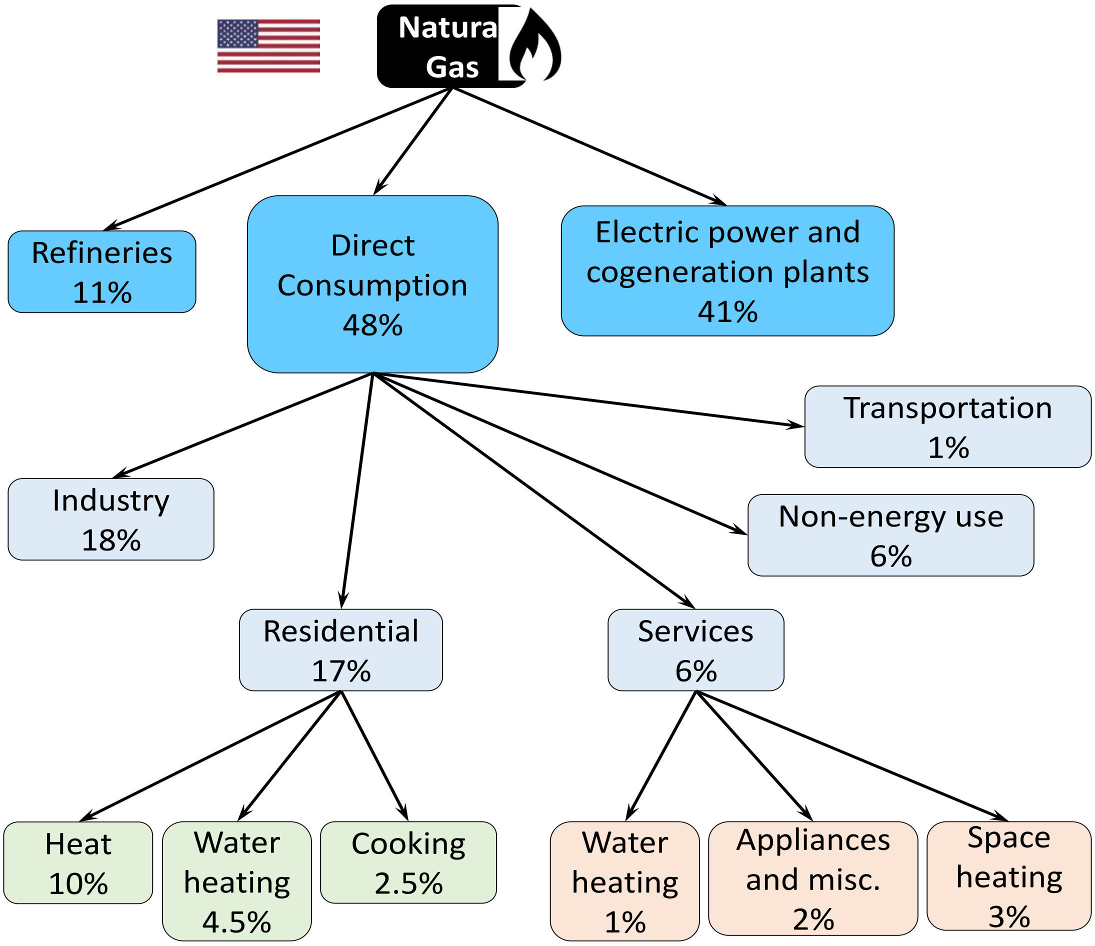

Figure 9.18. Uses of natural gas in the United States 2017
(Source: Using data from U.S. Energy Information Administration, Bentek Energy LLC.)
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In a combined cycle power station, the waste heat from the gas burnt to operate the turbine is used to boil water and create steam, driving a second turbine to produce even more electricity. This allows such power stations to convert as much as 50% of the energy contained in natural gas - far more than the 33% conversion of coal power stations. For this reason, combined cycle gas-fired power stations tend to be used to supply daily base load power, whilst open cycle stations operate during peak demand.

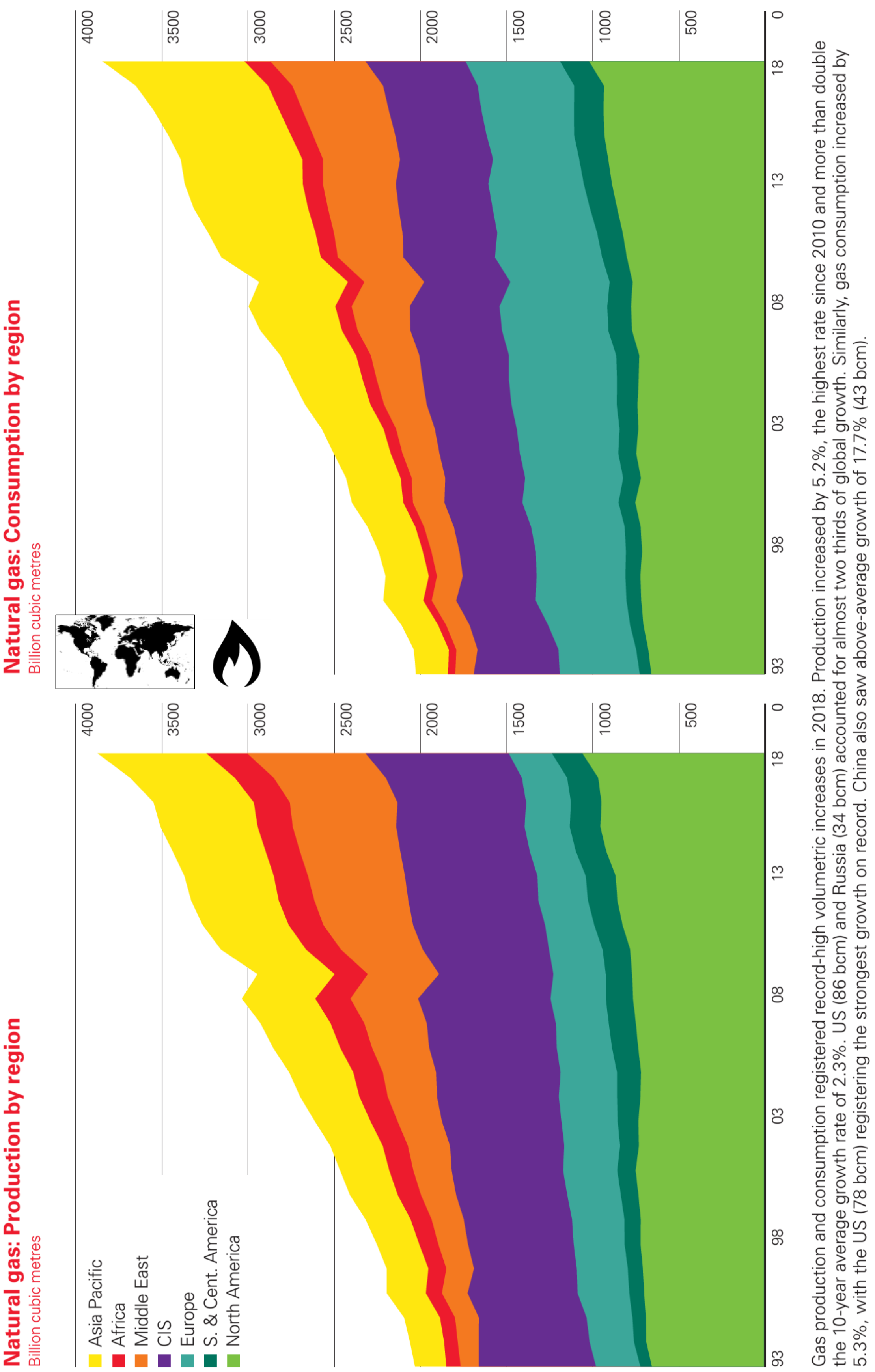

Figure 9.19. Global gas production and consumption by region
(Source: BP Statistical Review of World Energy 2019) (World Map Image by Clker-Free-Vector-Images from Pixabay)

Figure 9.20 shows a list of products that are manufactured from natural gas and what they can be used for. Gas is used extensively in the manufacture of fertilizers and plastics similar to oil.

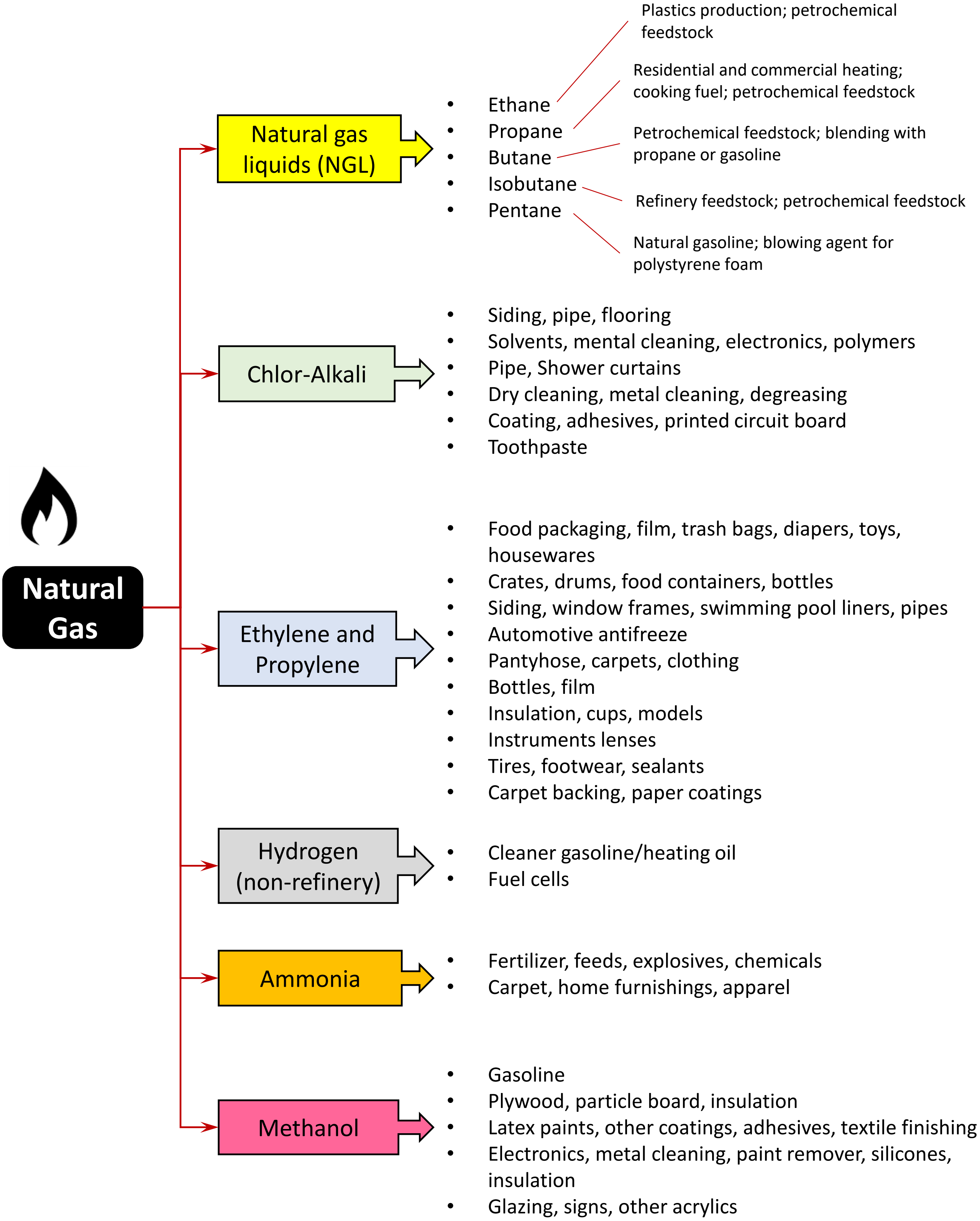

Figure 9.20. Products manufactured from natural gas
(Source: Using data from International Energy Agency IEA, and EIA)

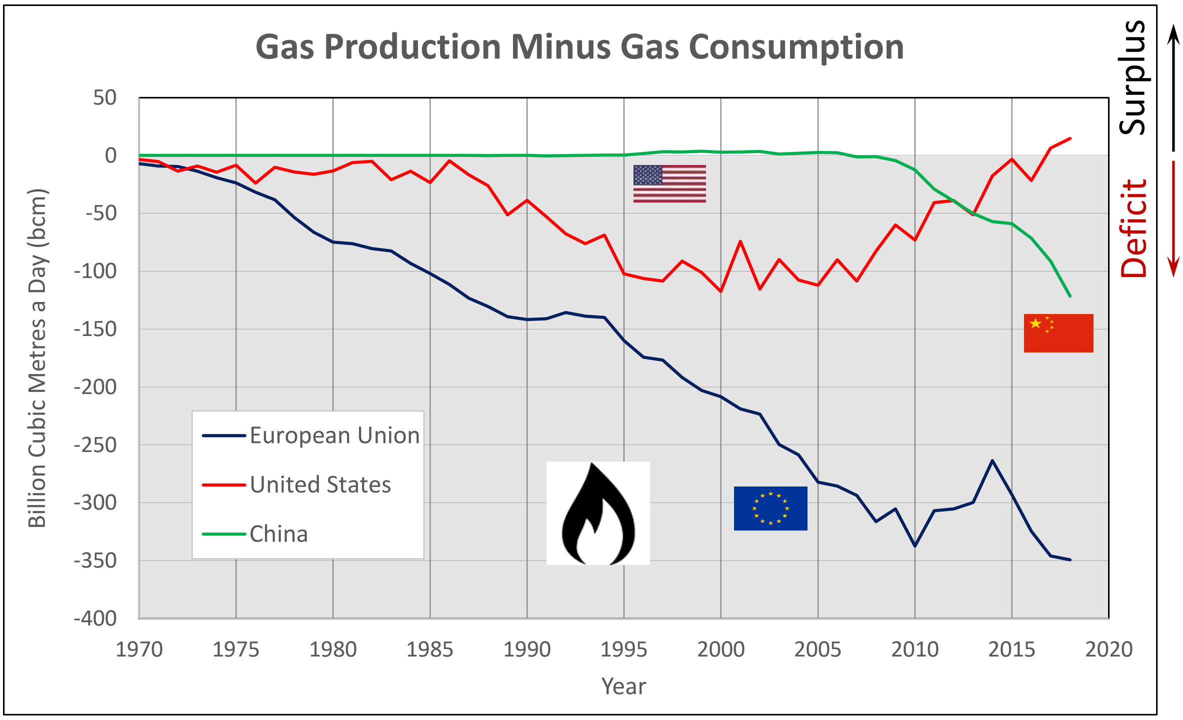

Figure 9.21. The net dependency of EU, US and China on gas imports 1970-2018
(Source: data from BP Statistical Review of World Energy 2019 and BP Statistical Review of World Energy 2011)

Figure 9.21 shows the yearly consumption of gas subtracted from the production of gas for the three largest economies, the United States, European Union and China (representing 65% of global GDP). Europe is clearly heavily dependent on natural gas imports (the 2018 deficit was 349.3 bcm, or 76.2% of EU demand). The United States has become a net exporter of natural gas as an outcome of the success of the fracking shale operations (in 2018, the net export of gas was 14.7 bcm, or 1.8% of US demand). China was self-sufficient until 2007. Since then it has become a net importer of natural gas where the 2018 deficit was 121.5 bcm of natural gas, or 42.9% of demand). The data for Figure 9.21 is shown in Appendix E.

Europe is dependent on gas as an energy source (Figure 9.22), where gas fulfils security and seasonal balancing functions that are not easily replicated by a renewables-based power system. The future for gas in Europe's electricity market depends, in particular, on how services such as flexibility and capacity provision are remunerated and incentivized in a system with increasingly variable power delivery, and how quickly renewables can be added.

Heating is the second most common application for gas. Heating applications can be supplied with a renewable source of energy, but the logistics are much more complex, and the effectiveness is much less efficient. Demand for heat in buildings means gas as an energy source is crucial in the seasonal balancing role that is difficult to replicate using electricity.

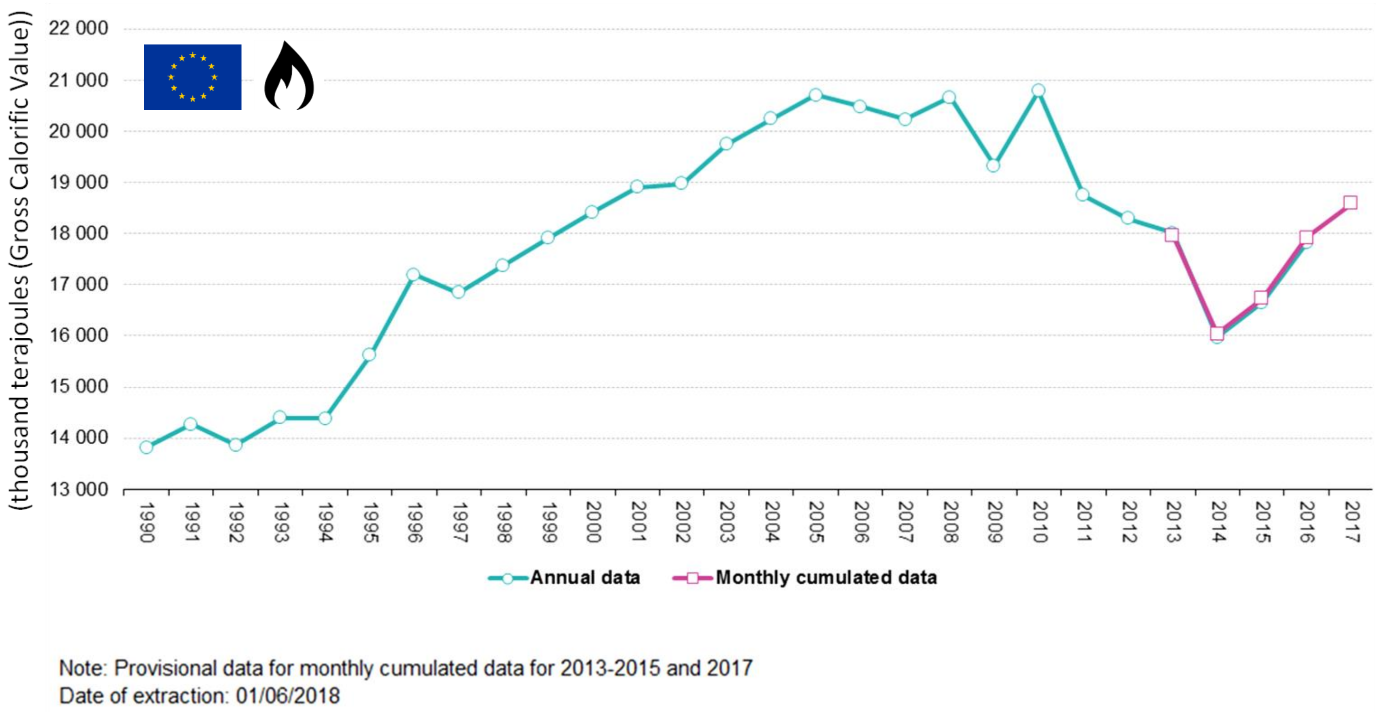

Figure 9.22. Gross inland consumption of natural gas, EU-28, 1990-2017
(Source: Eurostat online data codes: nrg_103m, nrg_103a, nrg_124m, nrg_134m)

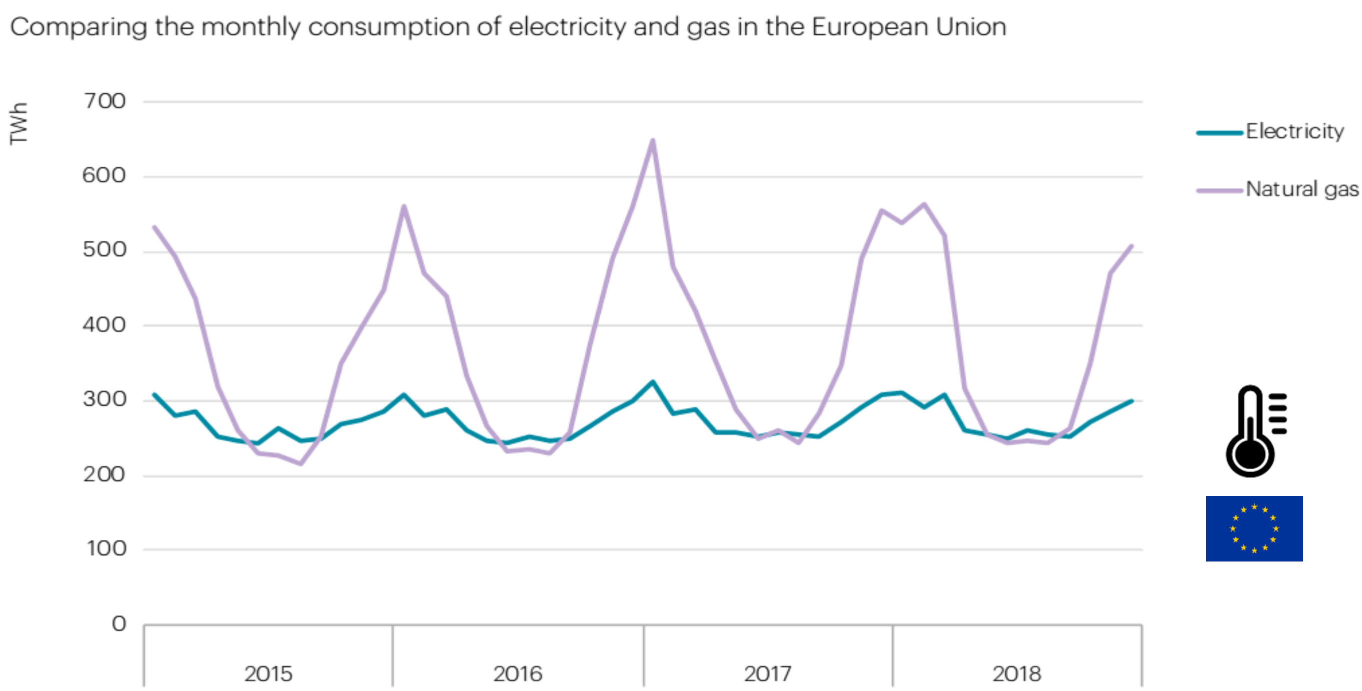

Figure 9.23. Gas infrastructure is sized to meet significant peaks in Europe’s energy service demand
(Source: The Role of Gas in Today’s Energy Transitions, IEA 2019, all rights reserved)

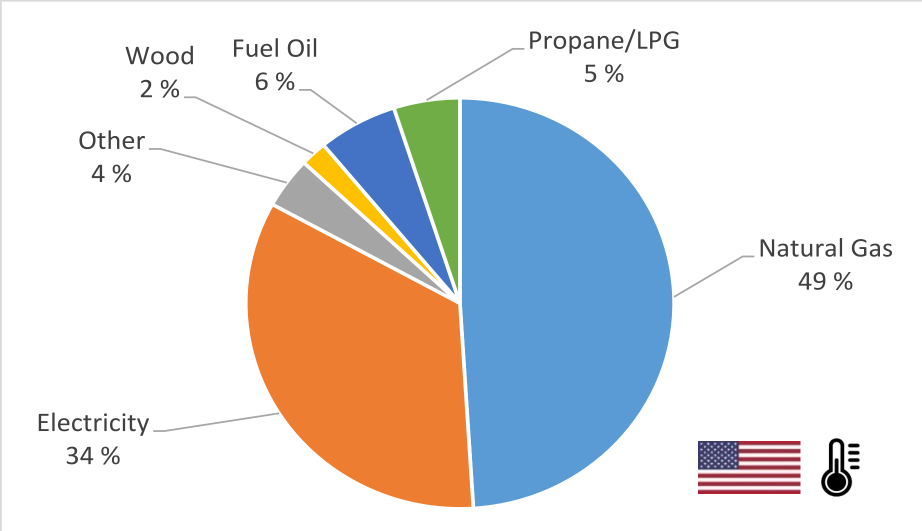

Figure 9.24. Heating of residential buildings in the United Sates
(Source: Data from U.S. Dept. of Energy, Buildings Energy Data Book 2011)
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Figure 9.24 shows the proportion of energy systems used for heating in the United States. Gas accounts for 49% of this demand and direct heating using electricity accounts for 34%. Europe may have a similar profile.

Heating during the winter season is a requirement for society to function in Europe and at these latitudes in general. While seasonal peaks gradually reduce over time thanks to ambitious efficiency policies, the European Union (EU-28) still requires a predicted gas delivery capacity of at least 60 billion cubic meters per month in 2040 to meet normal peak winter load. Europe's gas infrastructure comprises an annual energy delivery capacity of nearly 3.9 trillion cubic meters – nearly twice that of the electricity grid on an energy-equivalent basis. This could be due to the requirement for heating of buildings and the direct use of gas in industrial applications.

Short-term peaks in the demand for gas in the power sector are set to rise in order to help integrate larger shares of renewables. There is, therefore, a strong requirement for gas-based infrastructure for the flexibility and backup capabilities it provides for power systems with high levels of intermittent renewable energy, such as solar and wind.

One of the major advantages of using gas to generate electricity is that gas-fired power stations have extremely quick start-up times, which is why they're often used to meet peak power demands. It takes approximately 10-20 minutes for a gas turbine power station to reach full load capacity, compared to multiple hours for coal power stations and up to two days for nuclear stations. This makes gas very attractive as a flexible solution to meet dynamic demand load.

The cyclic seasonal demand for gas (driven by the need to heat buildings in winter) requires a flexible energy source to service it. Renewable energy sources like wind and solar are intermittent in supply. These two concepts in conjunction will make it very challenging for renewable power sources to replace gas as an energy source. The probable way this would work is multiple very large power storage stations are constructed, which would store power generated in other parts of Europe and/or power generated in the summer season. This stored power would be used in heating applications through the winter season. This solution would be very logistically challenging to achieve with current engineering practices and in the current economic environment.

In 2016, gross inland consumption of natural gas in EU-28 increased by 7.0 % in comparison with 2015, to reach 17 903 thousand terajoules. EA-19 consumption also increased, by 5.8 %, to 12 456 thousand terajoules. The most significant increases in consumption in comparison with 2015 were recorded in Greece (+30.2 %), Sweden (+13.0 %), United Kingdom (+12.9 %), Portugal (+12.4 %) and Ireland (+11.6 %). The biggest falls in consumption compared with 2015 were in Lithuania (-10.9 %), Luxembourg (-7.8 %), Finland (-6.7 %) and the Netherlands (-1.6 %).

Total EU-28 imports (entries) of natural gas increased by 5.5 % to total 25 452 thousand terajoules. The most significant increase in 2016 compared with 2015 was observed in Romania, with very high proportional increases also recorded in Greece, Croatia, Hungary, Slovenia and Sweden. In EA-19, imports of natural gas increased by 5.1 % to total 19 318 thousand terajoules in 2016. It is important to remember that following the change in methodology in reporting monthly natural gas trade, introduced starting with reference month January 2013, monthly data concerning imports by country of origin are no longer completely comparable with previous years' figures. The new reporting provides import figures by last transit country (mostly neighboring countries) instead of by country of primary or indigenous production.

As regards the origin of imports, Norway is the source of 26.9 % of the natural gas entering the EU (Intra-EU trade excluded) and Russia of 18.3 %, while also 17.1 % comes from Ukraine and 11.5 % from Belarus. Natural gas dependency in EU-28 was 70.4 % in 2016, slightly up from 69.3 % in 2015. Denmark and Netherlands are the only net exporters. In 16 Member States energy dependency is higher than 90 %. Figure 9.25 shows the applications and use of gas in the European Union in 2013. This data is a few years old, but it does show the approximate proportions and the kinds of applications gas is used for.

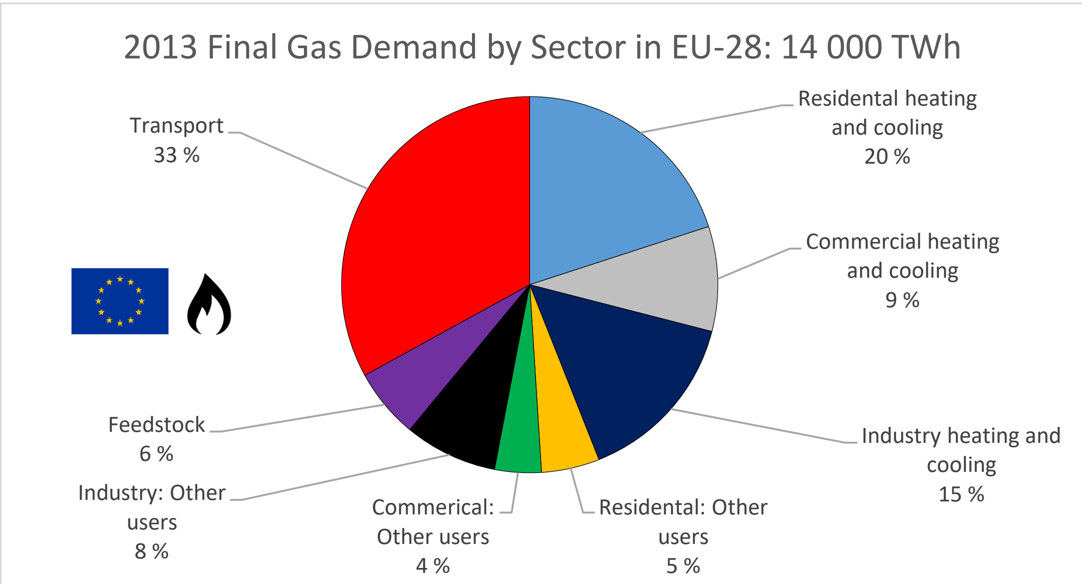

Figure 9.25. European final gas demand by sector of gas in 2016
(Source: IHS Multi-client study: Beyond the Flame, transformation of Europe's Heat Sector)
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9.5 Coal as a natural resource

Coal is the most abundant of fossil fuels. The world currently annually consumes over 7,800 million tonnes of coal which is used by a variety of sectors including power generation, iron and steel production, cement manufacturing and as a liquid fuel. The majority of coal is either utilized in power generation that utilizes steam coal or lignite, or iron and steel production that uses coking coal.

The role of coal in power generation is set to continue. Coal currently fuels 40% of the world's electricity and is forecast to continue to supply a strategic share over the next three decades. The largest coal producing countries are not confined to one region. The largest five producers are China, the US, India, Indonesia, Australia, and South Africa. The coal production and consumption in Table 9.6 is in units of million tonnes of oil equivalent. This is due to the differences in coal energy content (calorific value)

Table 9.6. Global coal reserves, production, and consumption
(Source: Appendix F, BP Statistical review of World Energy 2019)

Geographic Region	Proven Reserves Anthracite and Bituminous (Million tonnes)	Proven Reserves Sub-bituminous and Lignite (Million tonnes)	Total Proven Reserves (Million tonnes)	Annual Production (Million Tonnes of Oil Equivalent)	Annual Consumption (Million Tonnes of Oil Equivalent)
Global	734,903	319,879	1,054,782	3,916.7	3,771.9
Total North America	225,673	32,339	258,012	400.7	343.3
Total Central & South America	8,943	5,073	14,016	60.4	36.0
Total Europe	56,132	78,461	134,593	170	307.1
Commonwealth of Independant States	98,123	90,730	188,853	276	134.9
Middle East & Africa	14,354	66	14,420	156.5	109.3
Total Asia Pacific	331,678	113,210	444,888	2853.1	2,841.3
<u>Nations</u>					
United States	220,167	30,052	250,219	364.5	317.0
China	130,851	7,968	138,819	1828.8	1,906.7
European Union	22,612	53,356	75,968	125.8	222.4
Russian Federation	69,634	90,730	160,364	220.2	88.0

The history of coal mining goes back thousands of years. It became important in the Industrial Revolution of the 19th and 20th centuries, when it was primarily used to power steam engines, heat buildings and generate electricity. Coal mining continues as an important economic activity today. By the middle of the 16th Century, the British Isles had almost run out of wood lumber to produce charcoal to be used as a heat source (Nef 1977). By the early 1700's coal had been phased in as the new energy source in the British Isles. The coal resources of the British Isles were mined out over time down to the water table. The development of the steam engine by James Watt, was for the purpose of pumping water out of coal mines so they could mine below the water table.

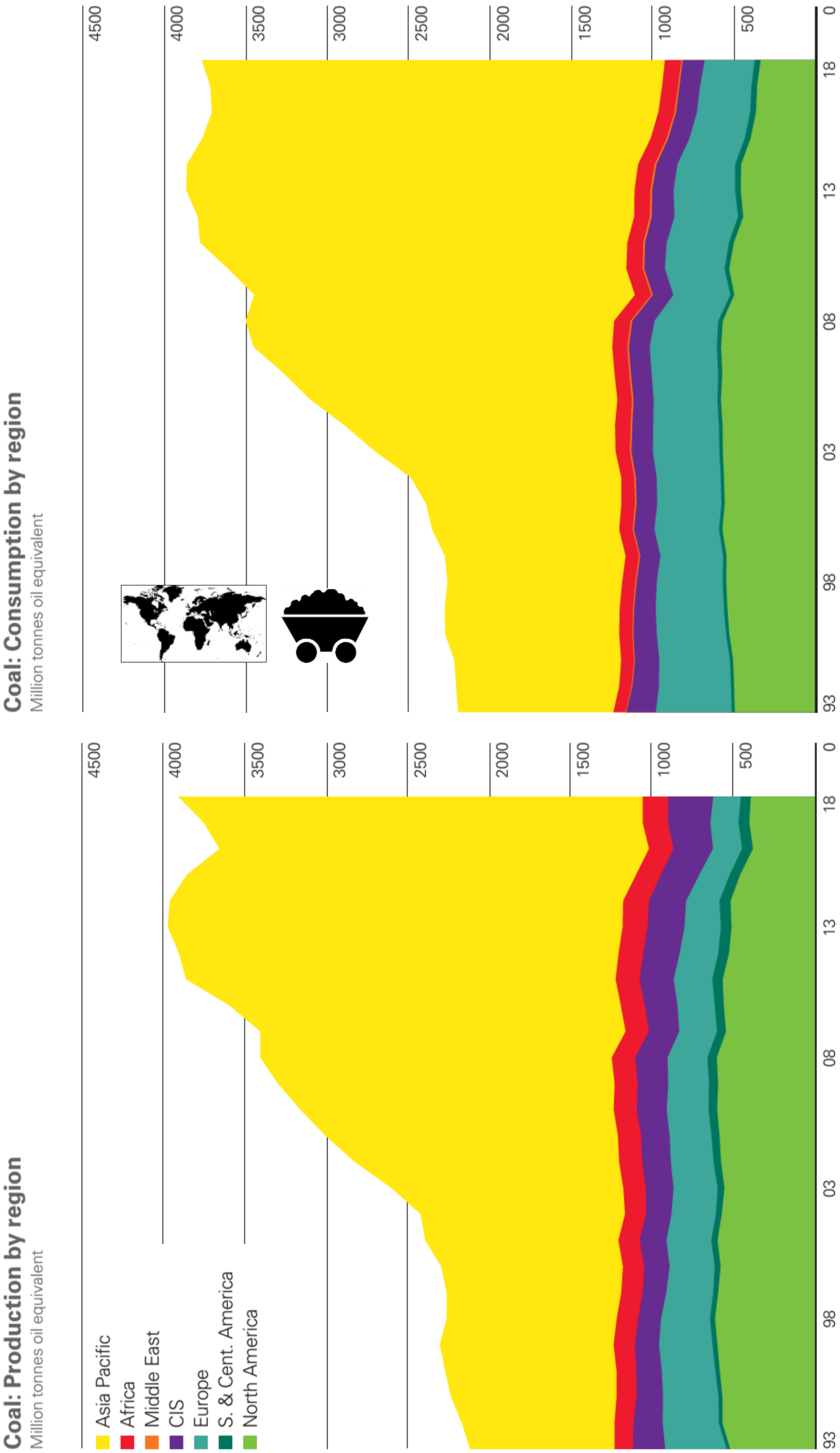

Figure 9.26. Global coal production and consumption by region
(Source: BP Statistical Review of World Energy 2019) (World Map Image by Clker-Free-Vector-Images from Pixabay)

Coal can be turned into gases and liquids that can be used as fuels or processed into chemicals to make other products. These gases or liquids are sometimes called synthetic fuels or synfuels. Synthetic fuels are made by heating coal in large vessels. These fuels produce fewer air pollutants when burned than burning coal directly.

Figure 9.29 shows how coal was used globally up in 2015. While this is an old chart it does show the applications in their approximate proportions. Note, most of coal consumption globally is associated with electrical power generation. A small fraction is related to steel manufacture. To manufacture steel, coal of a high grade and rank called coking coal is required.

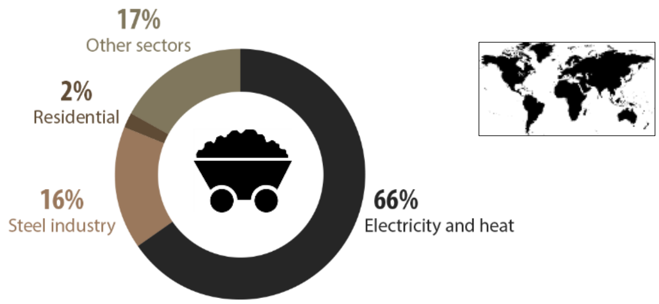

Figure 9.29. Global coal use by sector, from in 2015, in million tons oil equivalent.
(Source: World Steel Association, Natural Resources Canada, International Energy Agency, 2009)
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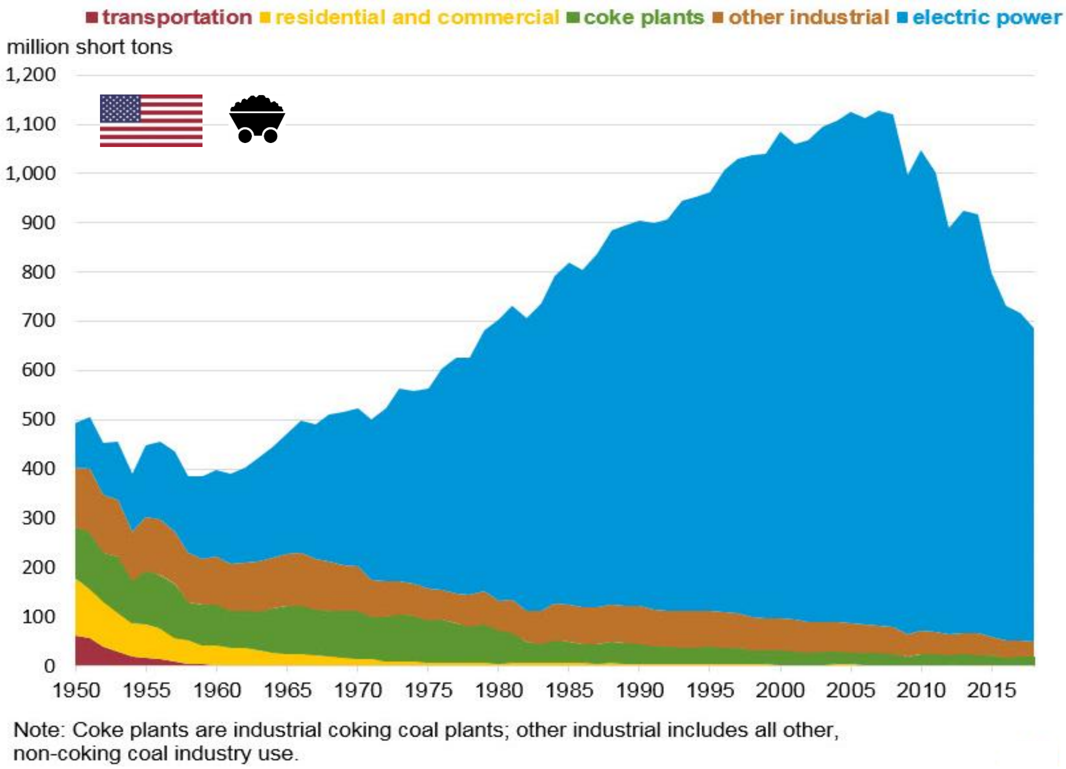

Figure 9.30. U.S. coal consumption by major end users, 1950-2018
(Source: U.S. Energy Information Administration, Monthly Review, Table 6.2, April 2019)
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Other important users of coal include alumina refineries, paper manufacturers, and the chemical and pharmaceutical industries. Several chemical products can be produced from the by-products of coal. Refined coal tar is used in the manufacture of chemicals, such as creosote oil, naphthalene, phenol, and benzene. Ammonia gas recovered from coke ovens is used to manufacture ammonia salts, nitric acid, and agricultural fertilizers. Thousands of different products have coal or coal by-products as components: soap, aspirins, solvents, dyes, plastics, and fibers, such as rayon and nylon (World Coal Association).

Figure 9.31 shows the yearly consumption of coal subtracted from the production of coal for the three largest economies, the United States, European Union and China (representing 65% of global GDP). Europe is clearly heavily dependent on coal imports (the 2018 deficit was 96.6 Mtoe, or 43.4% of EU demand. The United States has been a net exporter of coal most of the time period shown, where the rate of export in 2018 was 47.5 Mtoe (or 15.0% of US demand). China was self-sufficient until 2008. Since then it has become a net importer of coal, where the 2018 deficit 77.9 Mtoe (or 4.1% of Chinese demand). The data for Figure 9.31 is shown in Appendix F.

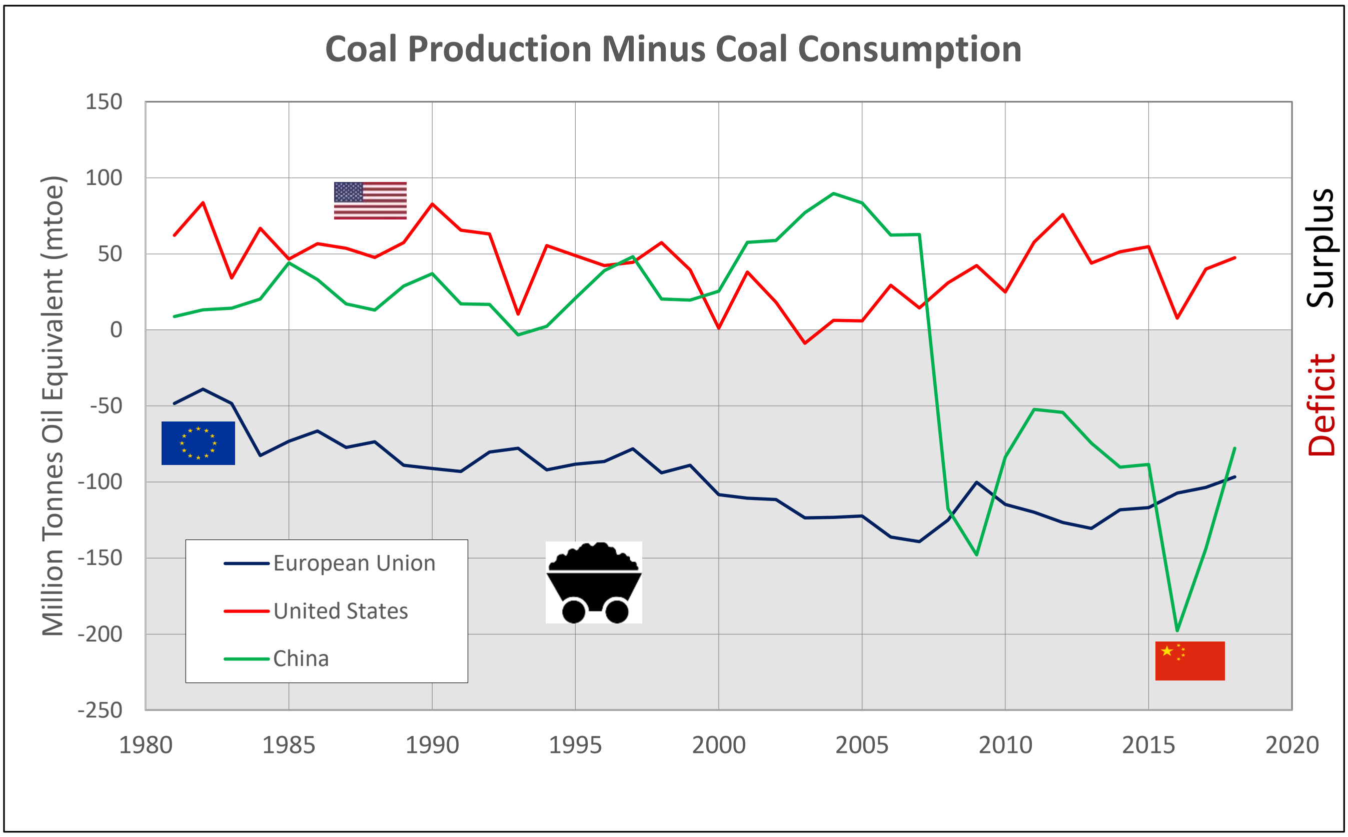

Figure 9.31. The net dependency of EU, US and China on coal imports 1981 - 2018
(Source: data from BP Statistical Review of World Energy 2019 and BP Statistical Review of World Energy 2011)

Shown in Figure 9.32 is the energy production by source. It can be shown about the same time China became a net importer of coal, the production of coal in China was ramped up.

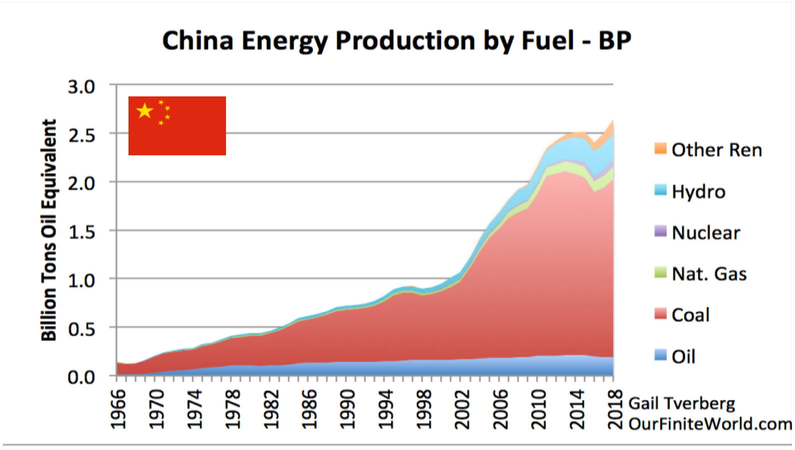

Figure 9.32. China energy production by fuel
(Source: Gail Tverberg, OurFiniteWorld.com, BP Statistical Review of the World Energy 2019)

Coal is ranked into four main categories in terms of quality, ash content and calorific content (Figures 9.33 and 9.34). The ranks are as follows:

- **Lignite**, or 'brown coal'. This is the youngest form of coal and is used almost exclusively for electric power generation.
- **Sub-bituminous coal**. This coal, which has spent more time underground than lignite before being recovered, is mainly used for power generation.
- **Bituminous coal**. Older than sub-bituminous coal, this coal can be used in heat and power manufacturing applications as a coking coal, mainly for steel and aluminum production.
- **Anthracite** (often included within bituminous coal). The oldest form of coal is used mainly for residential and space heating, and is perhaps the most familiar form of coal, the shiny black rock.

Rank is a measure of the progressive alteration in the series from lignite to anthracite. Higher rank coals are generally harder, contain less moisture and volatile matter, and have higher calorific values.

Coal has many important uses. The most significant uses of coal are in electricity generation, steel production, cement manufacturing and as a liquid fuel. Different types of coal have different uses.

- **Steam coal** - also known as thermal coal - is mainly used in power generation. Power produced by the burning of coal for steam to run turbines to generate electricity either to public electricity grids or directly by industry consuming electrical power (such as chemical industries, paper manufacturers, cement industry and brickworks). During power generation the coal is ground to a powder and fired into a boiler to produce steam to drive turbines to produce electricity. Steaming coal usually have high ash content ranging from as low as 20% to as high as high as 50%. Steaming coal is generally drawn from lower rank production and is not worth as much as coking coal.
- **Coking coal** - also known as metallurgical coal - is mainly used in steel production. Met Coking coal is used in the process of creating coke necessary for iron and steel-making. Coke is a porous, hard black rock of concentrated carbon that is created by heating bituminous coal without air to extremely high temperatures. The coal is baked in a coke oven which forces out impurities to produce coke, which is almost pure carbon. These kinds of coal are usually low in ash, Sulfur and Phosphorous Content. Although ash content can be regulated by washing process, low contents of sulfur and phosphorous are necessary as they tend to migrate to metals.

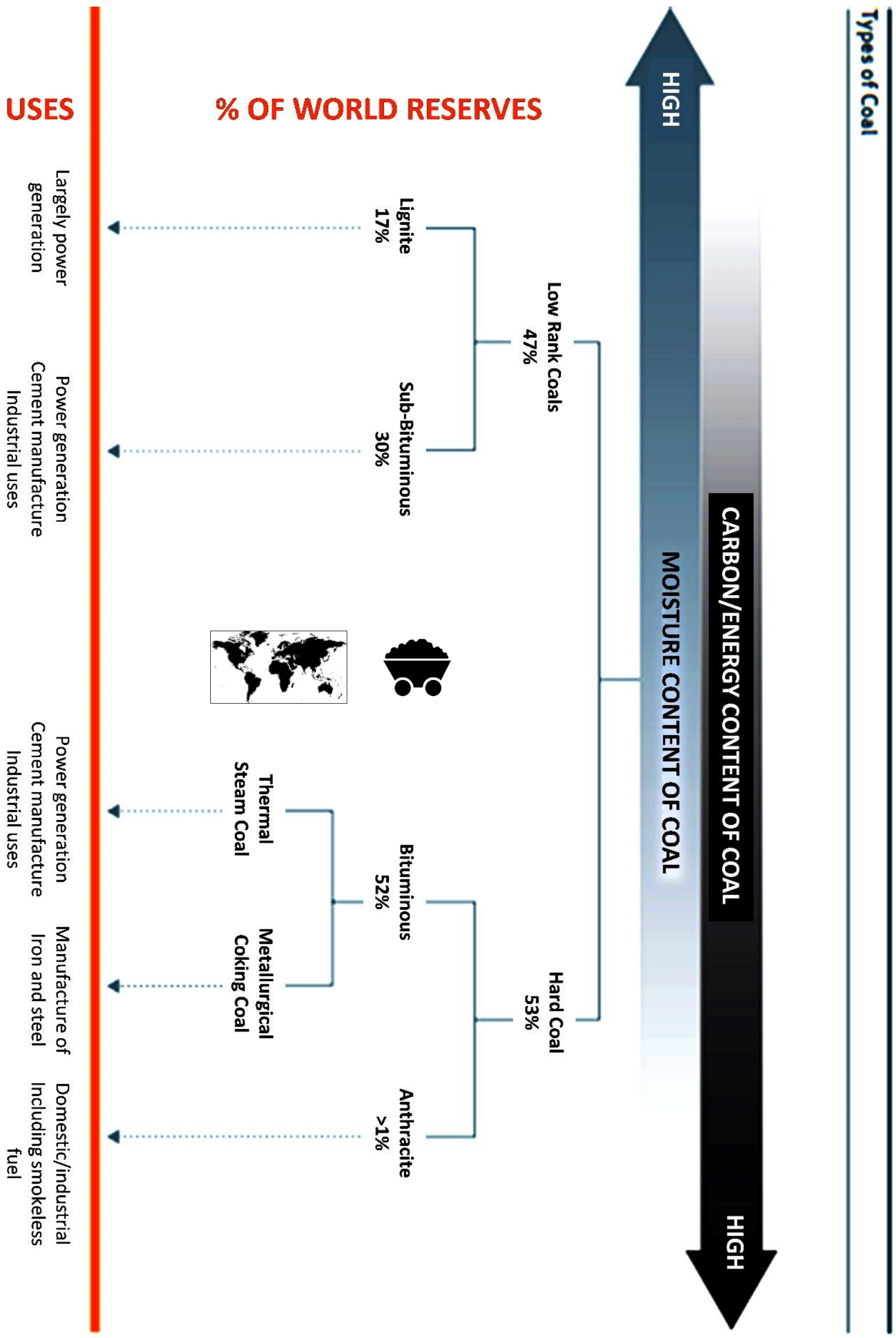

Figure 9.33. Ranks of coal and their uses (Source: Based on information from World Coal Association)
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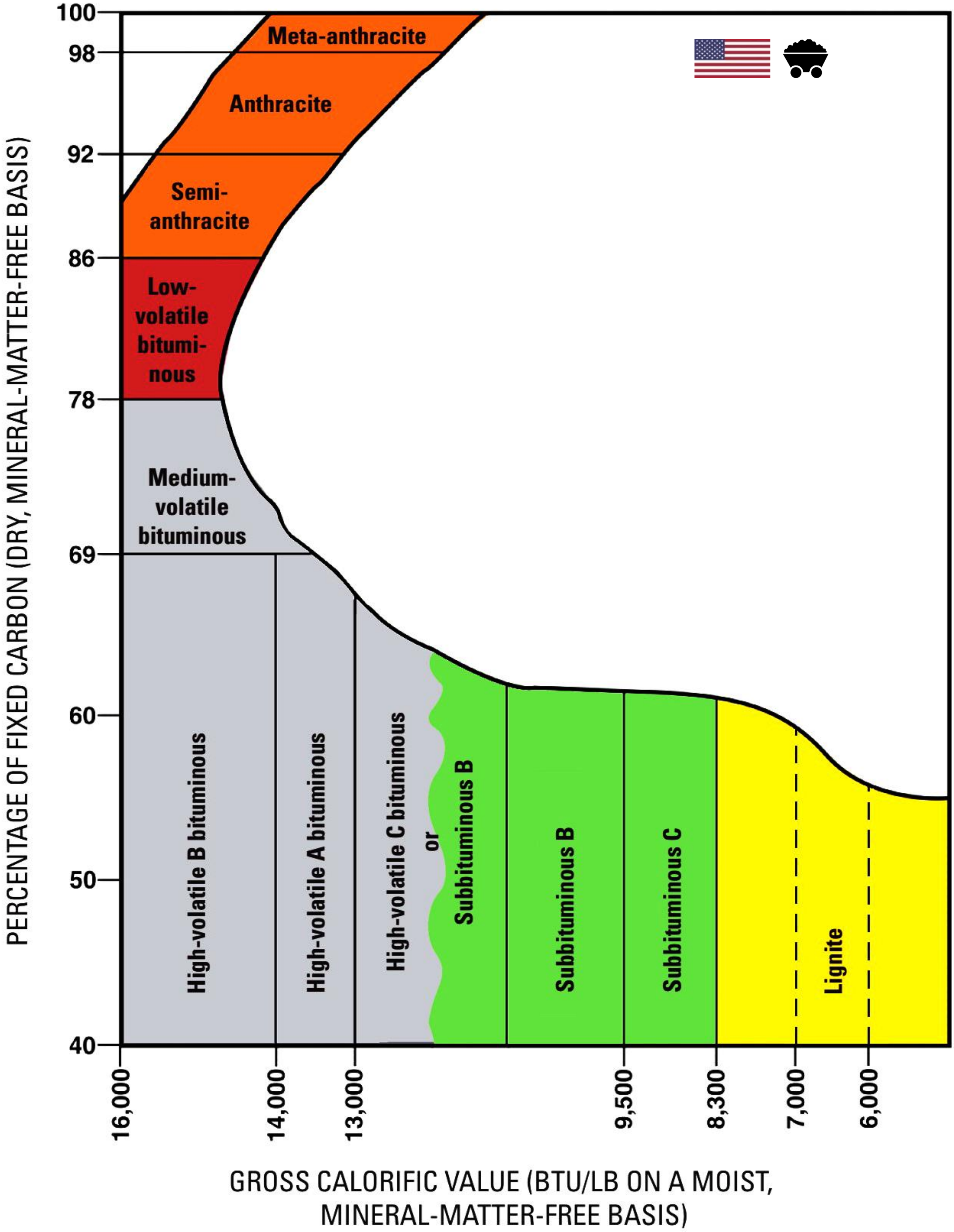

Figure 9.34. Ranks of coal and their calorific value in the United States
(Source: USGS, Schweinfurth 2009)

Global steel production is dependent on coal. Over 71% of the steel produced in 2016 was manufactured using coal. Metallurgical coal (or coking coal) is a vital ingredient in the steel making process. World crude steel production was 1.6 billion tonnes in 2017 (World Steel Association). Steel is an alloy based primarily on iron. As iron occurs only as iron oxides in the earth's crust, the ores must be converted, or 'reduced', using carbon. The primary source of this carbon is coking coal.

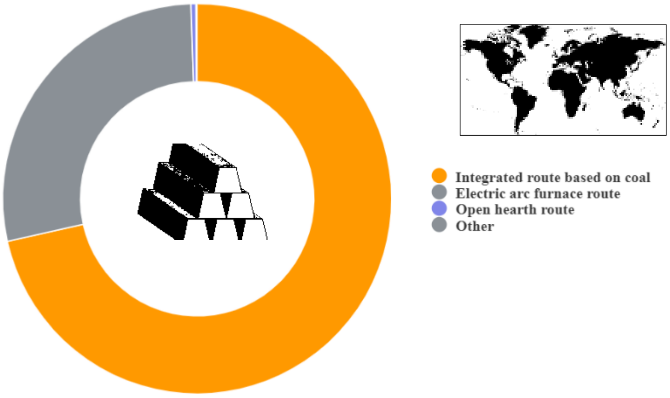

Figure 9.35. Crude steel production by process. (Source: World Steel Association, World Steel in Figures 2016)
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(World Map Image by Clker-Free-Vector-Images from Pixabay)

Coal is slowly being phased out and being replaced by renewable energy sources for electrical power generation. Currently, coal fired power plants provide around 40% of the world's electricity and they are primarily used in developing countries. International agreements to meet climate change targets will require the further phasing out of coal fired power stations. At this time there is no viable substitute for coking coal as used in the steel making industry. There are a number of conceptual projects like pyrolysis of forest harvesting waste (a CSIRO project) but so far they have not been able to be scaled up to production at an industrial level.

9.6 Use of coal in Europe

In Europe the use of coal for power generation has contracted since the year 2007, while the use of renewables continues to grow, according to a recent report on Europe's power sector (BP Statistical Review of World Energy 2019). The European Power Sector 2017, published by two climate and energy policy think tanks (Agora Energiewende & Sandbag 2019), reports that coal's share of Europe's total power generation fell to 20% last year, while the share from renewables increased to 30%. Nevertheless, Europe's progress in reducing the use of carbon-intensive power is gradual and uneven. It will need to accelerate if the EU is to meet its 2030 target to cut greenhouse gas (GHG) emissions by 40% from 1990 levels.

Coal dependence in Europe is not as high as generally thought; its 20% share of power generation is lower than in other OECD economies such as the US, China, Japan and Australia. Eight European states have pledged to phase out coal use completely – Austria, Denmark, France, Finland, Italy, Netherlands, Portugal and the UK – so coal-fired power will continue to decline as more capacity gets retired. In the year 2016-17 14 gigawatts of coal-fired capacity were retired in Europe, and there is little capacity in the construction or planning phase (with the little that there is being mainly located in Poland and South Eastern Europe). Figure 9.36 shows the coal consumption in Europe by nation state. Figure 9.37 shows the col still being produced through mining in Europe.

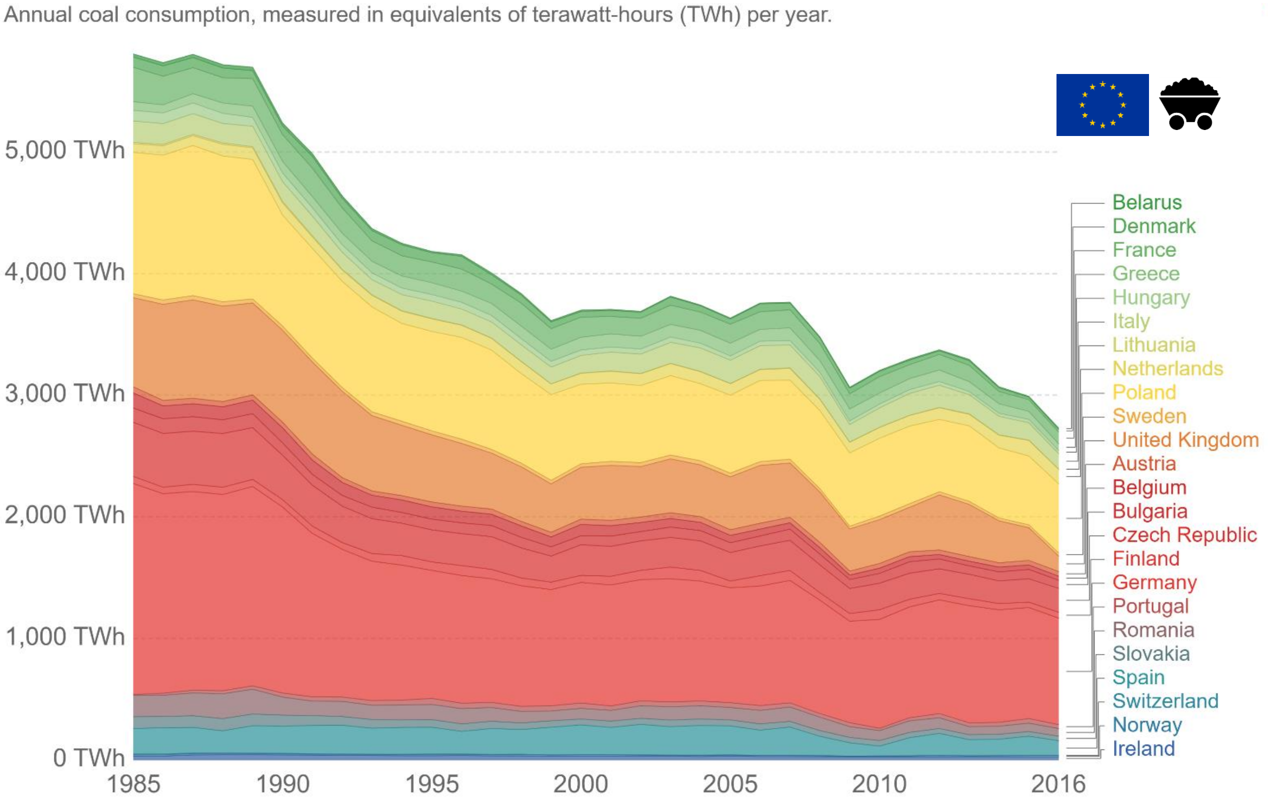


Figure 9.36. Coal consumption in Europe by nation state, terawatt-hours (TWh) between 1985-2016 (Source: OurWorldinData.org/fossil-fuels/, BP statistical Review of Global Energy 2018) (Copyright License: https://creativecommons.org/licenses/by-nc-sa/4.0/)

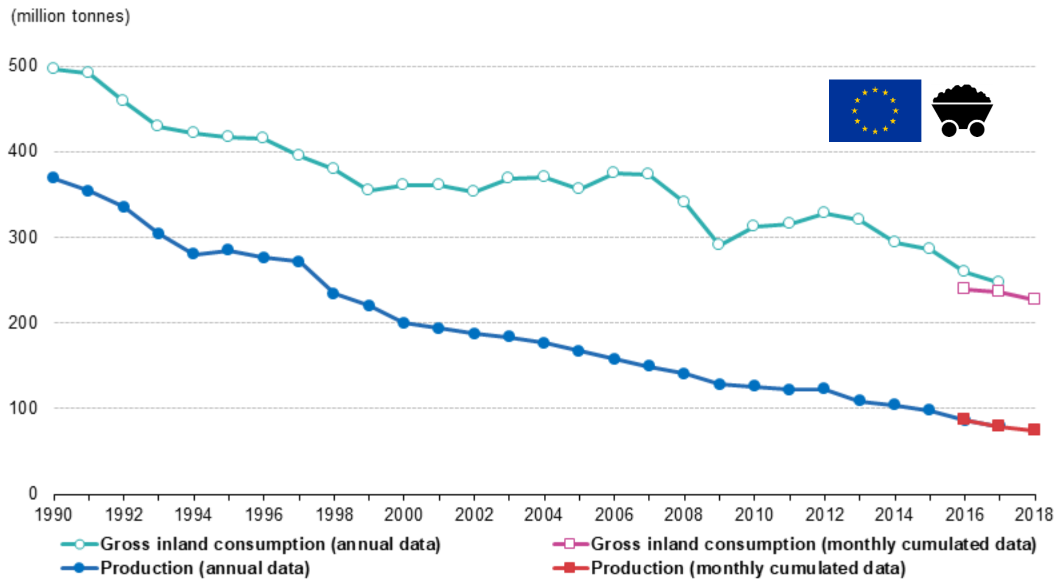
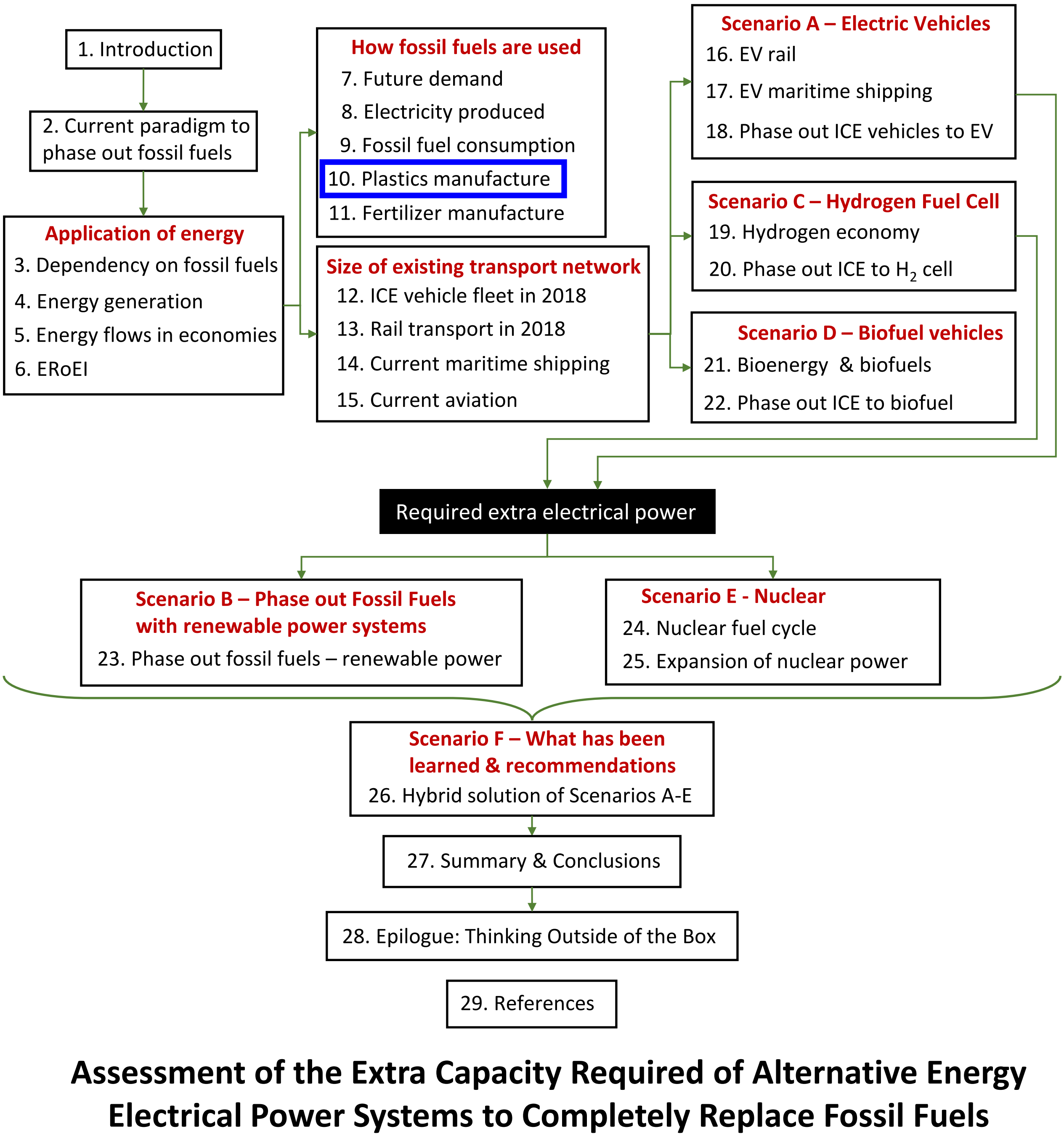


Figure 9.37. Gross inland consumption and production of hard coal, EU, 1990-2018 (million tonnes) (Source: Eurostat online data code: (nrg_cb_sff), (nrg_101m)) (Copyright License: https://creativecommons.org/licenses/by-nc-sa/4.0/)

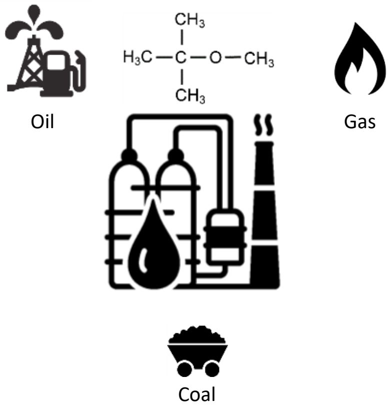
10 FOSSIL FUEL DEPENDENCY TO MANUFACTURE PLASTICS

Plastics made from petrochemicals represent a large proportion of the global consumption of oil and gas. The purpose of Section 10 was to examine how plastics are made and what the role of fossil fuels is as a feedstock raw material. Bioplastics as a substitute will be discussed.



Plastics are a wide range of synthetic or semi-synthetic organic compounds that are malleable and so can be molded into solid objects. Plastics are usually organic polymers of high molecular mass and often manufactured with a range of other substances. They are usually synthetic in manufacture, where the most commonly derived from petrochemicals, however, an array of variants are made from renewable materials such as polylactic acid from corn or cellulosics from cotton linters.

Plastics and petrochemicals are made using oil and gas feedstock (among other things). Globally, over 8.1 trillion kilograms of plastics have been produced from about 8 % of the world's oil (Gibbens 2018). About 10% of total world refinery output, or around 650 Million tons per year, is used by the plastics industry for its feedstock and energy needs. Countless numbers of manufactured products are either made from plastics or contain plastic components. Very few consumer products in today's market-place contain no plastic parts at all. It could be argued that our current technology now depends on plastics to operate.



The range of plastics on the market is enormous. But reduced to their common origins, commercial plastics are variants of a small originating family of organic compounds, made from the simplest components of crude oil and natural gas, the low molecular weight alkanes (the gases methane, ethane, and propane).

The concept the world's first fully synthetic of plastic was invented was with the material bakelite. Bakelite was invented in New York in 1907 by Leo Baekeland who coined the term 'plastics'. There have been a number of chemists who have contributed to the materials science of plastics, including Nobel laureate Hermann Staudinger who has been called "the father of polymer chemistry" and Herman Mark, known as "the father of polymer physics".

The modern polymer industry was effectively created by Wallace Carothers at DuPont in the 1930s. Currently in 2019, over 70 million tons of thermoplastics per year are used in textiles, mostly clothing and carpeting. More than 90 percent of synthetic fibers, largely polyethylene terephthalate, are produced in Asia.

Currently, petrochemicals are the first link in a chain of industries that ultimately use hydrocarbons as raw materials. This industry is the feedstock source of an industrial supply chain that generates a vast range of goods at all levels of complexity. Plastics, pharmaceuticals, synthetic rubber, and textiles are a few of the many industries that rely on a supply of raw material from petrochemicals and in turn from fossil fuels. Synthetic fertilizers are another major user of hydrocarbon feedstock.

In developed economies, about a third of plastic is used in packaging and roughly the same in buildings in applications such as piping, plumbing or vinyl siding. There are two broad bush categories of plastics being produced.

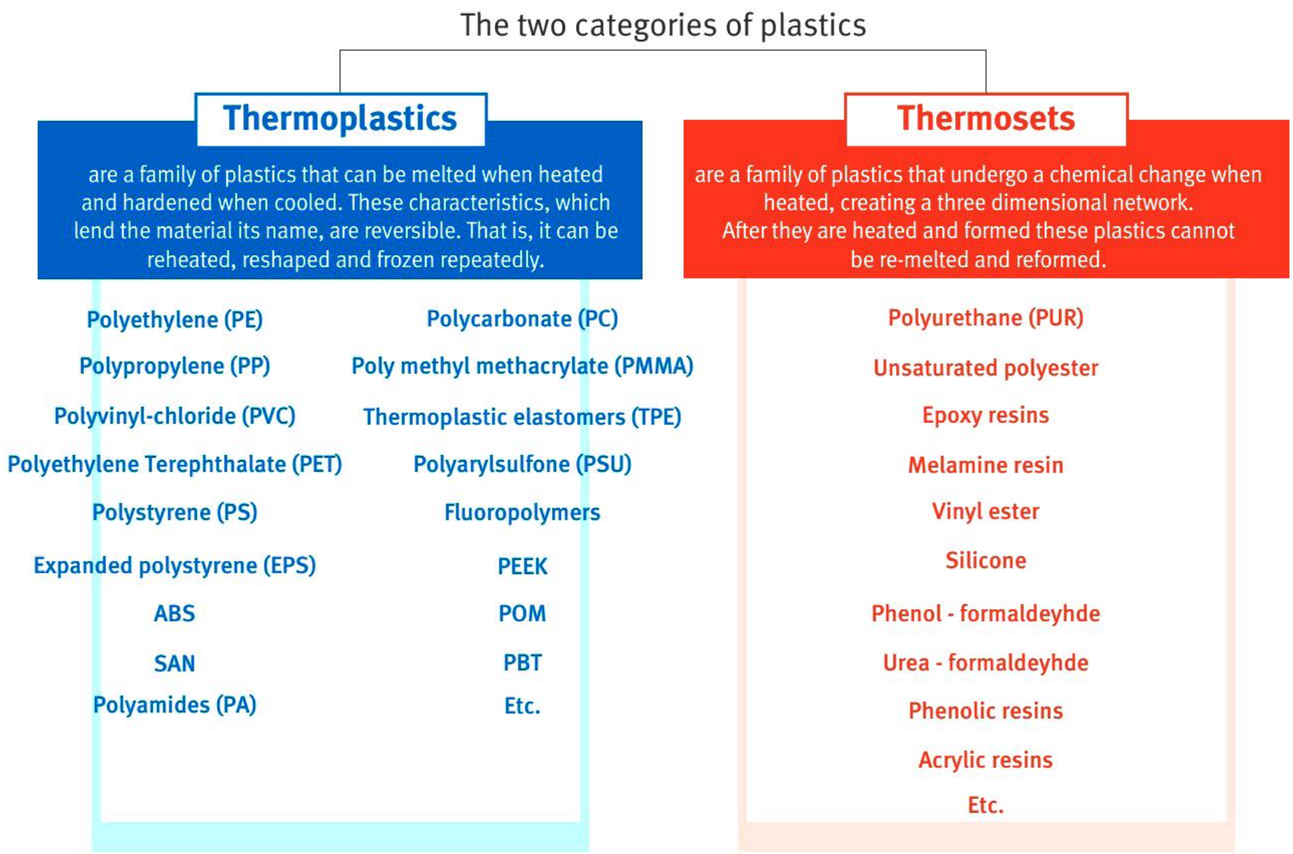


Figure 10.1. The family of plastics (Source: Plastics Europe 2018)
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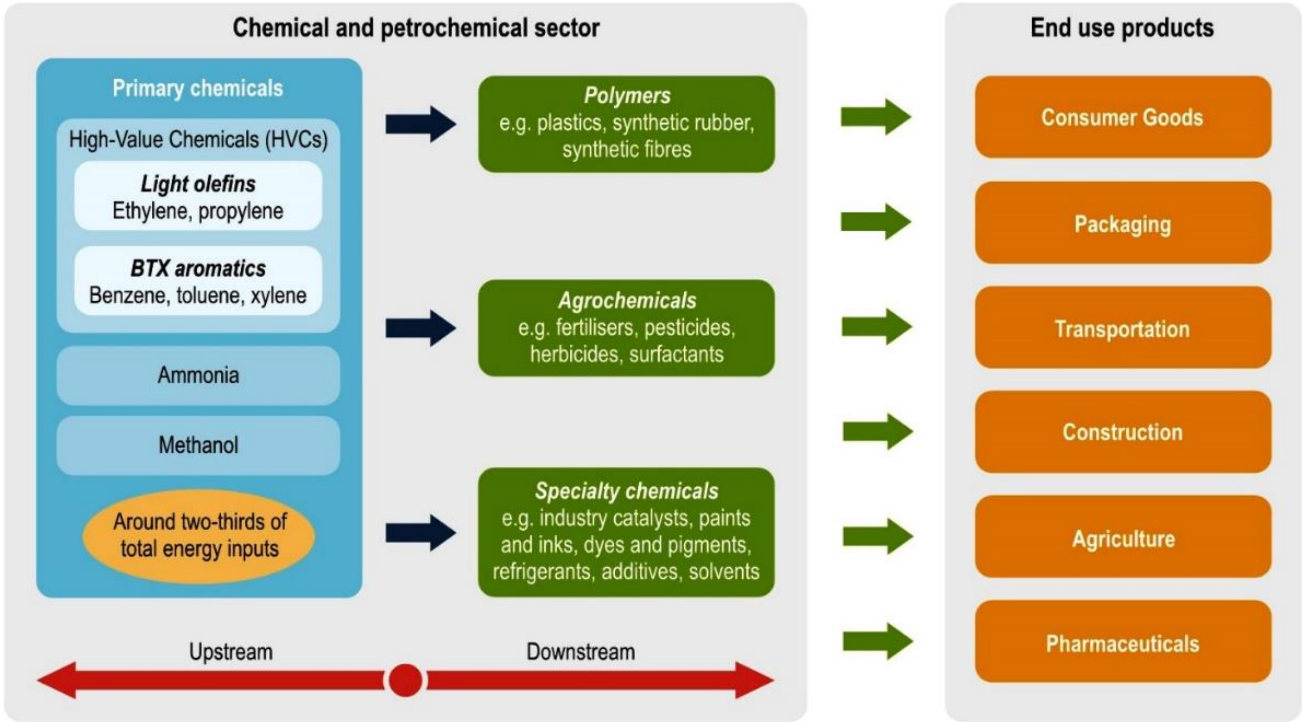

Figure 10.2. Primary chemicals in context of plastic manufacture (IEA 2018)
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Petrochemicals represent a major part of global energy fossil fuel demand. This market share is growing with the increase in technology complexity. Plastics are the most common petrochemical product. Demand for plastics has outpaced all other bulk materials (such as steel, aluminum, or cement), nearly doubling since the year 2000. The United States, Europe, and other advanced economies currently use up to 20 times as much plastic and up to 10 times as much fertilizer as India, Indonesia, and other developing economies on a per capita basis, underscoring the huge potential for growth worldwide (IEA 2018b).

Chemicals produced from oil and gas make up around 90% of all raw materials to make petrochemicals, which are known as feedstocks; the rest comes from coal and biomass. About half of the petrochemical sector's energy consumption consists of fuels used as raw materials to provide the molecules to physically construct products. The growing role of petrochemicals is one of the key "blind spots" in the global energy debate. The diversity and complexity of this sector means that petrochemicals receive less attention than other sectors, despite their rising importance.

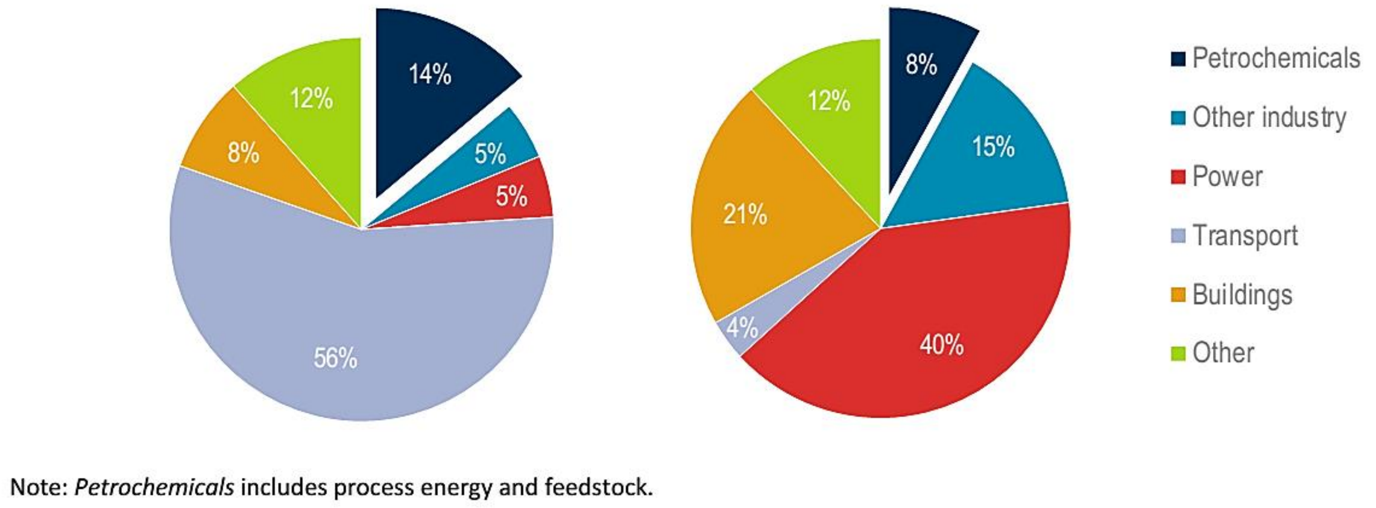

Figure 10.3. Primary oil (LHS) and natural gas (RHS) demand in 2017 by sector
(Source: IEA 2018 and BP Statistical Review of World Energy 2018)
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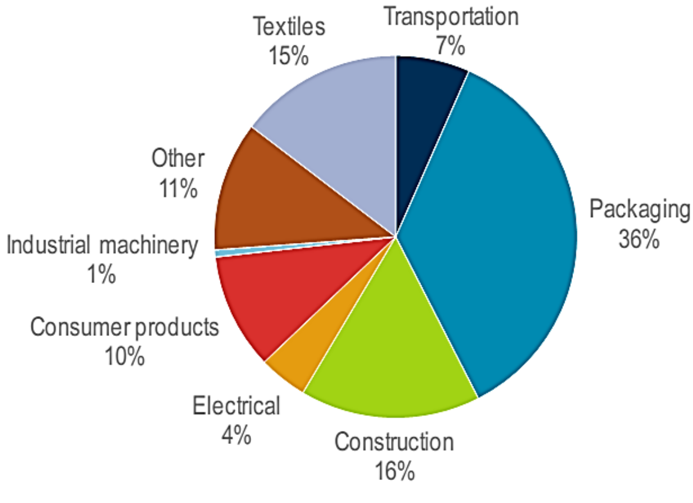
The raw materials for most plastic resins are found in fossil fuels, predominantly natural gas and oil resources (ACC 2015). While an increasing share of plastic resins are made with bio-based materials from plants and algae, fossil fuels continue to provide the vast majority of hydrocarbon raw materials, called feedstocks, for plastic resins. These feedstocks are broken down to create the building blocks that are recombined into plastic resins. Nearly three-quarters of U.S. plastic resin feedstock is derived from natural gas and natural gas liquids (NGLs). Roughly a quarter of feedstock comes from petroleum-based feedstocks. Feedstocks from natural gas liquids include ethane and propane that are especially important for petrochemical (and plastic resin) manufacturing.

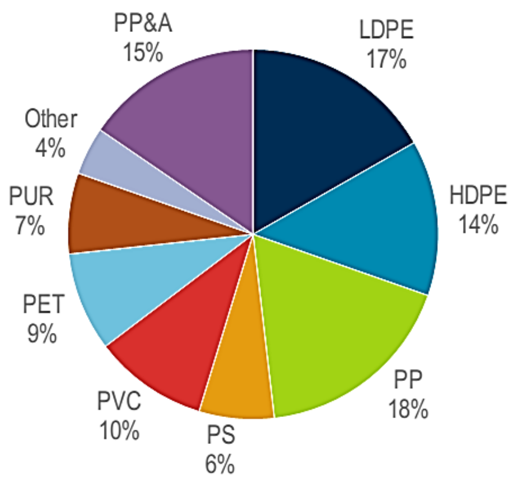
Plastics are often produced from natural gas, feedstocks derived from natural gas processing, and feedstocks derived from crude oil refining (and sometimes coal). Petrochemical feedstock naphtha and other oils refined from crude oil are used as feedstock for petrochemical crackers that produce the basic building blocks for making plastics. However, the petrochemical industry also consumes large quantities of hydrocarbon gas liquids (HGL), which may be produced by petroleum refineries or natural gas processing plants.

There are several key building block chemicals that are used to produce plastic resins. These building block chemicals are linked together to form long chains called polymers. Each polymer has its own signature of material properties and performance characteristics (i.e., strength, permeability, etc.). One of the most prevalent and largest-volume building block chemicals is ethylene. Ethylene is used to produce thousands of products, including plastic resins such as polyethylene (PE), polyvinyl chloride (PVC), and polyethylene terephthalate (PET). Ethylene is a critical feedstock for the production of polyethylene, polyvinyl chloride (PVC), polyethylene terephthalate (PET), and polystyrene, which combined represent approximately 61% of global plastics production by weight.

Another important building block chemical for resin production is propylene, which is the platform chemical for polypropylene. Therefore, the overwhelming majority of plastics can be traced to the product streams of just two industrial chemicals: ethylene and propylene (European Union 2018, A European Strategy for Plastics in a Circular Economy).

Until recently, most propylene was produced in oil refineries as a byproduct of gasoline fuel production. With shale gas, supplies of propane (a natural gas liquid) have become abundant. New technologies have emerged to convert propane into propylene which, like ethylene, has many uses, including the resin polypropylene (PP). Packaging is the leading end-use of plastic consumption globally. The most important types of plastic by volume are polyethylene (PE) and polypropylene. Multiple feedstocks can be utilized to make the same product, but with significant variations between the amounts of input required.





Notes: Resins may exclude additives. Estimates based on data are for Europe, the United States, China, and India for 2002-14. Polyester, polyamide and acrylic (PP&A) fibres are assigned exclusively to the textile sector, and the charts excludes synthetic fibres. LDPE = low-density polyethylene; PUR = polyurethane; LDPE includes linear LDPE.

Figure 10.4. Estimated consumption of plastic by end-use sector (LHS) and resin (RHS)
(Source: Geyer *et al* 2017 and IEA 2018)
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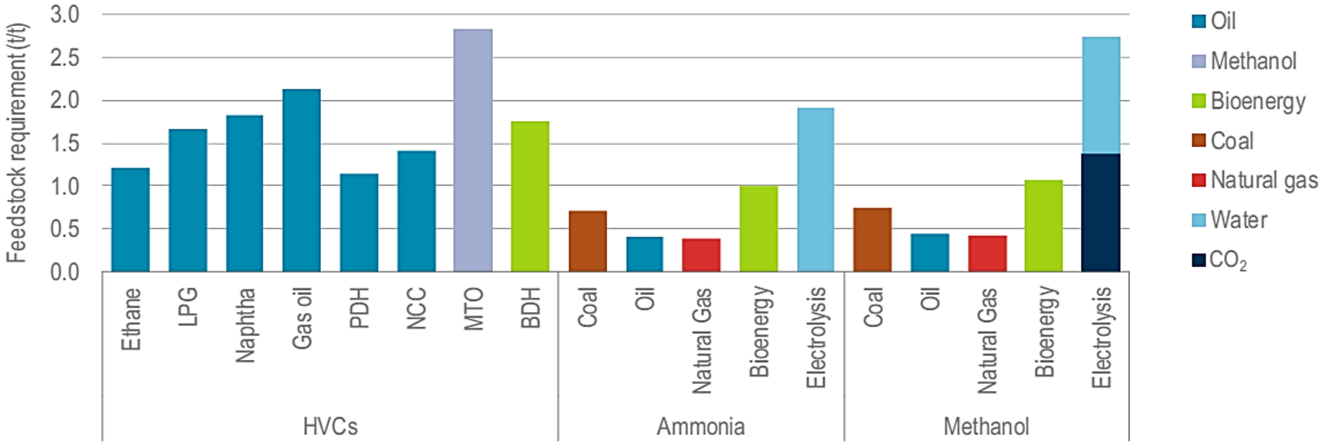

Notes: BDH = bioethanol dehydration; LPG = liquefied petroleum gas; NCC = naphtha catalytic cracking. The quantity pertaining to BDH is in terms of bioethanol.

Figure 10.5. Feedstock options by chemical product
(Source: IEA 2018b, The Future of Plastics)
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Because fossil fuel-based energy resources—which account for up to 70% of total costs for plastic resin producers—are the primary raw materials to make plastic resins, the price of energy feedstocks is critical to the global competitiveness of plastic resin producers. In the case of ethylene, ethane is the predominant feedstock in the U.S. In Europe and Asia, producers use naphtha, an oil-based feedstock. Ultimately, because the price of ethylene is effectively the same across the world, the competitiveness of one region over the other depends on the relative price of these feedstocks. Thus, the spread (difference) between naphtha and ethane prices is key to understanding petrochemical competiveness (IEA 2018b).

Oil products used as chemical feedstock may come from refinery operations or NGL fractionation. In volume terms, oil demand for chemical feedstock is dominated globally by the fractionation products of NGLs. Refineries do not produce ethane to any meaningful extent, and their LPG yields are typically below 5%. Thus, ethane, which accounts for almost a third of all chemical feedstock, and most of the LPG used as chemical feedstock, are supplied by NGL fractionation plants. In contrast, refineries provide the bulk of heavier feedstocks, including naphtha, which is the most popular feedstock, and other distillates. Average refinery naphtha yields are around 7% (IEA 2018b).

The proportion of chemical feedstocks sourced from refineries is restricted, not only because an average barrel of crude oil contains only a limited amount of light fractions (LPG), but also because of competition for straight-run yields of light distillates (naphtha) for gasoline blendstocks, to supplement that part coming from the upgrading of residual oils. Compounding these limitations, LPG and naphtha usually have negative margins (i.e. priced lower than crude oil), discouraging refineries from increasing their yields.

Petrochemicals are rapidly becoming the largest driver of global oil consumption. They are set to account for more than a third of the growth in oil demand to 2030, and nearly half to 2050, ahead of trucks, aviation and shipping (IEA 2018b). Petrochemicals are also predicted to consume an additional 56 billion cubic meters (bcm) of natural gas by 2030, equivalent to about half of Canada's total gas consumption today.

Approximately 190 Mt of chemicals, two-thirds of which are High Value Chemicals (HVC's), are also produced annually as byproducts in the refining sector, making their way into the chemical sector for further processing. The remainder of these refinery chemicals, butylene – also produced as a co-product in steam cracking within the chemical sector – is used for various fuel applications and forms the base of most synthetic rubber (IEA 2018b).

Approximately 12 million barrels per day (mb/d) of oil products enter the sector as feedstock and undergo a complex series of chemical transformations, eventually leaving the sector embedded in chemical products.

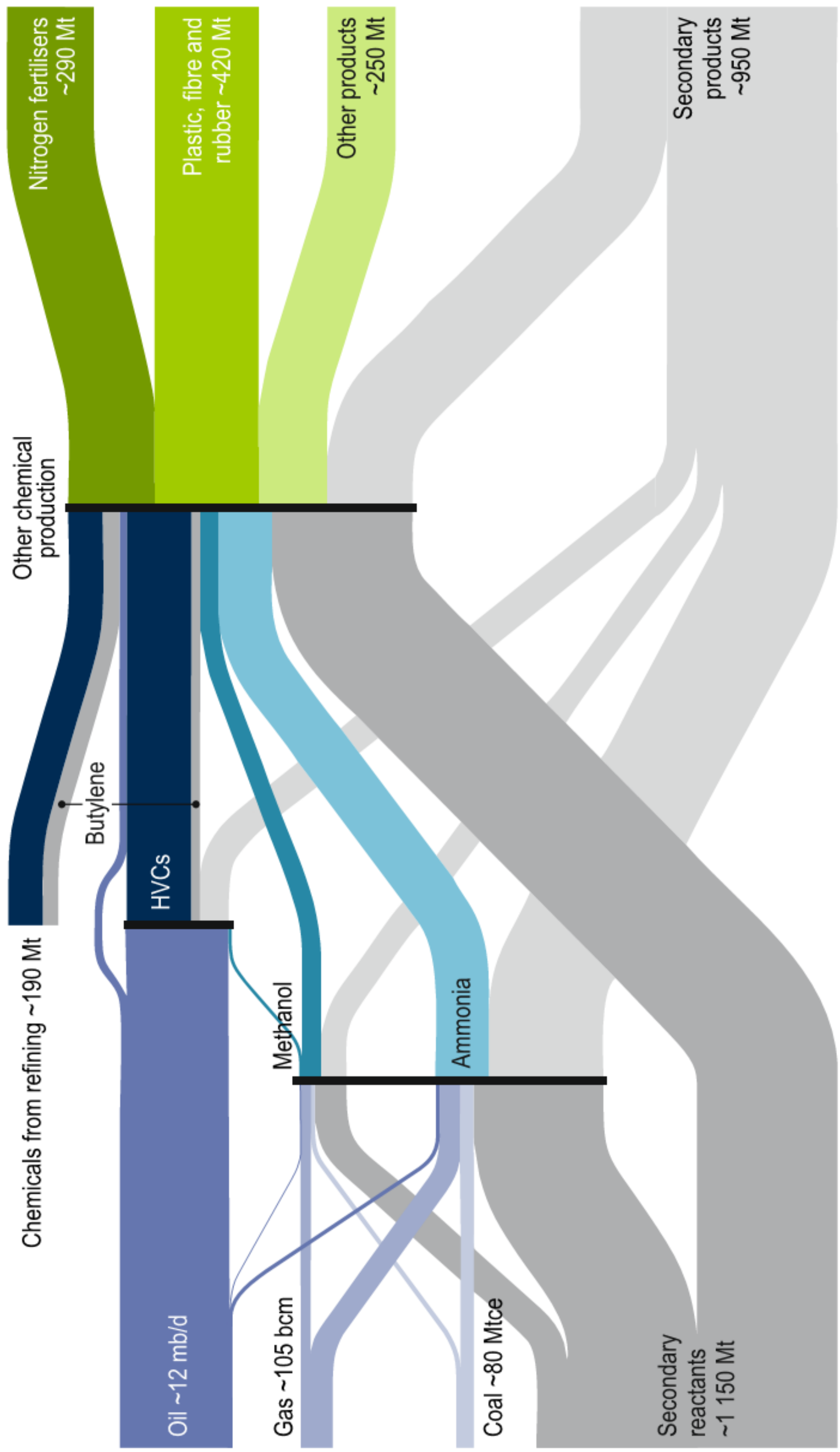
- More than 90% of the oil – mostly in the form of ethane or naphtha – entering the chemical sector as feedstock is transformed into high-value chemicals (HVCs). Very small amounts are used for methanol and ammonia production, with the rest being used for other chemicals, notably, carbon black.

- About 25% of gas demand for chemical feedstock is used to produce methanol, with the majority of the rest used to produce ammonia.

- Coal feedstock usage is split in fairly even proportions across methanol and ammonia.

More than 500 million tonnes of oil equivalent (Mtoe) of feedstock is consumed per year to make approximately 1 billion tonnes of chemical products. Oil is the dominant feedstock for HVC's whereas gas and coal are used for ammonia and methanol.

Nitrogen fertilizers, plastics, synthetic fibers, and rubber account for more than 70% of the total mass production of chemicals. The remainder of the products consist of a host of monomers and other intermediate chemicals that go on to be transformed into thousands of small volume downstream chemicals and products. The complexity at the margins in the chemical sector is hard to overstate. Figure 10.6 shows the passage of fossil fuels through the global plastics industry. Figure 10.7 shows a more complex picture in how plastics relate and compare to fertilizer manufacture.



Notes: All flows in the diagram are sized on a mass basis. Secondary reactants and products are the compounds specified within chemical reactions that do not form part of the feedstock or main products. Key examples include water, CO_2, oxygen, nitrogen and chlorine. Some of the secondary products entering the sector on the left of the figure may well coincide with those leaving it on the right – CO_2 emitted from ammonia facilities and utilised in urea production is a key example. Mtce = Million tonnes of coal-equivalent.

Figure 10.6. Passage of fossil fuel feedstock through the petrochemical industry in 2017
(Source: IEA 2018b, The Future of Plastics)

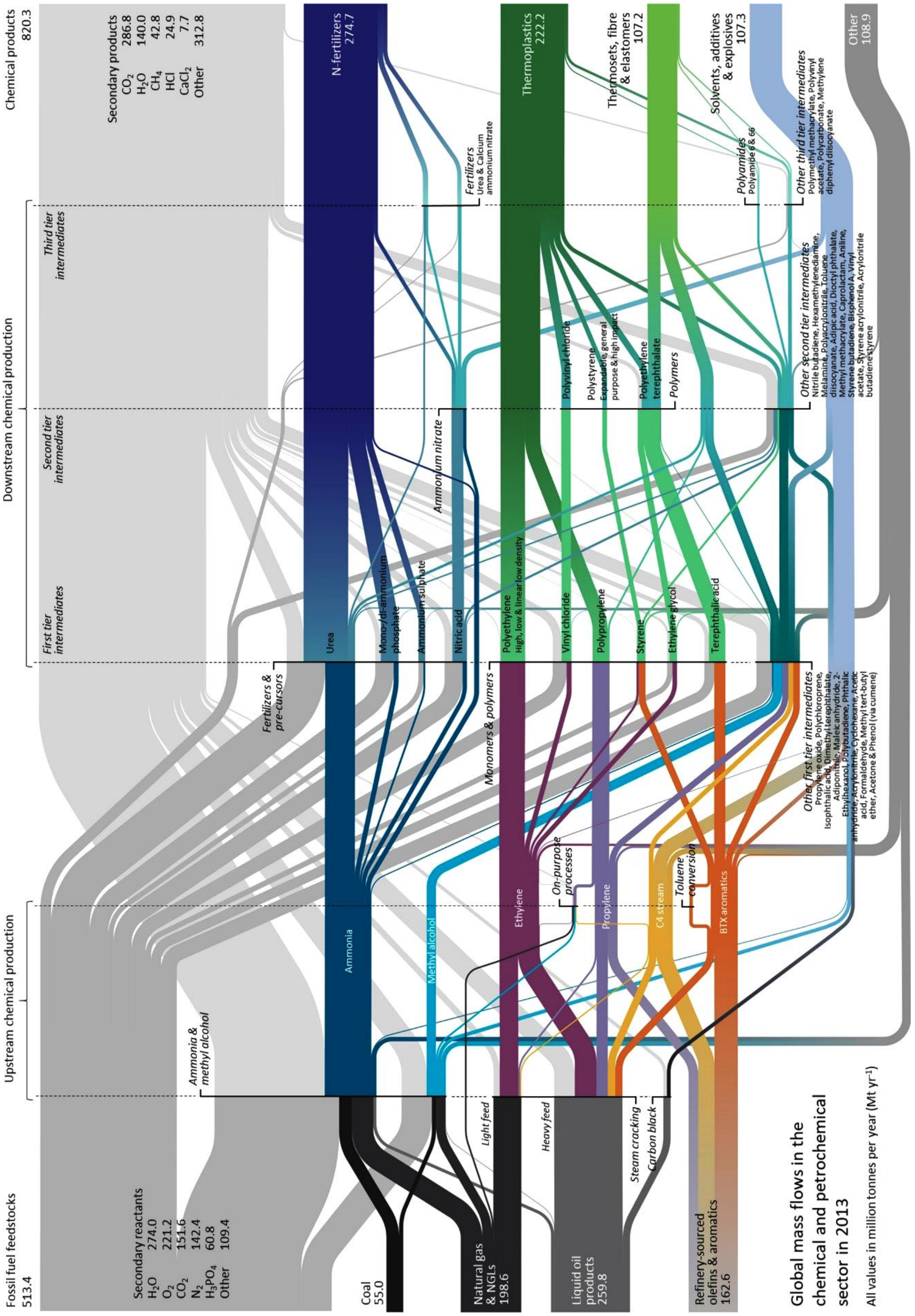


Figure 10.7. Sankey diagram depicting the passage of feedstock through the chemical sector: from fossil fuel feedstocks to chemical products. NGLs: Natural gas liquids, N-fertilizers: Nitrogenous fertilizers. (Source: Levi & Cullen 2018) (Copyright License: https://www.iea.org/media/copyright/Termsandconditions_2019update_FINAL.docx.pdf)

Globally in 2017, recycling of major plastic resins is estimated to have reached 16% of available waste, while global production capacity of bio-plastics stood at just over 2 Mt (European Bioplastics, 2018) (the latter equivalent to less than 1% of annual global plastic demand, if fully utilized). Theoretically, the chemical sector could do without fossil fuels altogether, but feedstock containing carbon and hydrogen will remain a requirement (IEA 2018b).

There are alternatives to making plastics from fossil fuels. They are not nearly as effective, but they are economically viable. Oil produced from pyrolysis of plastics have been known for its higher calorific value than wood-based oil, in which is comparable to conventional diesel. Even though many studies have been conducted on pyrolysis of plastics, the findings of those studies are not applied and reported yet according to the real portion of plastic waste.

A variety of carbon- and hydrogen-containing materials can replace oil, natural gas, and coal as chemical feedstocks (IEA 2018b). Key among these are bioenergy products, which are a source of both carbon and hydrogen. Alternatively, each element can be sourced separately, for instance from gases arising from the iron and steel industry (e.g. coke oven gas (COG)) or from CO^2 and water. The main advantage of alternative feedstocks is that they can offer a net reduction in CO^2 emissions:

- process emissions during production
- end-of-life emissions
- relative to traditional feedstocks.

The reductions stem from the fact that these substances would have otherwise remain unutilized (even if originally sourced from fossil fuels), or because they are renewable and therefore do not contribute to accumulation of CO^2 in the atmosphere (on a long-term basis).

While not all fossil fuels are used to produce plastic, all (or virtually all) plastic is made from fossil fuels. In addition, the largest players in each industry — DowDuPont (dissolved on June 1st, 2019), ExxonMobil, Shell, Chevron, BP, and Sinopec — are all integrated companies that produce both fossil fuels and plastics.

10.1 Pollution from plastics

One of the difficult outcomes of the widespread use of plastic is the large quantities of plastic pollution, in a fashion where they are not breaking down and being absorbed by the environment (Maser 2014).

After a short first-use cycle, 95% of plastic packaging material value, or USD 80–120 billion annually, is lost to the economy. 32% of plastic packaging escapes collection systems, generating significant economic costs by reducing the productivity of vital natural systems such as the ocean and clogging urban infrastructure (Ellen MacArthur Foundation 2017).

It is estimated to take something like 1000 years for plastic to degrade and be absorbed by the environment in a landfill waste dump, and over 600 years in the ocean, where 46% of the plastic consists of discarded fishing nets (Lebreton *et al* 2018).

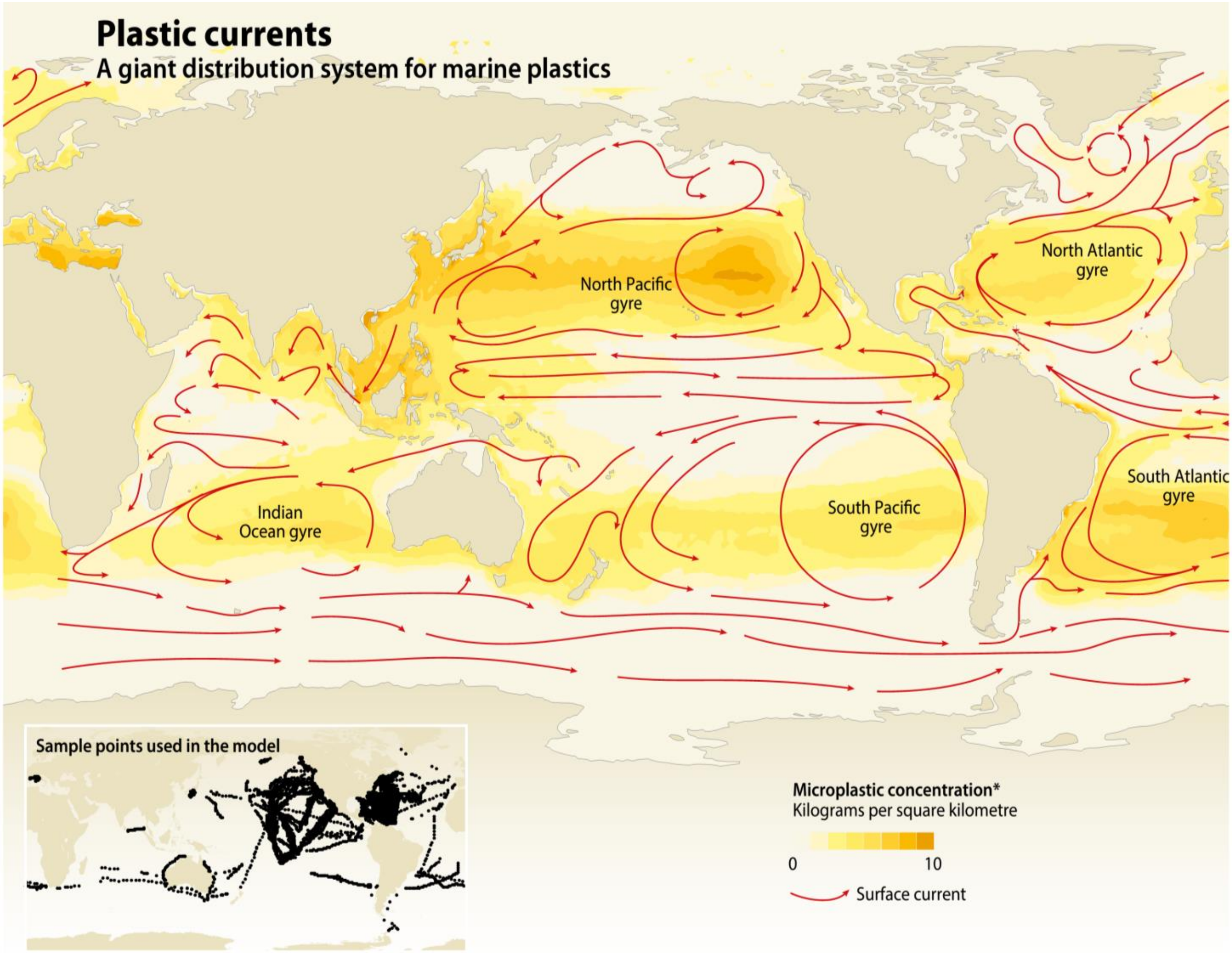


Figure 10.8. Plastic litter in the open ocean
(Source: United Nations 2019, GRID-Arendal 2016) (Copyright License: https://creativecommons.org/licenses/by-nc-sa/4.0/)

It is estimated that approximately '100 million tons of plastic are generated [globally] each year', and about 10% of that plastic ends up in the oceans. The United Nations Environmental Program recently estimated that 'for every square mile of ocean' there are about '46,000 pieces of plastic.' The small fibers of wood pulp found throughout the patch are 'believed to originate from the thousands of tons of toilet paper flushed into the oceans daily.' Plastic concenters into 'gyres', all of which are believed to have increased '10-fold each decade' since 1945 (Ocean Cleanup 2020).

Every year, 8 million metric tons of plastic end up in our oceans. It's equivalent to five grocery bags filled with plastic for every foot of coastline in the world. In 2025, the annual input is estimated to be about twice greater, or 10 bags full of plastic per foot of coastline (The Ocean Cleanup 2020).

An island of trash twice the size of Texas floats in the middle of the Pacific Ocean, circulated by the currents of the North Pacific Gyre. The trash, which is mostly made up of plastic debris, floats as deep as 30 feet below the surface (Dautel 2007).

Researchers from The Ocean Cleanup project claimed that the Pacific gyre patch covers 1.6 million square kilometers. The plastic concentration is estimated to be up to 100 kilograms per square kilometer in the center, going down to 10 kilograms per square kilometer in the outer parts of the patch. An estimated 87,000 metric tons of plastic inhabit the patch, totaling 1.8 trillion pieces (Ocean Cleanup 2020). 92% of the mass in the patch comes from objects larger than 0.5 centimeters, while 94% of the total objects are represented by microplastics (Ocean Cleanup 2020 &Philp 2013). Some of the plastic in the patch is over 50 years old and includes items (and fragments of items) such as plastic lighters, toothbrushes, water bottles, pens, baby bottles, cell phones, plastic bags, and nurdles (Ocean Cleanup 2020 & Albeck-Ripka 2018).

Solutions with practical outcomes to address this pollution issue, have struggled to produce any significant results. This could be due to the pollution has been observed in international waters, and international cooperation to address this issue to date have not been effective.

10.2 Bioplastics and plastics manufactured from biomass

There is no accepted economically viable substitution for plastics in current technology nor the fossil fuel feedstocks to make them in the volumes the global industrial ecosystem currently demands. Petrochemicals are economically cheaper to produce and often have better material performance properties.

However, it is now required to examine the phasing out of fossil fuels like oil, gas, and coal, all of which are used as feedstocks to plastics manufacture. There are a number of alternative process paths, but they are logistically impractical, currently difficult to scale and/or the resulting products have performance issues. The most promising is the bioplastics industry.

Bioplastics are plastic materials that have been manufactured from renewable biomass sources and raw materials. Not all sources are as effective in the production of a bioplastic, and it is appropriate to optimize the raw material to the bio plastic product to the final application. Examples of source materials could be vegetable fats and oils, corn starch, straw, woodchips, sawdust, recycled food waste, etc. Bioplastic can be made from agricultural by-products and also from used plastics (i.e. plastic bottles and other containers) by using microorganisms. Bioplastics are usually derived from sugar derivatives, including starch, cellulose, and lactic acid.

The IEA (2018b) estimates that to produce just chemicals with biomass as feedstock and process energy (including the refining sector), rather than with natural gas, coal, or oil, would require half of the world’s sustainable renewable biomass production by 2030 (Friedemann 2021). That much biomass would be about 2 385 million metric tons of oil equivalent (Mtoe) equal to 102 ExaJoules (EJ) each year. So, there are significant challenges with a direct substitution of bioplastics to replace petrochemical plastics.

A clear advantage of bioplastics is the are designed to be at least partially biodegradable. Figure 10.9 shows matrix of bioplastics in context of the source raw material and their approximate biodegradability.

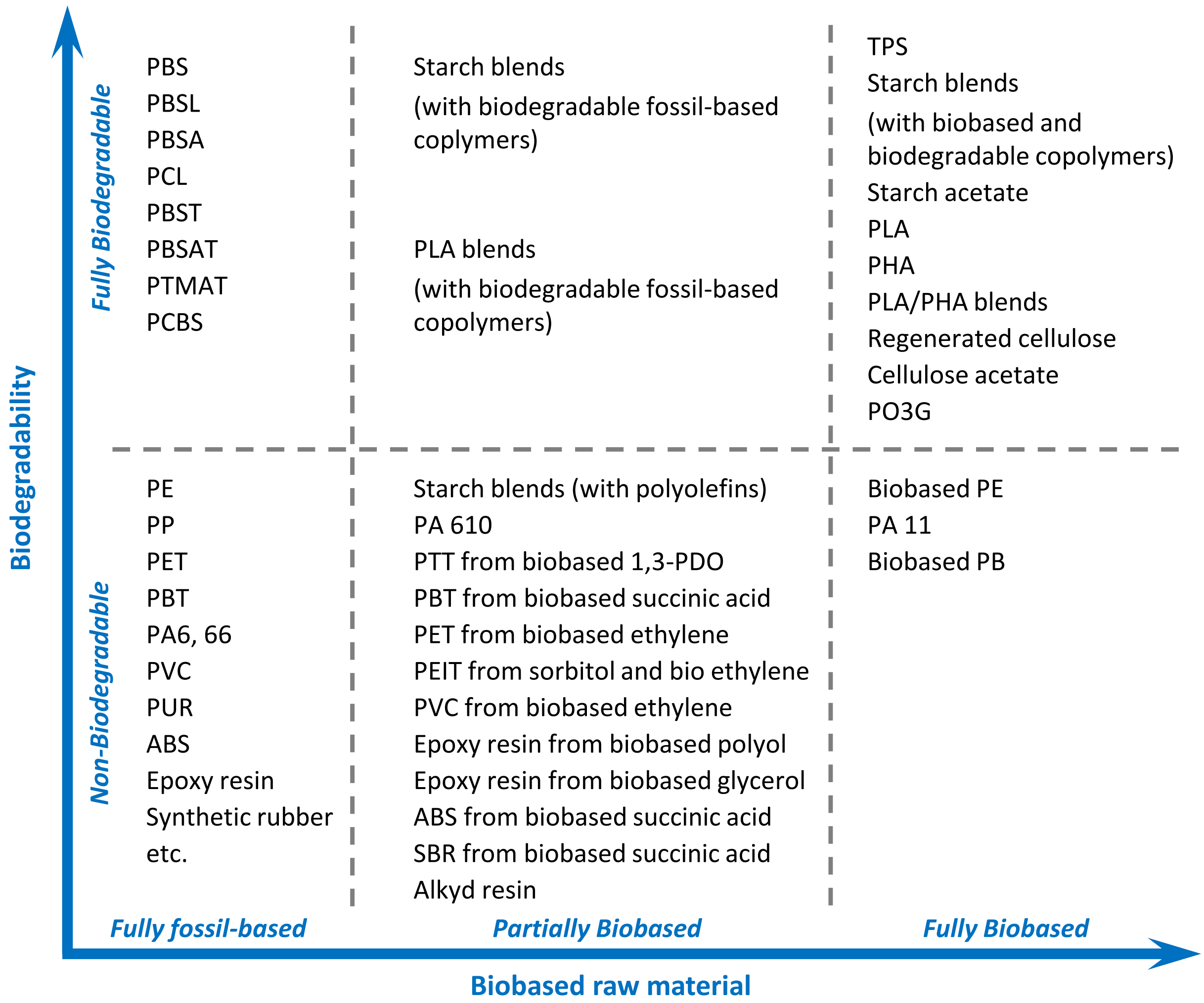


Figure 10.9. Bio-based plastics and their biodegradability (Source: Shen *et al* 2009)

Bioplastics are sustainable, largely biodegradable, and biocompatible. Today, bioplastics have become a necessity in many industrial applications such as food packaging, agriculture and horticulture, composting bags, and hygiene (Ashter 2016). Bioplastics have also found their use in biomedical, structural, electrical, and other consumer products. There are three fundamental methods to produce bioplastics.

1. To make use of natural polymers which may be modified but remain mostly intact. For example, starch plastics.
2. To produce bio-based monomers by fermentation or conventional chemistry and to polymerize these monomers in a 2nd step. For example, polylactic acid.
3. To produce bio-based polymers directly in microorganisms or in genetically modified crops.

There are twelve building block chemicals that can be produced from sugars via biological or chemical conversions (Table 10.1) (U.S. DoE 2004). The twelve building blocks can be subsequently converted to a number of high-value bio-based chemicals or materials. Building block chemicals, as considered for this analysis, are molecules with multiple functional groups that possess the potential to be transformed into new families of useful molecules. The twelve sugar-based building blocks are 1,4-diacids (succinic, fumaric and malic), 2,5-furan dicarboxylic acid, 3-hydroxy propionic acid, aspartic acid, glucaric acid, glutamic acid, itaconic acid, levulinic acid, 3-hydroxybutyrolactone, glycerol, sorbitol, and xylitol/arabinitol (U.S. DoE 2004).

Table 10.1. The twelve building block chemicals that can be produced from sugars via biological or chemical conversions (Source: U.S. Dept of Energy 2004)

Building Blocks
1,4 succinic, fumaric and malic acids
2,5 furan dicarboxylic acid
3 hydroxy propionic acid
aspartic acid
glucaric acid
glutamic acid
itaconic acid
levulinic acid
3-hydroxybutyrolactone
glycerol
sorbitol
xylitol/arabinitol

Below is a list of the approximate groupings of bioplastic products (also shown in Table 10.2).

- Cellulose polymers
- PLA (polylactic acid)
- PTT (polytrimethylene)
- PA (polyamides or nylon)
- PHA (polyhdroxyalkanoates)
- PE (polyethylene)
- PVC (polyvinylchloride)
- PBS (polybutylene succiniate)
- PET (polyethylene terephthalate)
- PEIT (polyehthylene-co-isosorbite terephthalate)
- PUR (polyurethane)
- Thermosets (e.g. epoxy resins)

Appendix Q shows a summary of the material properties and applications of some of these products.

While it is clear that bioplastics are not as sophisticated in material properties performance compared to petrochemical plastics, bioplastics may be the solution to phase out the use of petrochemicals. Bioplastics could be used in applications that do not need high performance material properties. A small number of plastic applications that <u>do</u> require high performance material properties could continue to be petrochemical based. This hybrid solution would phase out the majority of oil, gas and coal consumption currently tasked to plastics manufacture, but would also maintain industrial requirements.

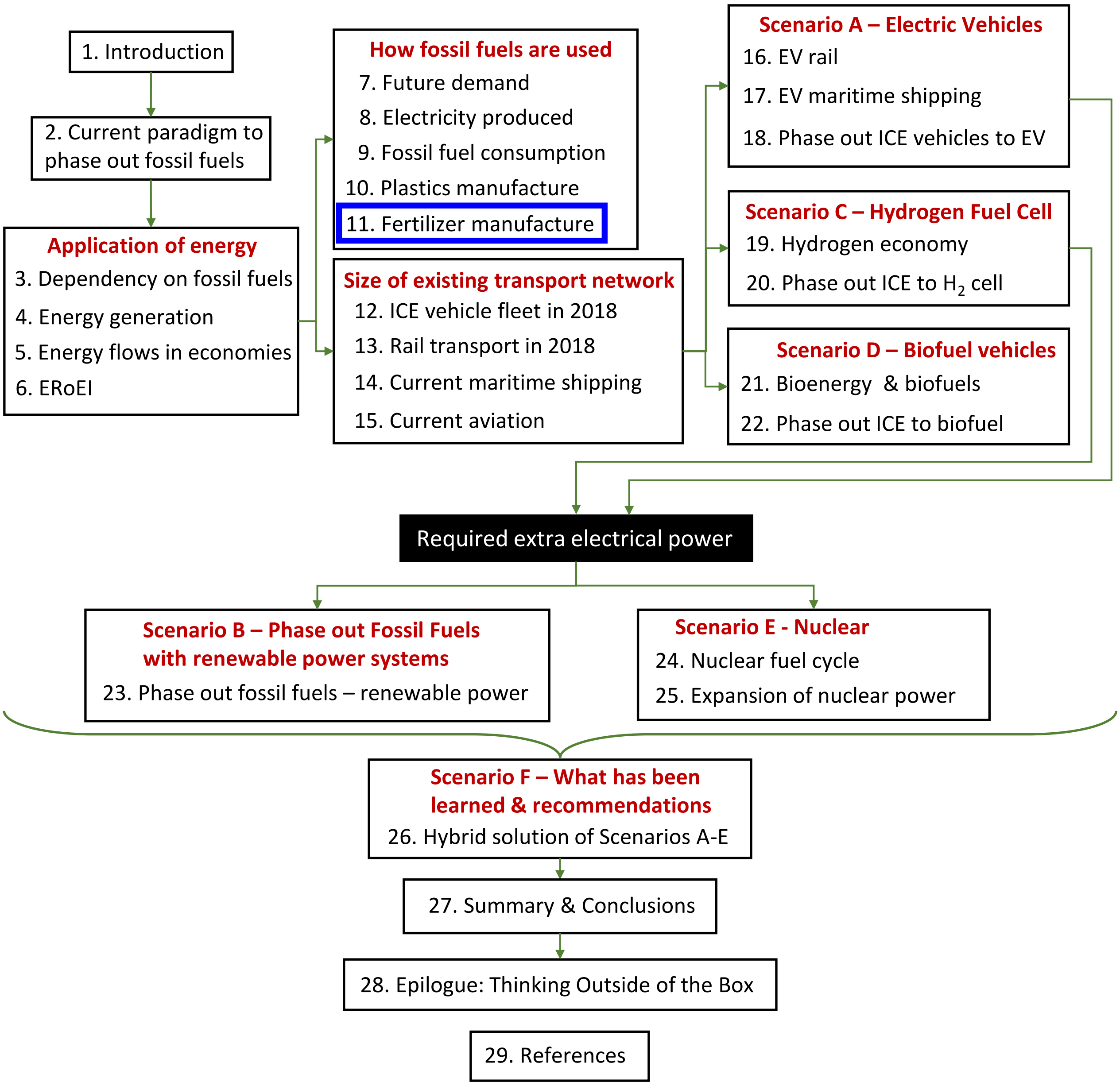
Table 10.2. Overview of most important groups and types of bioplastics (Source: Shen *et al* 2009)

Group	Bio-based plastics (group)	Type of polymer	Types/Structure/Production Method
1	Starch Plastics	Polysaccharides	Partially fermented starch; Thermoplastic starch (TPS); Chemically modified starch; Starch blends; Starch composites
2	Cellulose polymers	Polysaccharides	Organic cellulose esters; Regenerated cellulose
3	Polylactide (PLA)	Polyester	Bio-based monomer (lactide) by fermentation, followed by polymerisation
4	Polytrimethylene terephthalate (PTT)	Polyester	Bio-based 1,3-propanediol (1,3-PDO) by fermentation plus petrochemical terephthalic acid (or DMT)
5	Polyamides	Polyamide	
	a. PA11		Bio-based monomer 11-aminoundecanoic acid from castor oil
	b. PA610		Monomer sebacic acid from castor oil
	c. PA6		Bio-based monomer caprolactam by fermentation of sugar
	d. PA66		Bio-based adipic acid by fermentation
	e. PA69		Bio-based monomer obtained from oleic acid via azelaic (di)acid
6	Polyhydroxyalkanoates (PHA)	Polyester	Direct production of PHA by fermentation
7	Polyethylene (PE)	Polyolefin	Bio-based monomer ethylene obtained from ethanol; ethanol is produced by fermentation of sugar.
8	Polyvinylchloride (PVC)	Polyvinyls	Monomer vinyl chloride can be obtained from bio-based ethylene (from ethanol)
9	Other Thermoplastics *		
	a. Other polyesters (PBT, PBS, PBSL, PBSA, PBST, PBAT, PET, PEIT PVAc, Polyacrylates, PTN, PTI, thermoplastic elastomoers)	Polyester	Variou carboxylic acids, various alcohols
	b. Other ethylene-based compounds (e.g. polystyrene and EPDM rubber)	Various	Ethylene by dehydration of bio-ethanol, reacted with other compounds
	c. Methanol-based compounds (e.g. phenolic resins, urea formaldehyde resins, melamine formaldehyde resins)	Various	Syngas by gasification of biomass, and synthesis of methanol, reacted with other compounds
	d. Propylene-based compounds (e.g. PP, polyacrylates, PUR, PA)	Various	Thermochemical propylene production via bionaphtha plus steamcracking or via biomethanol, followed by Lurgi's methanol-to-propylene (MTP) process or UOP's methanol-to-olefins process.
10	Polyurethanes (PUR)	Polyurethanes	React polyol with isocyanate. Bio-based polyol can be prodcued from vegetable oils.
11	Thermosets	Cross-linked polymers	
	a. Epoxy resins	Epoxy resins	Diglycidyl ether of bisphenol A (DGEBA) derived from bisphenol A and epichlorohydrin (ECH). ECH can be produced by glycerine-to-epichlorohydrin (GTE) process; glycerine is a byproduct of bio-diesel production.
	b. Epoxidised vegetable oils	Epoxide	Addition of oxygen to alkenes
	c. Thermosets based on 1,2-PDO and 1,3-PDO	Unsaturated polyester	Polycondensation of unsaturated and saturated dicarboxylic acids with diols.
	d. Alkyd resins	Alkyd resin	Condensation polymerization of polyols, organic acids and fatty acids or triglyceride oils

* Abbreviations: PBT=polybutylene terephthalate; PBS=polybutylene succinate; PBSL=polybutylene succinate-co-lactate; PBAT=polybutylene adipate-co-butylene terephthalate; PET=polyethylene terephthalate; PEIT=polyethylene-co-isosorbite terephthalate; PVAc=polyvinyl acetate; PTN=polytrimethylene naphthalate; PTI=polytrimethylene isophthalate; EPDM=ethylene propylene diene M-class rubber; PP=polypropylene; UOP=Universal oil Products LLC.

11 FOSSIL FUEL DEPENDANCY OF INDUSTRIAL AGRICULTURE

The petrochemical industry represents a large proportion of the global consumption of oil and gas. Industrial agriculture and global food supply are now dependent on petrochemical fertilizers, herbicides, and pesticides. The purpose of Section 11 is to examine how fossil fuels are used to manufacture petrochemical fertilizers, which in turn relates to global demand patterns in food consumption.



Assessment of the Extra Capacity Required of Alternative Energy Electrical Power Systems to Completely Replace Fossil Fuels

The production of fertilizer accounts for a sizeable proportion of the energy consumed to produce food in industrial agriculture. In the late 1990's, the energy consumed to produce fertilizer accounts for 28% of the global energy consumed for industrial agriculture (Heller & Keoleian 2000). This is mainly the consumption of gas to produce ammonia (see below). Petroleum products like diesel are critical inputs for the functioning of the industrial production of food (most agricultural equipment vehicles are diesel ICE fueled).

Currently, the average human consumes about 2 800 kcal per day (increasing from an average of 2 360 kcal/day in the mid-1960's, www.fao.org). It is convenient to remember that 2400 kcal equals 10 MJ (megajoules), so that per year we consume endosomatically about 3.6 GJ (gigajoules). The exosomatic use of energy in rich countries per person per year reaches 150 or 200 GJ on average, reflecting the fact that most energy (from fossil fuels, biomass, hydroelectricity, nuclear fission, wind) goes to production and consumption processes different from those directed to basic food needs (Martinez-Alier 2011).

The systems that produce the world's food supply are heavily dependent on fossil fuels (Green 1978), which was accelerated by what was termed the Green Revolution. To feed the global 2021 population of 7.9 billion (as of May 2021, https://www.worldometers.info/world-population/) without fossil fuel-derived fertilizers would require half of all ice-free land on the planet instead of the 15% of land used today (Smil 2011). Approximately 9 % of global gas demand is used to produce ammonia for the manufacture of fertilizer (Martinez-Alier 2011).

Figure 11.1: How NPK fertilizer was marketed as part of the petrochemical Green Revolution. Test cropping in 1940s Tennessee Franklin D. Roosevelt Presidential Library and Museum
(Source: Faradji & de Boer 2016).

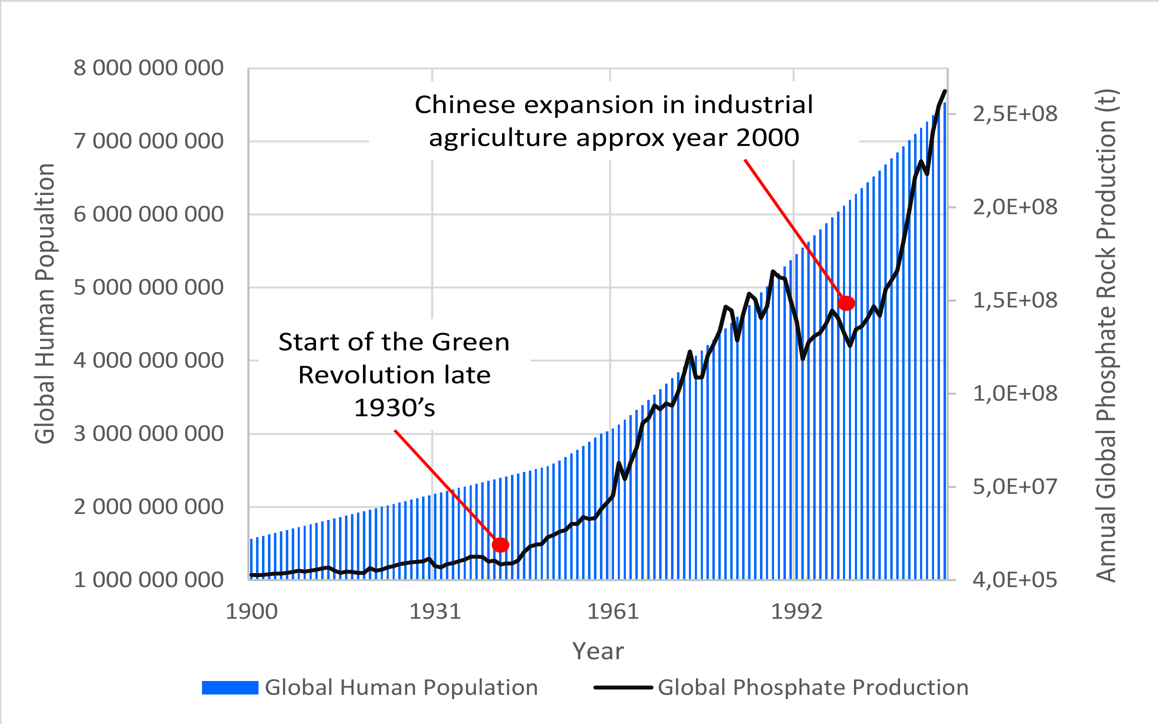


Figure 11.2: (in blue columns) Historic human global population growth 1900 to 2017 (United Nations, Department of Economic and Social Affairs, Population Division 2017). (black solid line) Historical global phosphate rock production 1900 to 2017 (source USGS).

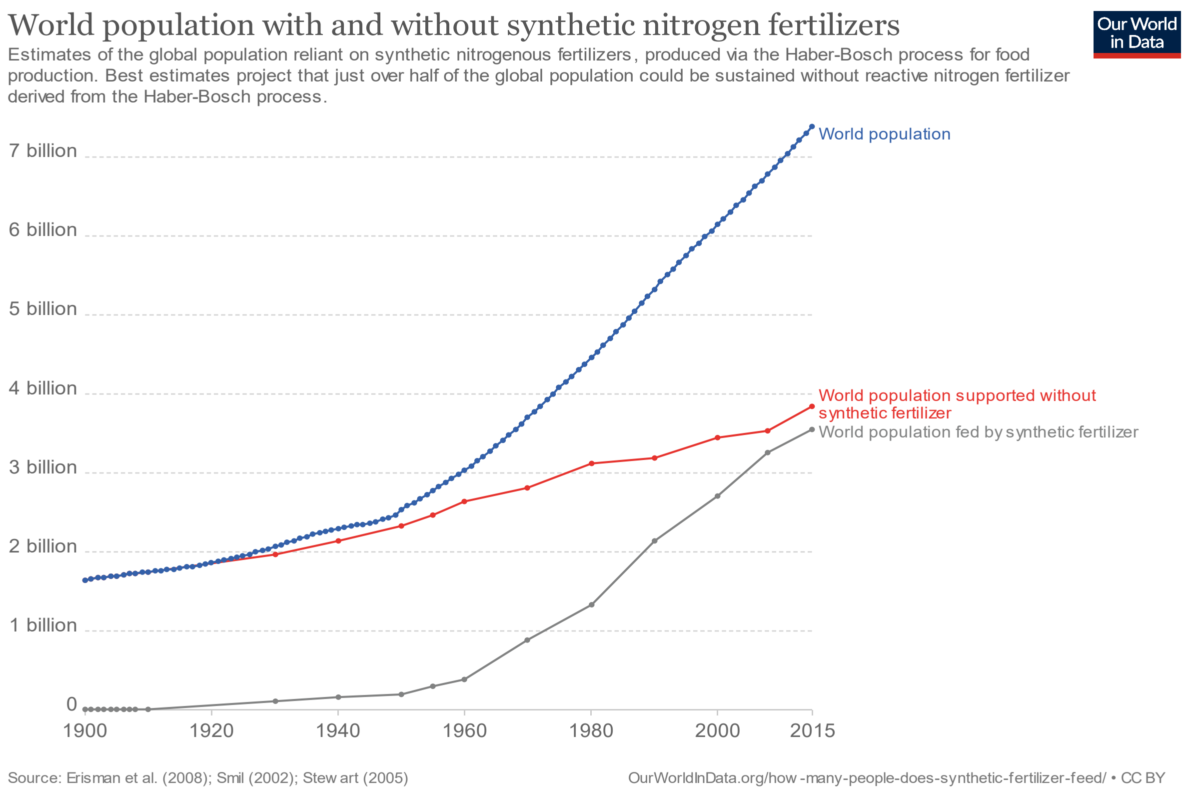


Figure 11.3. World population supported with and without synthetic nitrogen fertilizers (Source: Max Roser and Hannah Ritchie (2013) - "Fertilizers". Published online at OurWorldInData.org. Retrieved from: 'https://ourworldindata.org/fertilizers' [Online Resource])

The decrease in global Phosphate production in the end of 1980's is an interesting data signature. This decline could be due to be the decline of P fertilization in Eastern Europe and Central Asia. This correlates with the end of the Soviet Union.

The Green Revolution, or Third Agricultural Revolution, refers to research and the development of technology transfer initiatives occurring between 1950 and the late 1960s, which increased agricultural production worldwide, particularly in the developing world, beginning most markedly in the late 1960s (Farmer 1986). Figure 11.1 shows a picture used to gain public understanding and acceptance of NPK fertilizers.

The consumption of phosphate mineral to manufacture petrochemical fertilizers, herbicides, and pesticides, are linked to the industrial agriculture manufacture of food, which in turn correlates strongly with human population growth (Cordell et al 2009). With the benefit of hindsight, it can be seen that the late 1930's was the time when the petrochemical supported Green Revolution initiated a significant expansion of food production after World War II (1945) (Figure 11.2 and 11.3). After the Second World War, increased deployment of technologies including pesticides, herbicides, and fertilizers as well as new breeds of high yield crops greatly increased global food production (Erisman *et al* 2008, Fisher 2001).

Due to predicted human population growth, future food demand is projected to require an increase food production by 70 - 100 % by 2050 (FAO 2015a, United Nations 2019). To achieve a doubling of crop yields in the next 30 years, an annual yield increase of 2.2% would be required. To put this in context, this is more than the average annual increase of the past 50 years (Weber and Bar-Even 2019). So more efficient production than ever before is required to meet food requirements of the global human population. This puts unprecedented pressure on the global arable land capacity.

The rate of growth of 14 types of food that provide the majority of our calories had an average peak rate year of 2006 (Seppelt *et al* 2014).

Petrochemical technology applied to the processing of phosphorous (sourced from phosphate rock), nitrogen and potassium developed a spectrum of capabilities that accelerated the ability to manufacture food (NPK fertilizer and pesticides) (NPK = Nitrogen-Phosphorus-Potassium). A common phosphorus-based fertilizer on the global market is DAP (diammonium phosphate). The initiatives resulted in the adoption of new technologies, including High-Yielding Varieties (HYVs) of cereals, especially dwarf wheat's and rice's, in association with chemical fertilizers and agro-chemicals, and with controlled water-supply (usually involving irrigation) and new methods of cultivation, including mechanization. All of these together were seen as a 'package of practices' to supersede 'traditional' technology and to be adopted as a whole.

Petrochemical fertilizers are another name for the synthetic products because they are produced using large quantities of petroleum, gas, and coal. Some common examples include ammonium nitrate, super phosphate, and potassium sulfate.

Figure 11.4 and 11.5 shows the market share of different NPK industrial fertilizers.

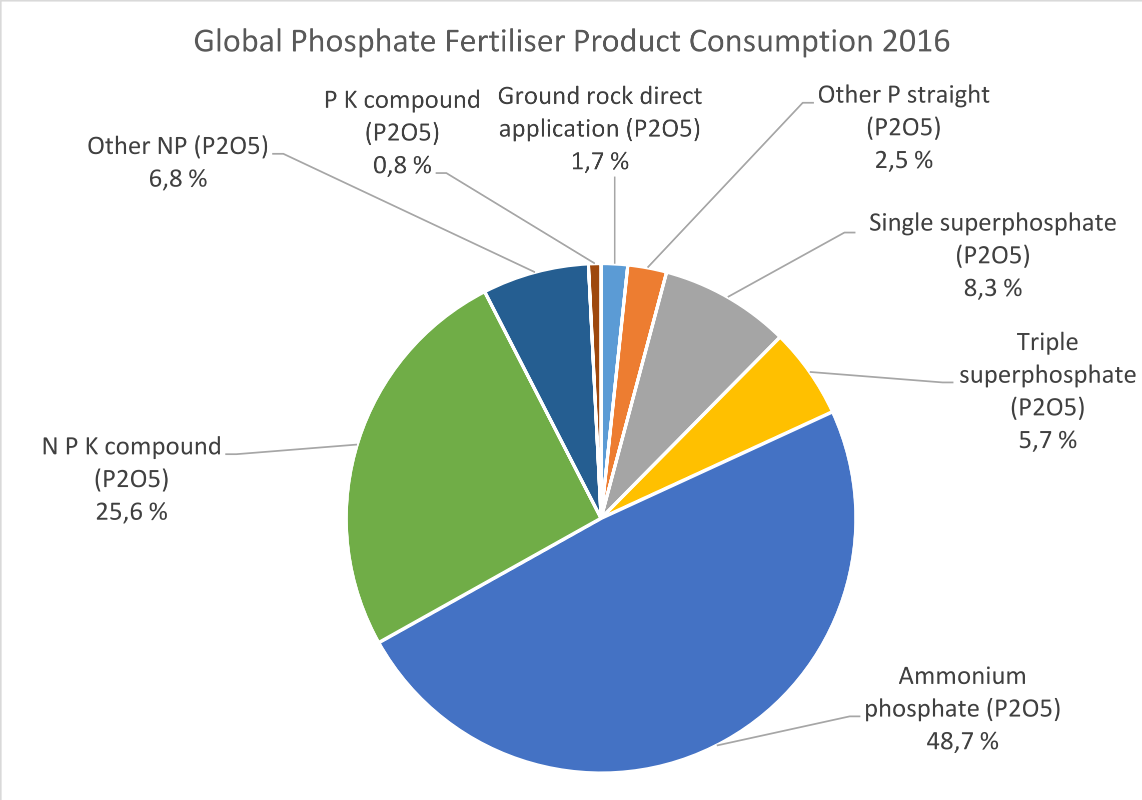


Figure 11.4. Global phosphate fertilizer product consumption in 2016 by product (Source: International Fertilizer Association IFA data)

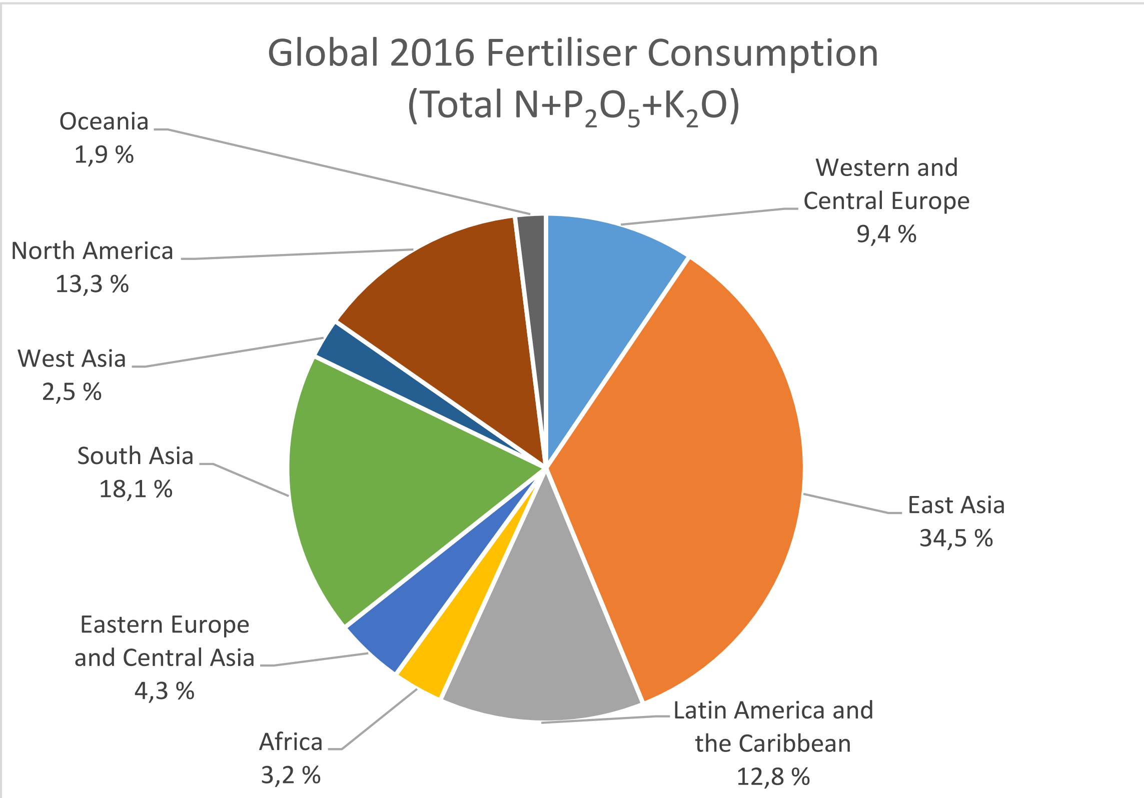


Figure 11.5. Global phosphate fertilizer product consumption in 2016 by product (Source: International Fertilizer Association IFA data)

11.1 Industrially produced nitrogen fertilizer

Nitrogen is a key component of most synthetic fertilizers, as plants require it for photosynthesis. The use of industrially produced nitrogen fertilizers has expanded significantly in the last few decades. Currently, 70% of the world's agricultural land requires nitrogen to become productive and produce food crops. More than half of the synthetic nitrogen fertilizers ever produced globally, have been used since 1985 (UN 2005, Friedemann 2021).

It is made by using heat to force the combining of nitrogen (sourced from the air, and sometimes sourced from gasifying coal) with hydrogen to produce ammonia (NH_3). This is achieved through the use of the Haber-Bosch process (Appl 1982), which is an artificial nitrogen fixation process and is the main industrial procedure for the production of ammonia. The hydrogen is sourced from natural gas, with the majority content being methane. The reaction is reversible, and the production of ammonia is exothermic.

$$N_2 + 3H_2 \xrightarrow{yields} 2NH_3 \qquad \text{Equation 11.1}$$

At each pass of the gases through the reactor, only about 15% of the nitrogen and hydrogen converts to ammonia (Appl 1982). Gases are cooled and ammonia turns into liquid. Liquid ammonia is separated, and rest of the gas is recycled (Figure 11.6). By continual recycling of the unreacted nitrogen and hydrogen, it is possible to produce ammonia from about 97 to 98% of the feedstock. This conversion requires to be conducted at pressures above 10 MPa (is often much higher for efficiency of output) and between 400 and 500 °C. The ammonia is then used to create other forms of nitrogen including ammonium nitrate and urea (ammonia + CO_2).

Nitrogen fertilizers are intimately dependent on gas, resulting in the petrochemical classification. 80% of the gas is used as feed-stock for fertilizer to make hydrogen (31.5 Mt were consumed in this fashion in 2018), while 20% is used for heating the process and producing electricity. Based on the two main end products, ammonium nitrate and urea, different fertilizer types are manufactured by mixing with ingredients such as phosphorus and potassium to form NPK class products.

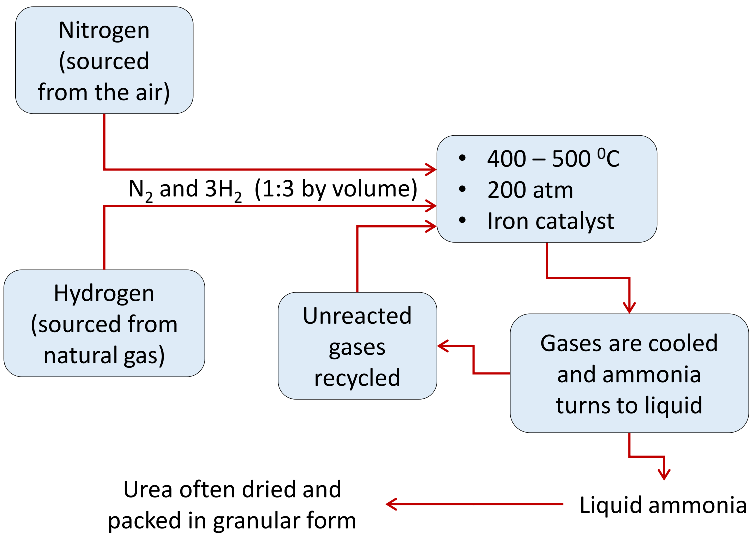


Figure 11.6. the Haber-Bosch procedure to produce ammonia (Image: Simon Michaux)

Ammonia, NH_3, has 82% of nitrogen by mass (Patzek 2004).

Urea, $CO(NH_2)_2$, has 45% of nitrogen by mass, and is obtained from ammonia and carbon dioxide:

$2NH_3 + CO_2 \rightarrow CO(NH_2)_2 + H_2O$ (Patzek 2004).

Ammonium Nitrate, NH_4NO_3, has 35% nitrogen by mass, and is produced from nitric acid and ammonia: $HNO_3 + NH_3 \rightarrow NH_4NO_3$ (Patzek 2004).

11.2 Industrially produced phosphorus fertilizer

The element phosphorus underpins the ability to produce food. It is second to nitrogen as the most limiting element for plant growth on 40% of the world's arable land. With too little phosphorus, plants are stunted with low yields. With enough phosphorus, crop yields can increase by 50% (UNFAO 2015).

At the time of writing this report, there is no element that can substitute for phosphorus, nor can it be manufactured. The closest element to Phosphorous in the same family of the periodic table is arsenic. Due to toxicity to living organisms, the substitution of arsenic into fertilizers is unlikely. This means that it will be very difficult to find an alternative to P in future work in this application. As a mitigation strategy, it is possible to reduce the use significantly by increasing phosphorus availability through modifying soil properties. This has been the subject of research since the beginning of the Green Revolution (Goeller & Weinberg 1978). Petrochemical application of phosphorus also manufactures pesticides. Phosphorous is one of the macronutrients (as with nitrogen and potassium) and cannot be substituted in its role in manufacturing petrochemical fertilizer use in industrial agriculture (Steiner and Geissler 2018). While other critical global resources, such as oil, can be replaced with renewable energy sources, such as wind or solar power, no other element can replace phosphorus in food production.

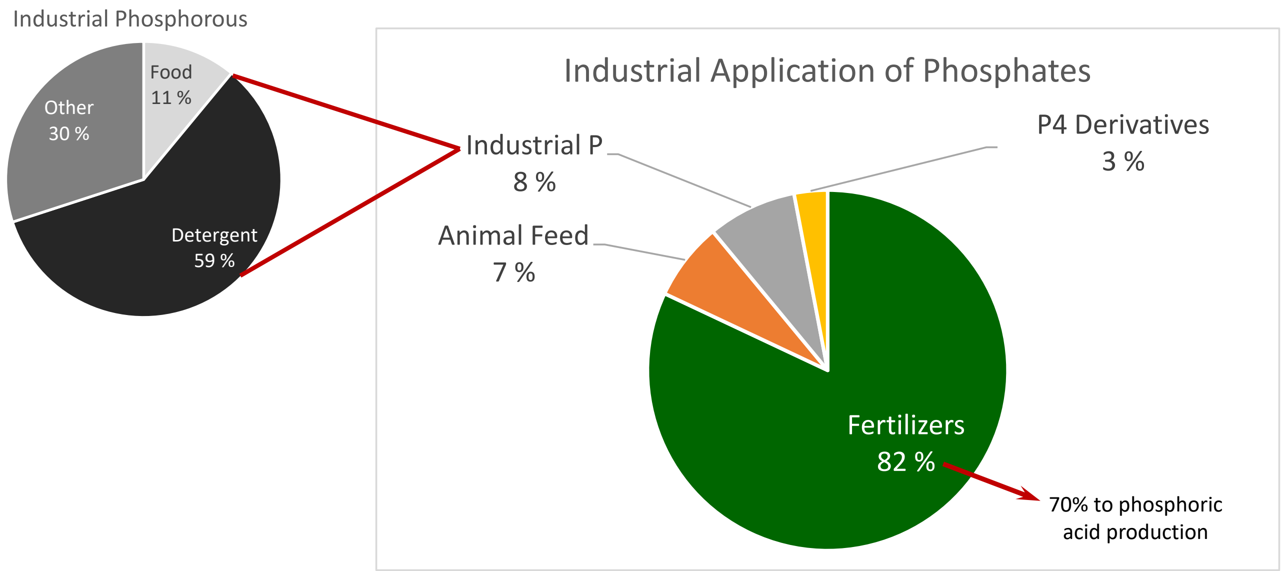


Figure 11.7. Industrial application and use of phosphate. Source British Sulphur Consultants (CRU Group)

Ultimately, only 20% of phosphorous mined for food production actually is retained in the food consumed by the human population each year (Cordell & White 2013). Close to 100% of phosphorous eaten in food is excreted. The current food production system is extremely inefficient with respect to phosphorous use. The remaining 80% of phosphorus mined for food production is lost to the environment during food manufacture in a number of ways. Some of those losses have the potential to be recycled. The UN's Food & Agricultural Organization (FAO) and the international fertilizer industry (IFA) have called for more integrated nutrient management that ensures crop productivity through optimizing soil fertility and meeting nutrient needs from a range of organic and inorganic sources (IFA 2007, FAO 2006, FAO 2008).

To extend the life of existing reserves of phosphorus in the face of emerging scarcity, efficiency measures and recycling initiatives could be considered (Cordell & White 2013):

- Minimizing phosphorous losses from the farm (estimated at 8MT Phosphorous)
- Minimizing losses in the food commodity chain (estimated at 2MT Phosphorous)
- Alternative renewable phosphorous sources like manure (around 15 MT Phosphorous), human excreta (3MT Phosphorous) and food residues (1.2MT Phosphorous)

Other important mechanisms to reduce overall demand include optimizing soil carbon to improve phosphate availability and influencing a shift in diets.

As a general trend, phosphate fertilizers are needed to ensure a constantly high level of crop yields. In some geographical areas (in Europe for example), high P fertilizer rates and use animal manure have created many fields, where soil P supply is sufficient for high crop yields and annual P fertilization is not necessary. So in short term phosphate fertilizers are not necessary is some parts of the world, but after a while zero P-rates would again lead to demand of mineral P.

Phosphorus is a limiting nutrient in crop growth and hence can limit global crop yields. Currently the majority of global food production is dependent on phosphate rock as a raw supply. This underpins the viability of the Green Revolution. These, in turn, are necessary to meet the world's food demand, and to sustain agricultural livelihoods. Most of the fertilizers consumed have phosphate rock as their primary ingredient. Figure 11.4 shows the relative proportions of the different fertilizer products. Figure 11.5 shows the regions around the world that consume fertilizer products in industrial agriculture industries.

Phosphorus fertilizers are produced by acidulating phosphate rock. By itself, phosphate rock is not soluble and so cannot provide phosphorus in an available form for plant use. To produce a phosphorus fertilizer, the rock is treated sulfuric, phosphoric, or nitric acid Each method has its advantages and constraints. The sulfuric acid route produces a low phosphorus fertilizer – single superphosphate - which is half gypsum.

The use of phosphoric acid produces a higher concentration phosphorus fertilizer. The third manufacturing process is to use nitric acid to acidulate the rock phosphate. This process is a cleaner process with no waste products and produces two fertilizers:

- Nitrophosphates which are combined with potassium to produce the complex NPK fertilizers such as YaraMila.
- Calcium nitrate (from the nitric acid combining with the calcium in the rock phosphate) as found in the YaraLiva range.

The limitation of this process is that the phosphate content of the fertilizer cannot exceed the nitrogen content.

Phosphate and phosphoric acid are produced from the igneous fluorapatite $Ca_{10}(PO_4)_6(F, OH)_2$, and the sedimentary francolite $Ca_{10}(PO_4)6_x(CO_3)_x(F, OH)_{2+x}$. For example, superphosphate maybe produced as follows (Patzek 2004):

$$2Ca_3(PO_4)_2 + 6H_2SO_4 \rightarrow 4H_3 PO_4 + 6CaSO_4$$

$$Ca_3(PO_4)_2 + 4H_3PO_4 \rightarrow 3Ca(H_2PO_4)_2$$

11.2.1 Production of phosphate rock

The phosphate rock is processed to produce fertilizers, food-grade and feed-grade additives, and detergents. Other marginal applications include metal surface treatment, corrosion inhibition, flame retardants, water treatment, and ceramic production. Despite such widespread use, the latter applications represented only ~3% of the total consumption of various phosphates. Phosphate rock is mined, beneficiated (extracted with flotation), and either solubilized to produce wet-process phosphoric acid or smelted to produce elemental phosphorus. Phosphoric acid is reacted with phosphate rock to produce the fertilizer triple superphosphate or with anhydrous ammonia to produce the ammonium phosphate fertilizers.

There have been several source types of phosphorous. Before industrialization, phosphorus was sourced from animal manure and in some cases from deposits of guano (avian manure). The first superphosphate was produced by treating bones with acid. In the late 1800's, it became viable to mine phosphate rock and use it to produce phosphorus at an industrial scale. Deposits which contain phosphate in quantities and concentrations that are economic to mine are not particularly common. The two main sources for phosphate are guano, formed from bird droppings, and rocks containing concentrations of the calcium phosphate mineral, apatite.

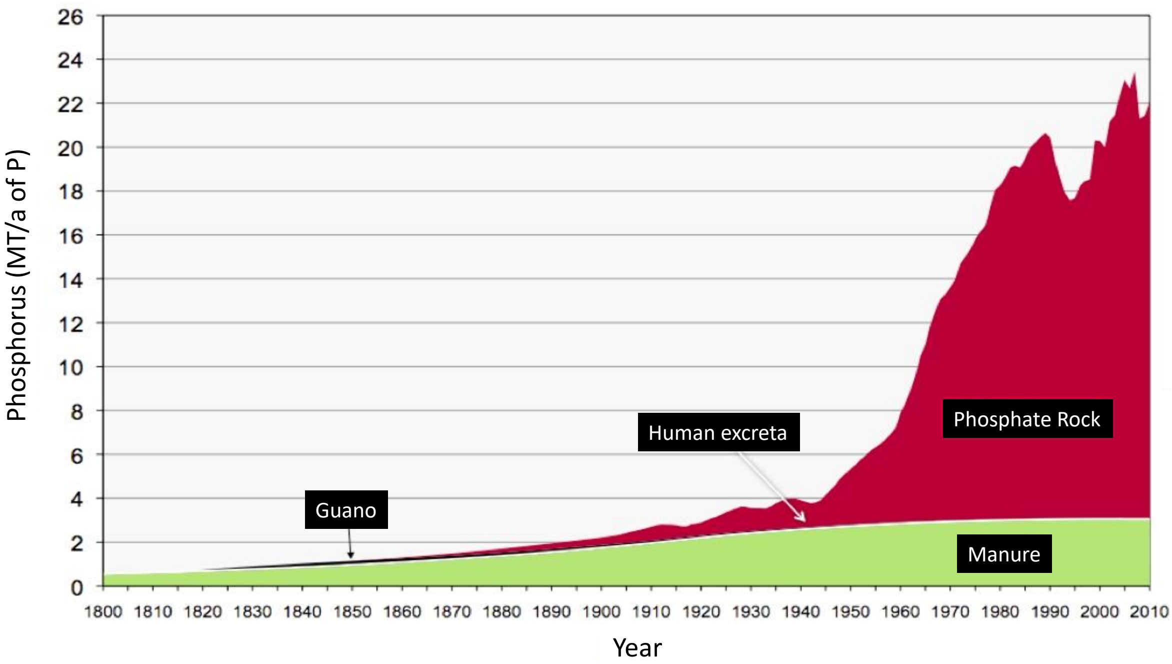


Figure 11.8. Historical sources of phosphorus (Cordell *et al* 2009)

Historically, 90% of phosphate rock was mined to manufacture fertilizer to sustain food production in pace with human population food demand (Bennet and Elser 2011). Phosphorous rock that is high grade, with lower contaminant content and that is easy to access has usually been mined first (Sinding-Larsen and Wellmer 2012). The agricultural utilization of petrochemical fertilizer of what was applied per unit land area has been typically low, where nearly 90 % of phosphorous has been lost to the environment following primary consumption (Cordell *et al* 2009a and 2009b). Loss of P is also related to poor recycling of organic matter, when animal manure and sewage sludge are not recycled back to the fields.

Global production of phosphate rock was in 227 million tonnes in 2019 (USGS Annual Mineral Statistics 2021). China produced 140 000 000 tonnes or 53.3% of global production. The United States produced 27

700 000 tonnes or 10.5 % of global production. Morocco and West Sahara produced 27 000 000 tonnes or 10.3% of global production.

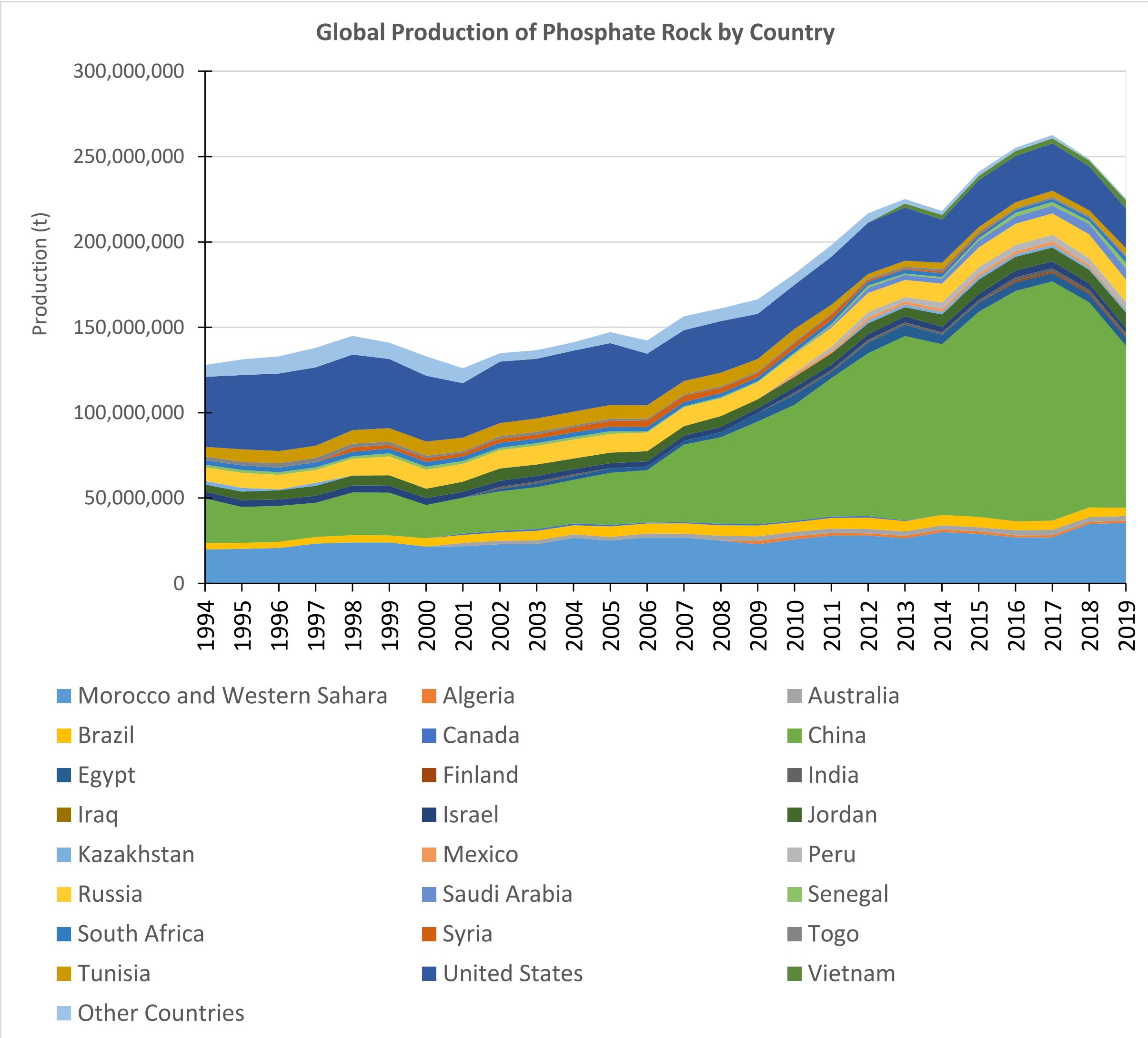


Figure 11.9. Global phosphate rock production by country (Source: USGS Annual Mineral Statistics 1994 to 2021)

11.2.2 Phosphate rock reserves

Phosphate rock has been defined as a Critical Raw Material (CRM) by the European Commission, due to its necessity in the production of food through the application of industrial agriculture. Most of the phosphate reserves are not developed yet for production. Supply to market with existing production in context of growing demand (in context growing population and required increasing tonnes per unit area to meet yield targets), may produce an inelastic supply gap at market in the decade of 2020 to 2030 (Chowdhury *et al* 2015).

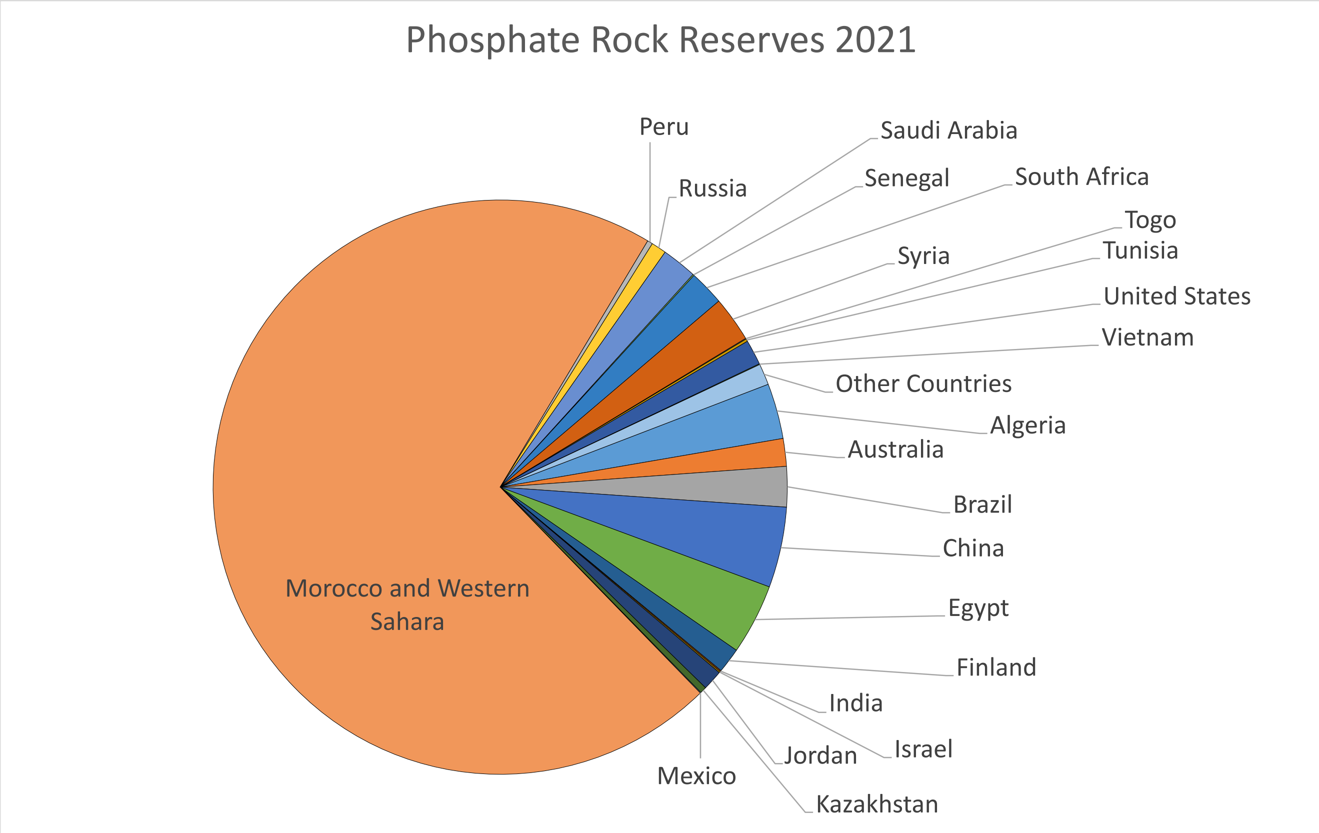


Figure 11.10. Phosphate Reserves as stated in 2017 (Source: USGS Annual Mineral Statistics 2021)

In 2021, global reserves of phosphate rock were stated at 70 553 million tonnes (USGS 2021). In 1994, global reserves of phosphate rock were stated at 11 410 million tonnes, or just 16% of 2021 reserves (Figure 11.10). This highlights the importance and impact of the 2010 reporting of the 44 300 million tonne reserve in Morocco.

In all the data collected, there was not consistent information about the mineral quality of phosphate reserves. It is known that like all other mineral reserves, heavy metal content in phosphate deposits varies between deposits. The deposits in northern Africa are high in harmful penalty elements (Nino-Savala *et al* 2019). There are process solutions to mitigate the presence of penalty elements like the decadmination process.

The concern for potential future scarcity of phosphate resources relates to two sectors of the value chain. Availability (or potential availability) of viable phosphorus mineral reserves, and the increasing expansion of demand for phosphorus derived products.

There is considerable uncertainty regarding the quantity of existing recoverable reserves of phosphate. As shown in Figure 11.11, 70.87 % of global reserves of phosphate rock resulted from the reporting of a deposits in Morrocco in one year (2010). However, this nation state does not publicize the details (grade, quantity, position, etc.) of those reserves in context of an external audit. The production of phosphate rock is more reliably known. Figure 11.11 below shows the addition of new reserves each year over the last 23 years. As can be observed, new reserves are not that common. Often, demand driven production will deplete reserves where there is a net reduction in reserves quantity.

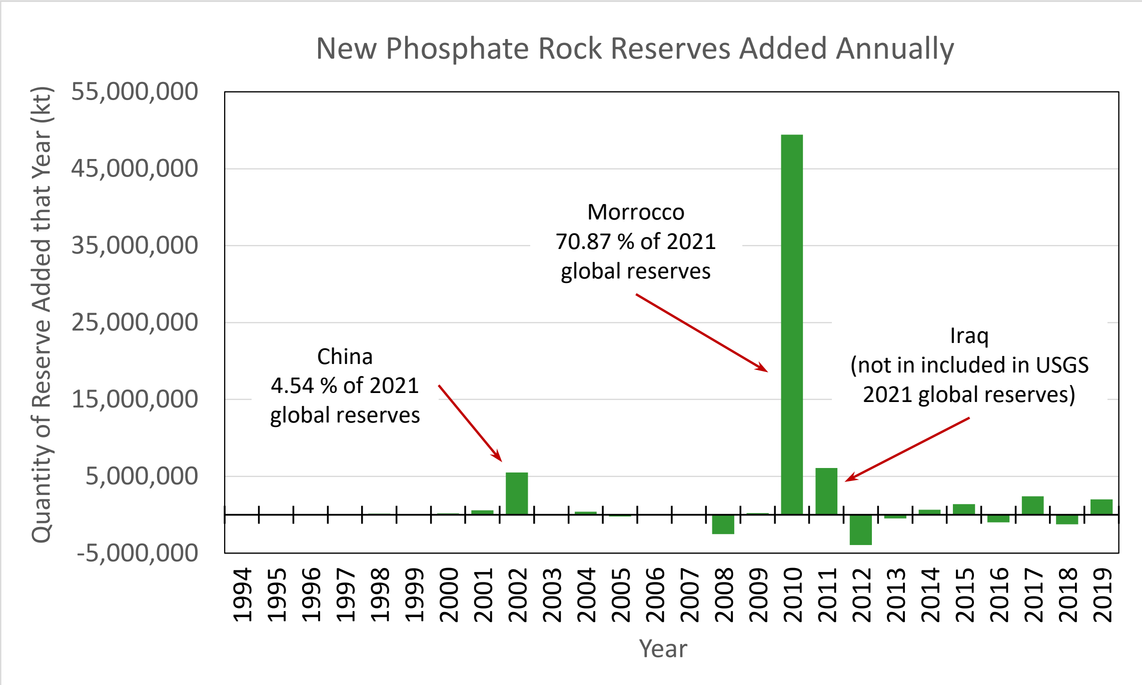


Figure 11.11: New phosphates reserves added by year. Calculated by tracking the net change of stated reserves each year. Annual global production of phosphate rock subtracted from quoted global reserves for each year. (Source: USGS Annual Mineral Statistics 1994 to 2021)

China consumed 26% in 2019 of global demand (FAO) for phosphate rock and produced 42.2 % of the phosphate brought to market in 2019, yet it has only 4.54 % of global reserves (first reported in 2002). The deposit that was reported in 2011 in Iraq is no longer considered part of global reserves. In 2010, a new reserve was reported in Morocco (in addition to the existing deposit in that country). This one reporting accounts for 70.87 % of globally reported reserves in 2021. What is unfortunate is that the Morocco government will not allow external audits to be done on this deposit and is managed in a similar manner to how Saudi Arabia manages its oil reserves. While it is that nation's right to do so, this is an unfortunate state of affairs for the rest of the world that have become reliant on this non-renewable natural resource, with no viable substitute.

The Upper Cretaceous geological period represents a phosphogenic period in which many phosphorites have been discovered worldwide. Based on paleo-environmental considerations along with findings from borehole evidence e.g., the late Cretaceous Series of eastern Ethiopia has great potential for phosphate accumulations. Unfortunately, the Upper Cretaceous sediments do not crop out at the surface, covered by Paleogene successions, which might be the case in many parts of the world. This could be potential for undiscovered resources.

11.2.3 Industrially produced potassium fertilizer

Most potassium used in fertilizer production is taken from natural deposits of potassium chloride (KCl). The mined material is crushed and purified by the removal of rock particles and salt. Deposits of potassium sulfate and potassium nitrate are rarer, but when used, are treated in a similar manner.

The Danakil depression in Ethiopia and Eritrea is the largest unexploited potash basin the world to date with a possible 7 to 9 billion tonnes of potassium bearing salts (Warren 2015, Chernet 2021).

11.3 Industrial fertilizer consumption

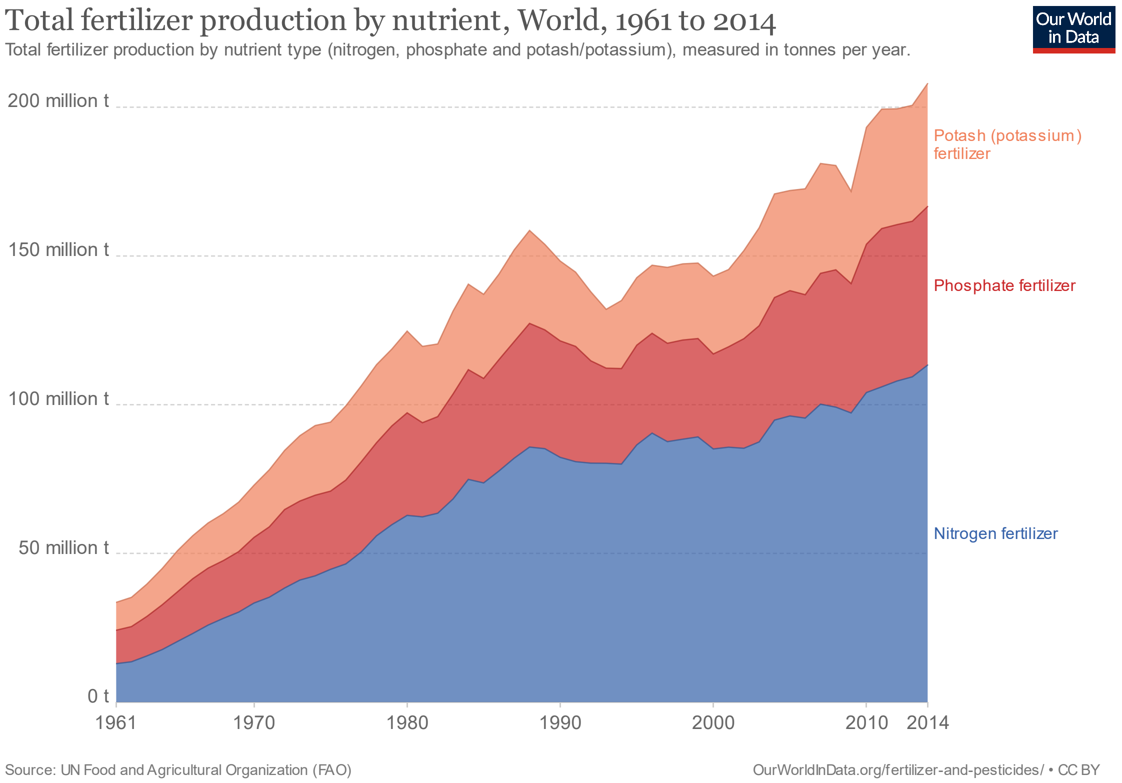


Figure 11.12. Total fertilizer production by nutrient, World, 1961 to 2014
(Source: Max Roser and Hannah Ritchie (2013) - "Fertilizers". Published online at OurWorldInData.org. Retrieved from: 'https://ourworldindata.org/fertilizers' [Online Resource])

In approximately the year 2000, Chinese consumption of petrochemical fertilizer (derived from among other things phosphate rock) aggressively expanded. The PRC (Peoples Republic of China) has made a series of long term strategies to ensure long term economic security for the nation (Xiaoqiang *et al* 2017). One of the strategies listed was to dominate the industrial agriculture manufacture sector and aggressively expand the industrial production of food. One of the driving forces behind this was the PRC desire to urbanize 400 million people from a simple rural society into a modern industrial society. There was a future perceived food supply gap within China. In the year 2000, the expansion of the industrial agricultural industry was given a new priority as a matter of national security. As can be seen in Figure 11.13, China now far exceeds the rest of the world in not only how much Chinese phosphate rock is produced, but in the consumption of and application of petrochemical fertilizer per unit area of arable land. It is not clear whether the data presented in Figure 11.13 is entirely NPK based nutrients.

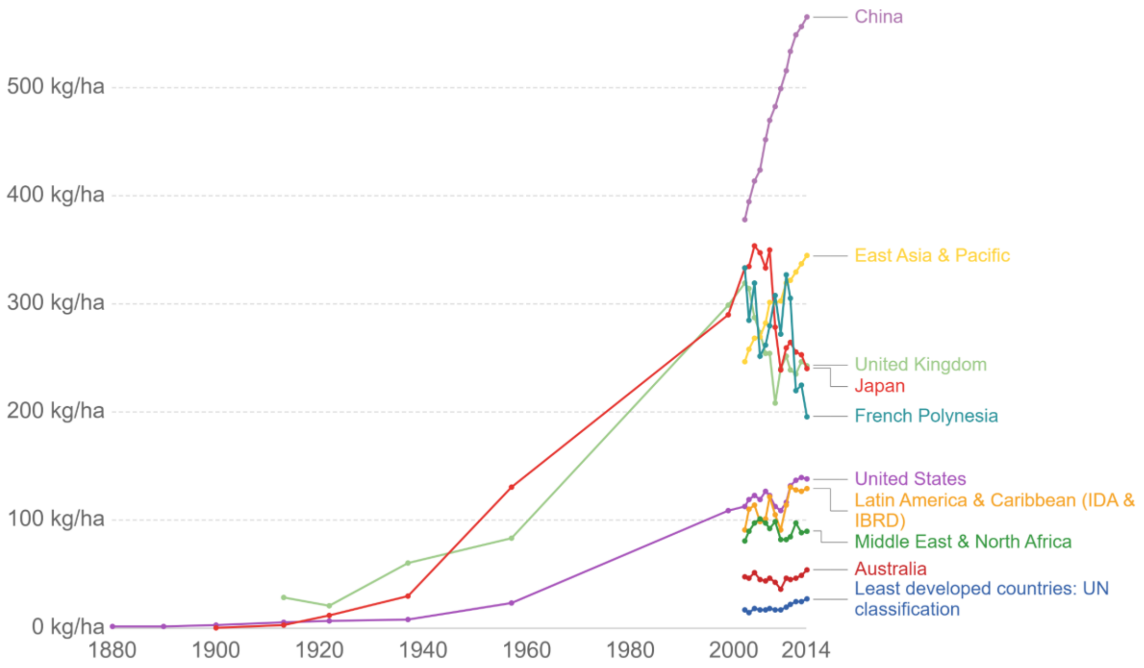


Figure 11.13. Fertilizer application rates between 1880 and 2014. Average fertilizer application rates for select counties and regions over time. Measured in kilograms of nutrient per hectare of arable land.
(Source: World Bank and Federico 2008, OurWolrdindata.org/fertilizer-and-pesticides/)
(Copyright: Our World in Data authorized)

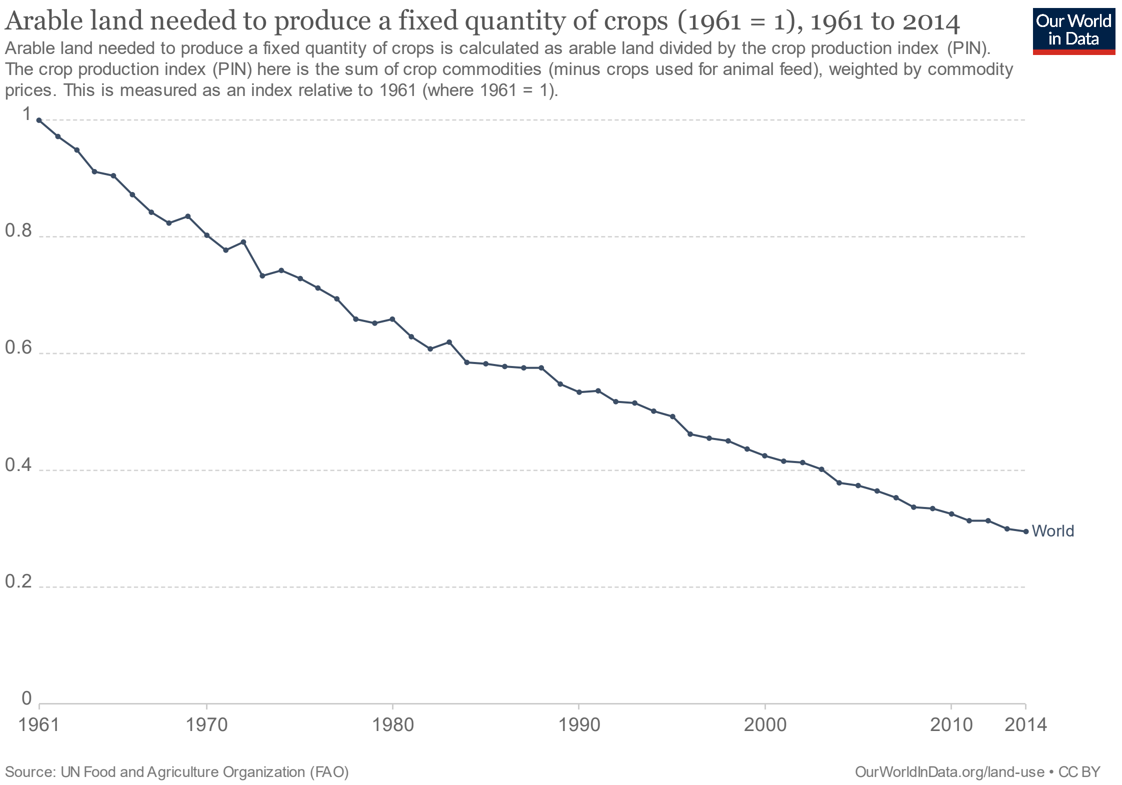
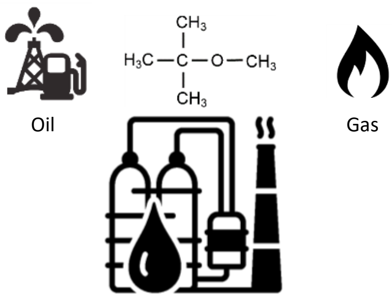


Figure 11.14. Arable land needed per unit of crop production (Source: Hannah Ritchie and Max Roser (2013) - "Land Use". Published online at OurWorldInData.org. Retrieved from: 'https://ourworldindata.org/land-use' [Online Resource])

The introduction of petrochemical fertilizers have consistently increased the yield, where each unit of land becomes more productive (Figure 11.14). China's grain yield increased from 1 t/ha in 1961 to 6 t/ha in 2015, while successfully feeding not only its large population but also supplying agricultural products all over the world. These achievements were greatly supported by modern technology and distinct governmental policy (Li *et al* 2013). In the past 60 years, China's total grain output increased by fivefold, from 113 million tons (MT) in 1949 to 571 MT in 2011, a statistic which provides inspiration to producers in other parts of the world. Grain production per capita doubled, from 209 to 425 kg during the same time period. At the national scale, China has succeeded in maintaining a basic self-sufficiency for grain for the past three decades. However, with the increasing population pressure and a growing appetite for animal products, China will need 776 MT grain by 2030 to feed its own people, a net increase of 35.9% from its best year on record (Li *et al* 2013). All of which is petrochemical dependent.

In summary, petrochemical fertilizers and pesticides are needed to ensure a constantly high level of crop yields. These, in turn, are necessary to meet the world's food demand and provide a living for the farmer engaging in planting and harvesting the crops. Most of the fertilizers consumed have phosphate rock as their primary ingredient. Currently, for every calorie of food consumed, there was 10 calories of fossil fuel energy consumed to create and deliver that food (Ruppert 2004, Martenson 2011 and Turner 2008).



Vast amounts of petroleum products are used as raw materials and energy in the manufacture of fertilizers and pesticides, and as cheap and readily available energy at all stages of food production: from planting, irrigation, feeding and harvesting, through to processing, distribution, and packaging. In addition, fossil fuels are essential in the construction and the repair of equipment and infrastructure needed to facilitate this industry, including farm machinery, processing facilities, storage, ships, trucks, and roads. The industrial food supply system is one of the biggest consumers of fossil fuels. There is good potential to recycle food waste to recover nutrients (Geneviève *et al* 2020), where this could resolve some of the challenges facing the fertilizer industry. Many of these recommendations have not been implemented. Figure 11.15 shows the FAO Food Price Index (an index used by the World Bank to model a basket of food based commodities in the production of food at a global scale) and the North Sea Brent Oil price.

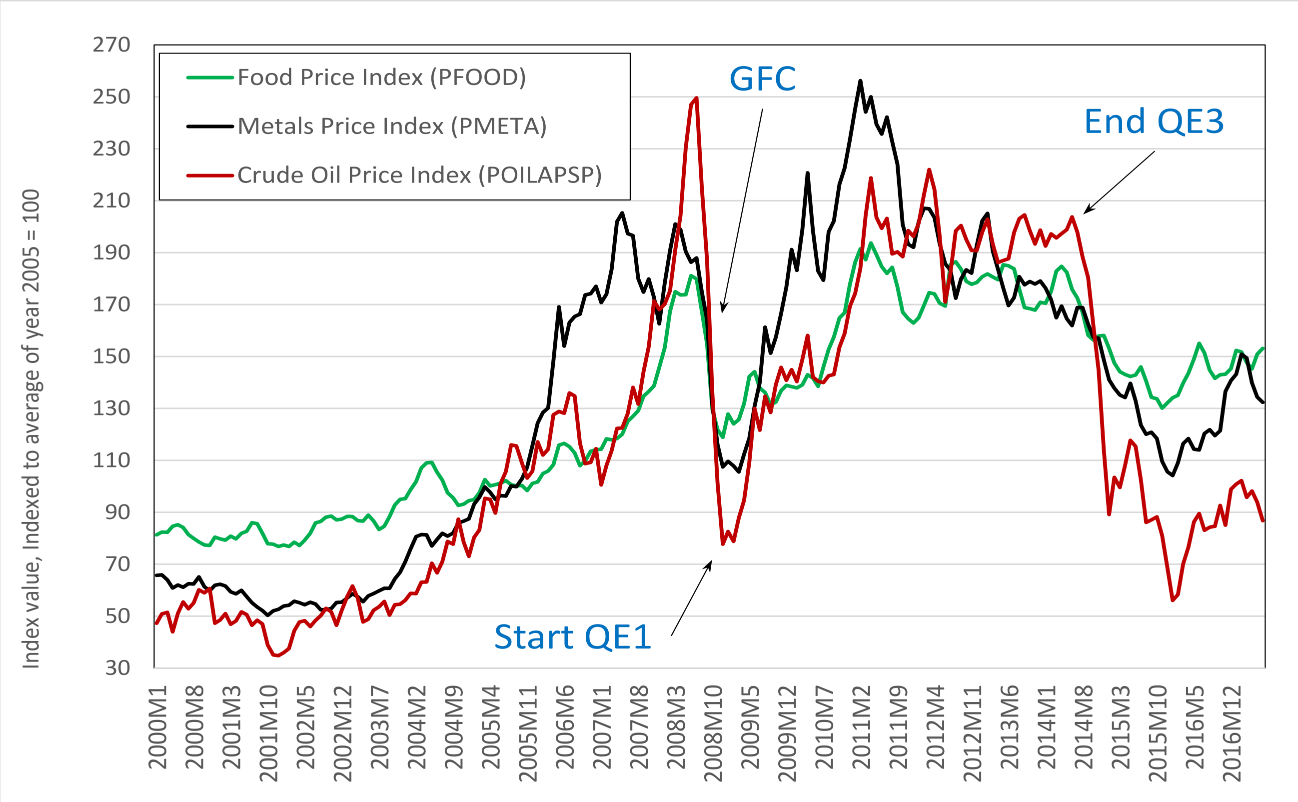


Figure 11.15. Correlation between global food price, metal price and crude oil
(Source: IMF Primary Commodity Price System, http://www.imf.org/external/np/res/commod/External_Data.xls)

As can be seen, industrial agriculture food production (Food price Index) strongly correlates with the oil price index (which reflects demand). Initially, the concept of food being dependent on oil seems counter intuitive. For every calorie of food that is produced in the United States, 10 calories of fossil fuel energy are put into the system to grow that food in terms of production, storage, and transport (Green 1978, Canning *et al*. 2017). Figure 11.16 shows how this happens. This is a systems modelling approach to examine and model farming. The words in red show the sections that depend on fossil fuels either directly (consumption of diesel fuel) or indirectly (consumption of electricity generated from fossil fuels).

The manufacture of phosphate to make petrochemical fertilizer is also dependent on oil and gas (Michaux 2018). Phosphate rock first has to be mined then refined. This requires energy as well, including oil and gas.

There is however a complication in the analysis of food to oil correlation. What was considered arable agricultural land for food production is now being diverted to the production of biofuels (Muller *et al*. 2007). This is being reinforced by land clearance and a wide spectrum of climate change derived outcomes.

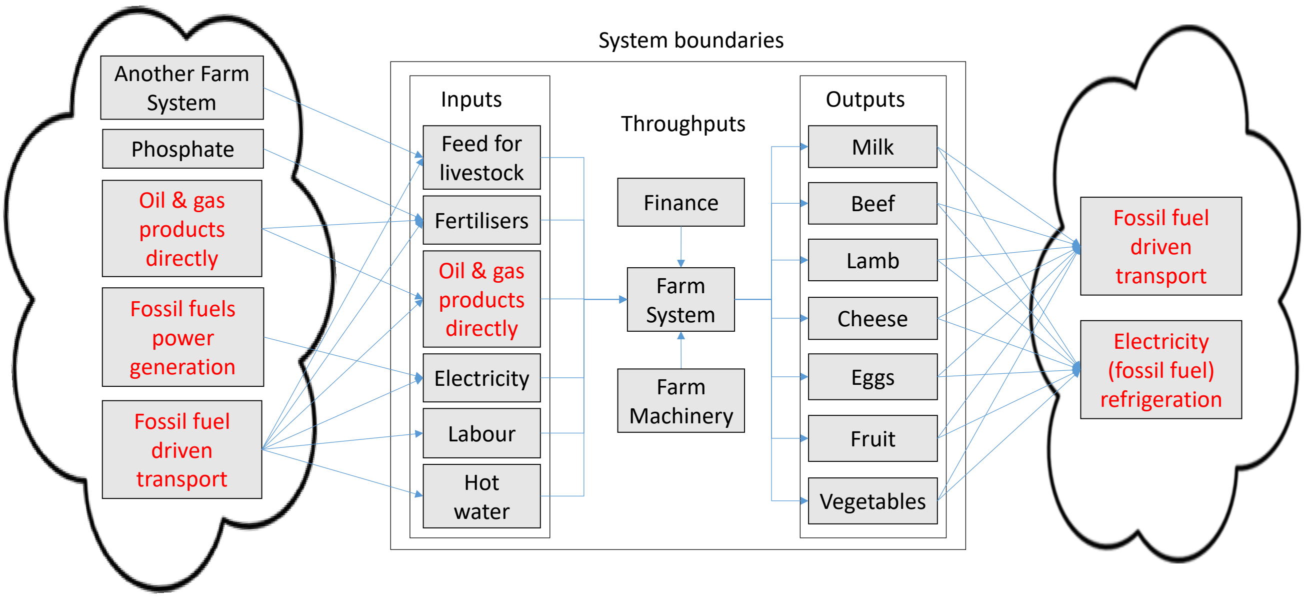


Figure 11.16. Industrial agriculture farming modelled as a system
(Image: Simon Michaux)

In December 2007, the United Nations Food and Agriculture Organization (UN FAO) calculated that world food prices rose 40% in 12 months prior, and the price hikes affected all major biofuel feedstocks, including sugarcane, corn, rapeseed oil, palm oil, and soybeans (FAO 2008). In 2007, the International Herald Tribune quoted FAO head Jacques Diouf warning of “a very serious risk that fewer people will be able to get food,” particularly in the developing world. In the summary proceedings of the First FAO Technical Consultation Bioenergy and Food Security, held in April 2007 in Rome, authors from a group of UN agencies cautioned that “possible income gains to producers due to higher commodity prices may be offset by negative welfare effects on consumers, as their economic access to food is compromised.” (“Welfare” here refers to standard of living, not government payments.) (FAO 2008).

Studies have found that there is a close correlation between global food prices and the incidence of riots in North Africa and the Middle East (Figure 11.17) (Lagi *et al* 2011). In 2008 more than 60 riots occurred worldwide in 30 different countries during a peak in food prices. After declining temporarily in 2009 (mirroring the fall in oil price), even higher prices at the end of 2010 and the beginning of 2011 coincided with additional food riots as well as the larger protests and revolts that have become popularly known as the Arab Spring. In contrast, there were relatively few incidents of collective violence when food prices were low. (This does not include incidence of rioting in China, or the food index data from China in these time periods). Incidence of civil unrest and instances of political violence seem to becoming more frequent. It can be argued that this increasing frequency and impact is linked to a range of trends showing growing complex interdependencies (Ahmed 2016).

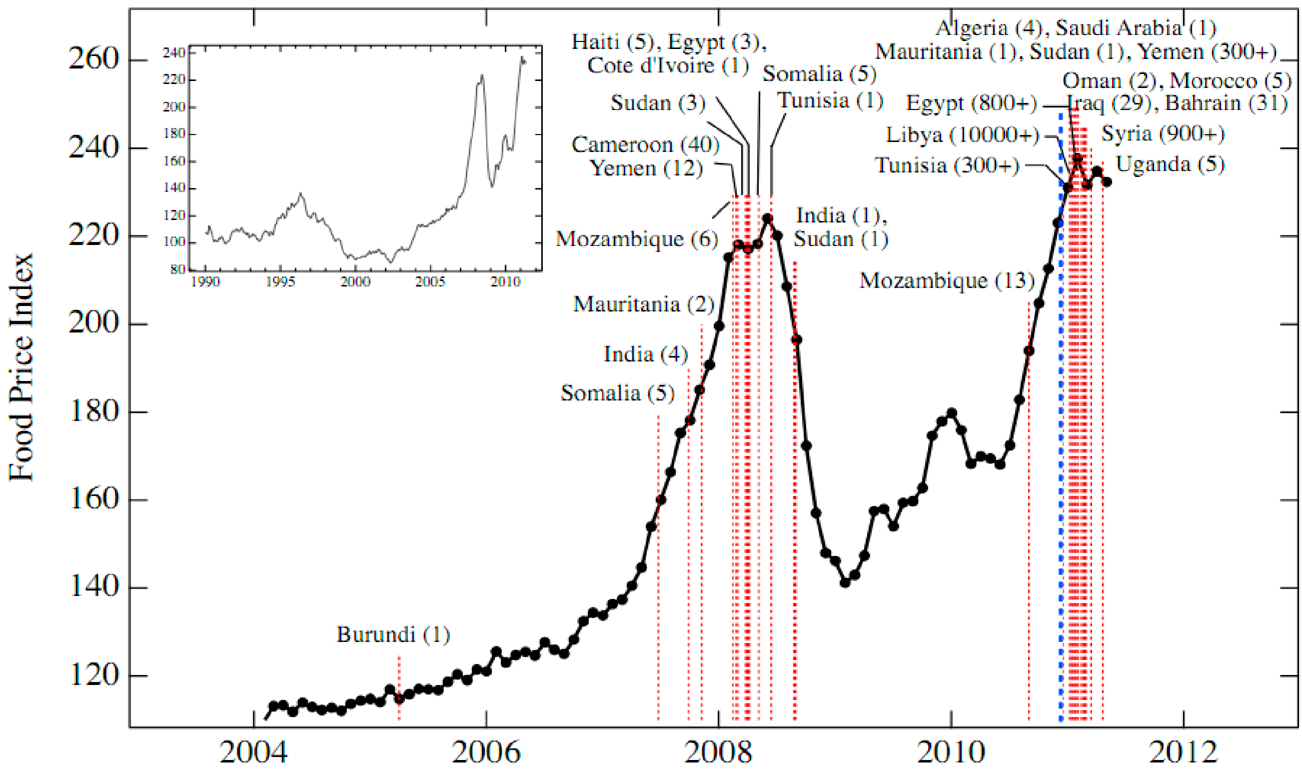


Figure 11.17. FAQ Food Index and incidence of civil unrest
(Source: Lagi *et al* 2011) (Copyright granted)

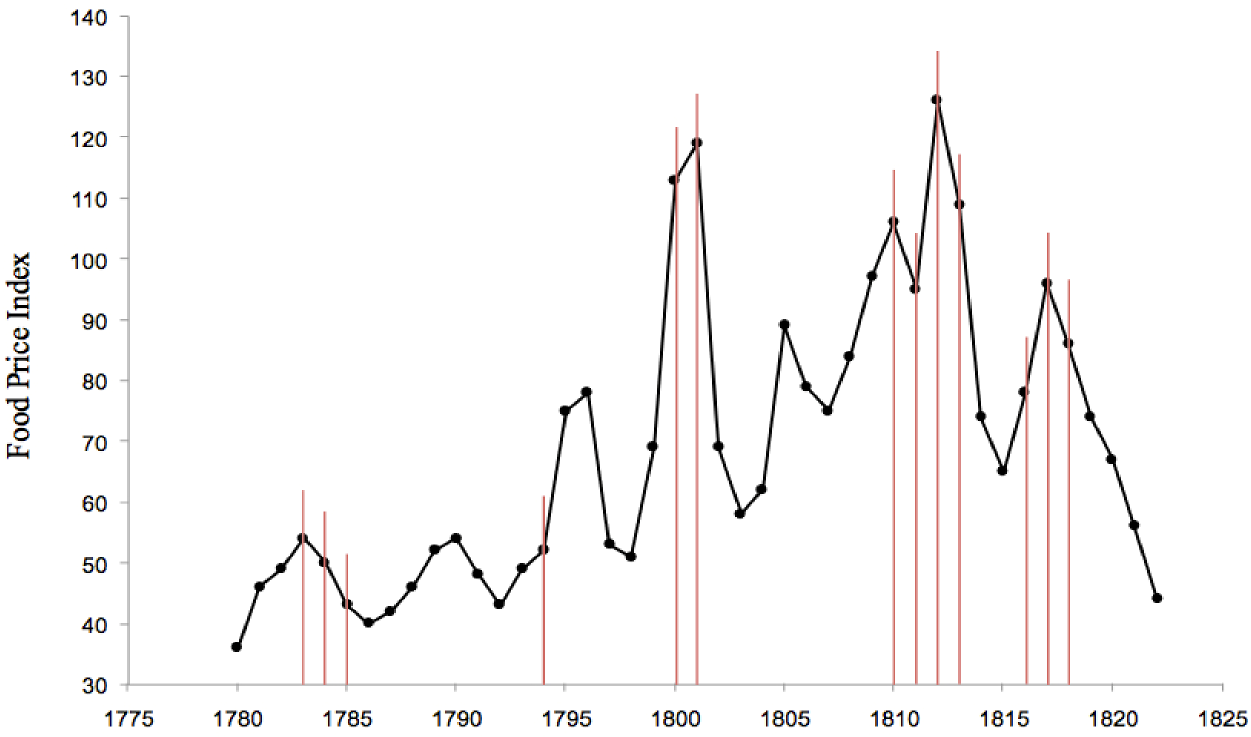


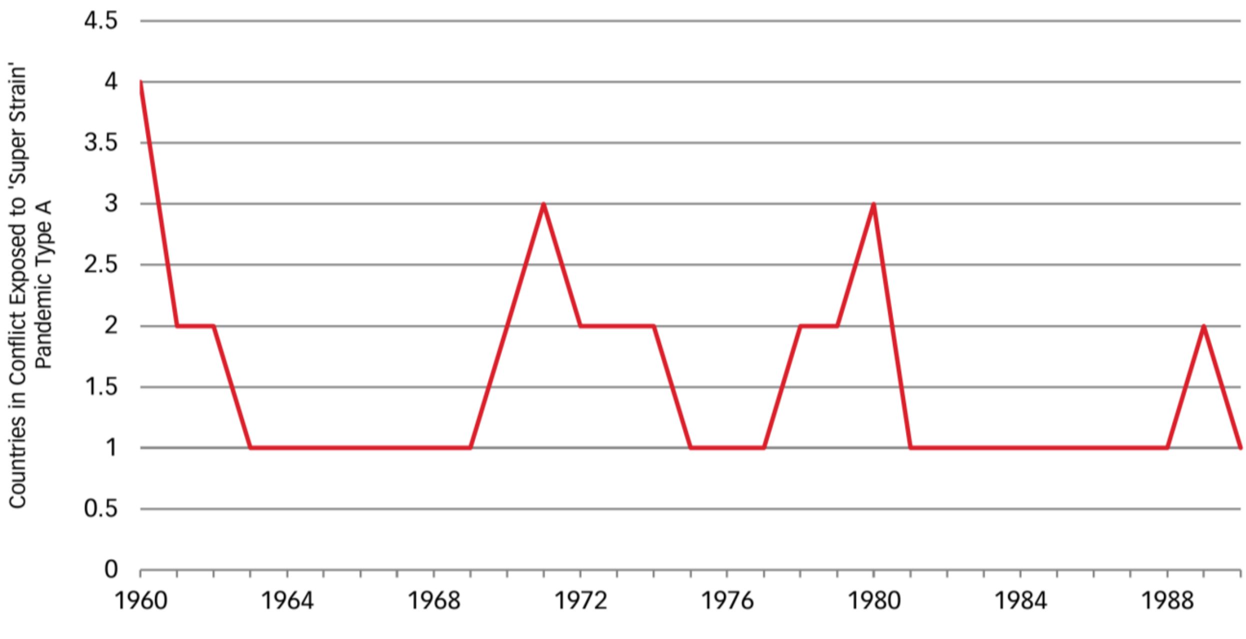
Figure 11.18. Major outbreaks of rioting in England (red lines) correlate with average price of wheat between 1780- 1822.
(Source: Johnson 2011 & Figure using data from Archer (2000) (Copyright granted)

As discussed by (Johnson 2011, Archer 2000), the identical pattern in the British Isles (Figure 11.18). In nearly all cases the riots were preceded by a sharp rise in price and once the price fell the incidence of riots fell with it. This isn't to suggest that wheat price alone was the cause, or that a rise in price always resulted in a riot. But it does suggest that the two were correlated and that a rise in food price promoted the same kind of social discord that lay behind incidents of collective violence.

To put the peaks seen in Figure 11.17 and 11.18 in context, the dates are compared to a global study of civil unrest. Lloyd's Risk Advisory published a report on political violence in a global context between 1950 and 2013 (Wilkinson 2016). They identified three sub-categories of civil unrest.

- Type A - Anti-imperialist, independence movements, removing occupying force
- Type B - Mass pro-reform protests against national government
- Type C - Armed insurrection, insurgency, secessionist, may involve ideology (e.g. Marxism, Islamism)

Type C (armed insurrection, insurgency, secessionist, may involve ideology) appears to represent by far the most contagious form of political violence (although this may also reflect the wider trend of civil conflict representing by far the most prevalent form of armed conflict today). Correlated Type B outbreaks tend to be more cyclical (mass pro-reform protests against national governments) and tend to be more cyclical and occur in spikes, and appear to precede the incidence of Type C outbreaks or, in other words, popular mass uprisings may trigger or at least contribute to the spread of armed insurrections.



Source: The Risk Advisory Group plc

Figure 11.19. Political violence pandemic frequency (Type A) 1960-2013
(Source: The Risk Advisory Group, Wilkinson 2016) (Copyright granted)

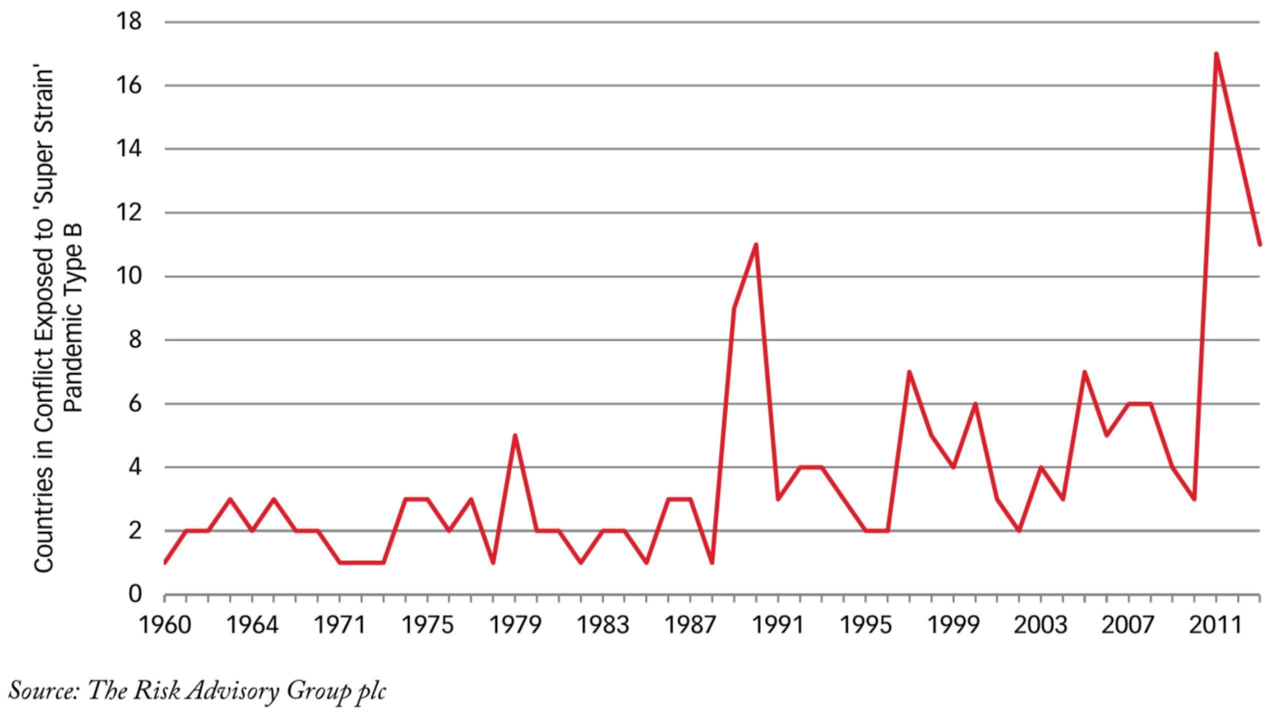


Figure 11.20. Political violence pandemic frequency (Type B) 1960-2013
(Source: The Risk Advisory Group, Wilkinson 2016) (Copyright granted)

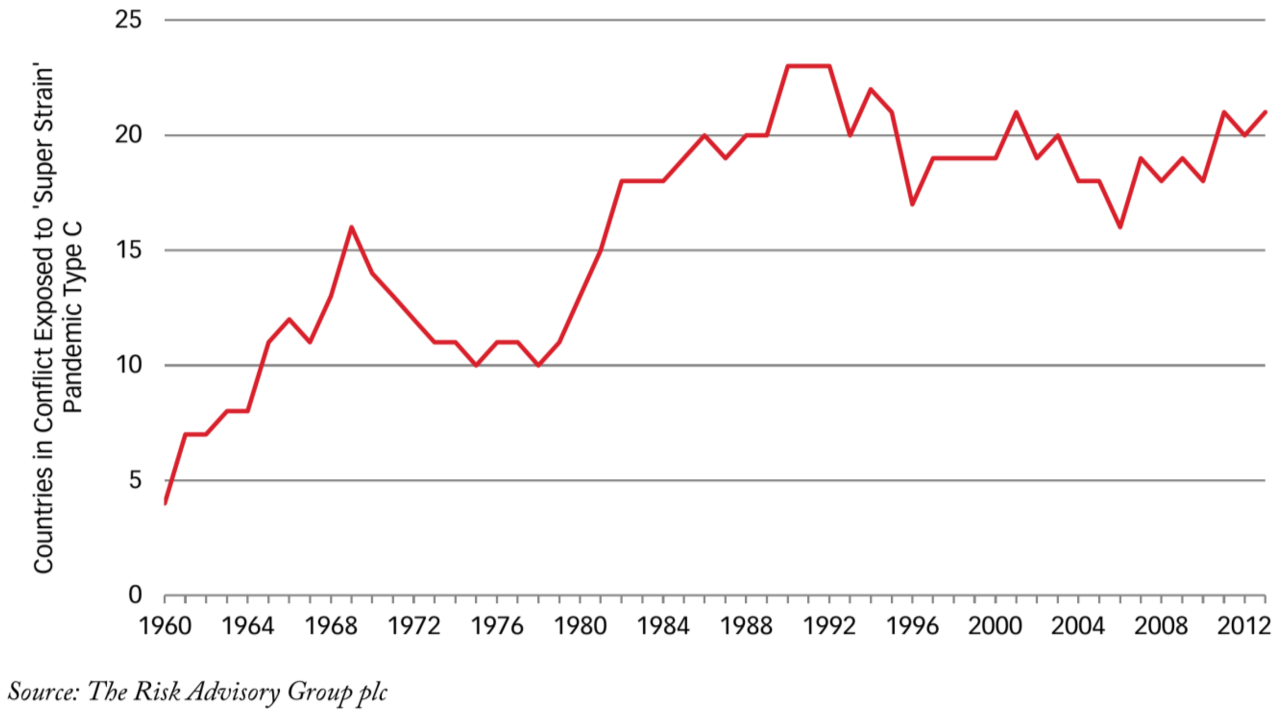


Figure 11.21. Political violence pandemic frequency (Type C) 1960-2013
(Source: The Risk Advisory Group, Wilkinson 2016) (Copyright granted)

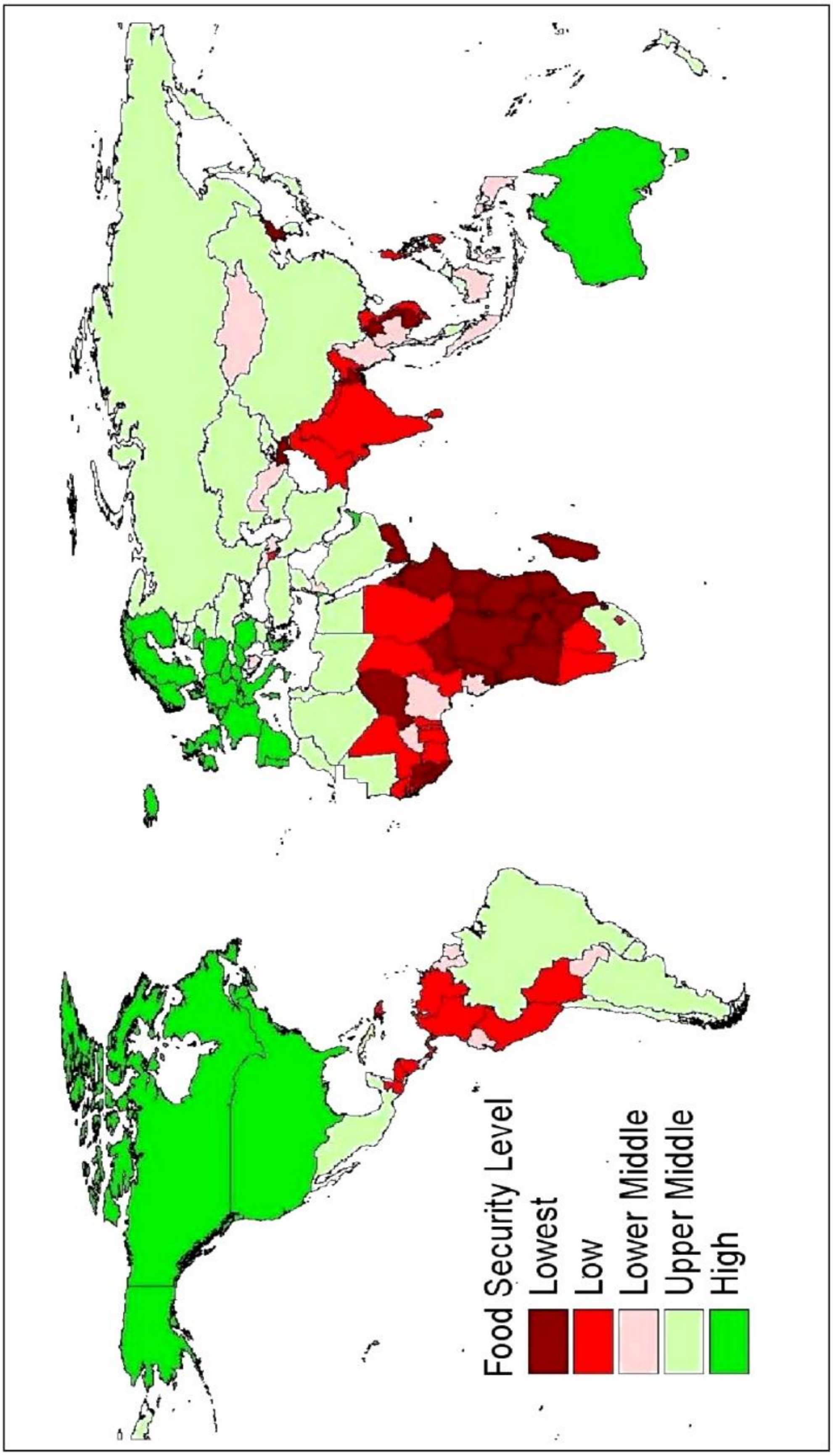


Figure 11.22. Food security levels in the face of high food prices
(Source: Bingxin Yu et al 2009) (Copyright granted)

Figures 11.19 to 11.21 show all the recorded incidents of civil unrest (unclear if all China examples are included). This suggests that the incidents of civil interest shown in Figures 11.17 are of Type B, which spiked in 2011 at a much greater rate than any other part of the data set. So, the civil unrest correlating with the rising cost of food are the largest seen in decades and are driven by public dissatisfaction with their governments. In speculation, the rioters were demanding a change in behavior from their governments that would fix the rising cost of food. For example, 1kg of meet that was sold with $1 USD in 2000 became $15 USD in 2021 in Ethiopia, and the value of every commodity increased the same fold, with no or little increase in the income of the public (Chernet 2021).

For some time now there has been widespread civil unrest in China, which has not been reported in the Western media due to State imposed controls by the People's Republic of China government. The cause of the civil unrest in China could be due to a number of factors, the severity of which are unknown outside China. This is mentioned as this data has not been included in Figure 11.17. Figure 11.22 shows the global vulnerability to increase food prices in 2009. So, in summary:

- Lack of food = civil unrest
- Currently, raw materials oil, gas & phosphate rock make fertilizer = food
- In some cases, food is replaced by an oil substitute, biofuel (ethanol), creating competition
- Oil price in particular directly correlates with the food price index, where a high oil price predicts incidence of civil unrest.

Since the late 1960's, the global human population has depended on the use of petrochemical fertilizers to grow food. With this innovative technology, crops have always produced carbohydrates and sugars shared with soil organisms in exchange for nitrogen, phosphorus, potassium, minerals, and disease protection, through the application of NPK fertilizers. Over time, it has been noticed that an increasing high quantity of industrially produced nitrogen fertilizer is needed to produce the same crop yield (Buckley 2010). It appears that the effectiveness of NPK industrial fertilizers, industrially produced herbicides and pesticides are all becoming less effective (Buckley 2010).

It has been postulated in the organic farming community that plants bred for the green revolution, were able to get the elements of nitrogen, phosphorus, and potassium from manufactured fertilizers, but the elements received were not in a sustainable form across many generations of plants. The phrase used by an experienced organic farmer in Australia was "industrial fertilizers are like baby food for plants, where the plants have no choice but to absorb the elements but are weakened by them long term" (Buckley 2014). With each passing generation of crops, the cellular structure of plants may have stopped working symbiotically with soil microbes as well (Buckley 2010, Porter and Sachs 2020).

Improper use of industrial fertilizer can damage the soil ecosystem and the microbe soil food web. A balanced diet for soil organisms is about 20 parts carbon to one part nitrogen. Too much nitrogen and too little carbon starves the soil microbes and eventually kills them. The beneficial functions microbes perform for plants, such as defending crops from pests and diseases, also are lost, so farmers add even more fertilizer and pesticides, creating a reinforcing loop (Friedemann 2021). This suggests that not only is the use of industrial fertilizers causing land degradation, but they are becoming increasingly ineffective. It also could be that plants that have been conditioned to depend on industrial fertilizers may not be able to function very well on organic fertilizers sources like plants do in the natural habitat. The previous few sentences are describing a debate between organic farming practitioners and industrial agricultural practitioners in the proper use of fertilizer. It would be most useful to resolve this debate in future work.

11.4 Environmental deterioration as a consequence of overloading natural biogeochemical cycles

Many of the natural biogeochemical cycles are now overloaded (Cameron & Osborne 2015), nitrogen and phosphorus in particular (related to industrial agriculture production) (Steffen *et al* 2015) (Figure 11.23). To date, the global environment has been required to absorb these impacts, with no real understanding of the implications being reflected in development of the global industrial ecosystem. The flash point for this trend will be around the production of food for the global population, and now possibly the production of biofuels.

During the past seven decades, global population, food production, and energy consumption have increased approximately 240 %, 300 % and 500 %, respectively (United Nations, FAO, EuroSTAT). Through activities such as petrochemical fertilizer (NPK based in particular) use, fossil fuel consumption and the cultivation of leguminous crops, the application of industrial agriculture has more than doubled the rate at which biologically available nitrogen (N) enters the terrestrial biosphere compared to preindustrial levels (Bouwman et al 2009).

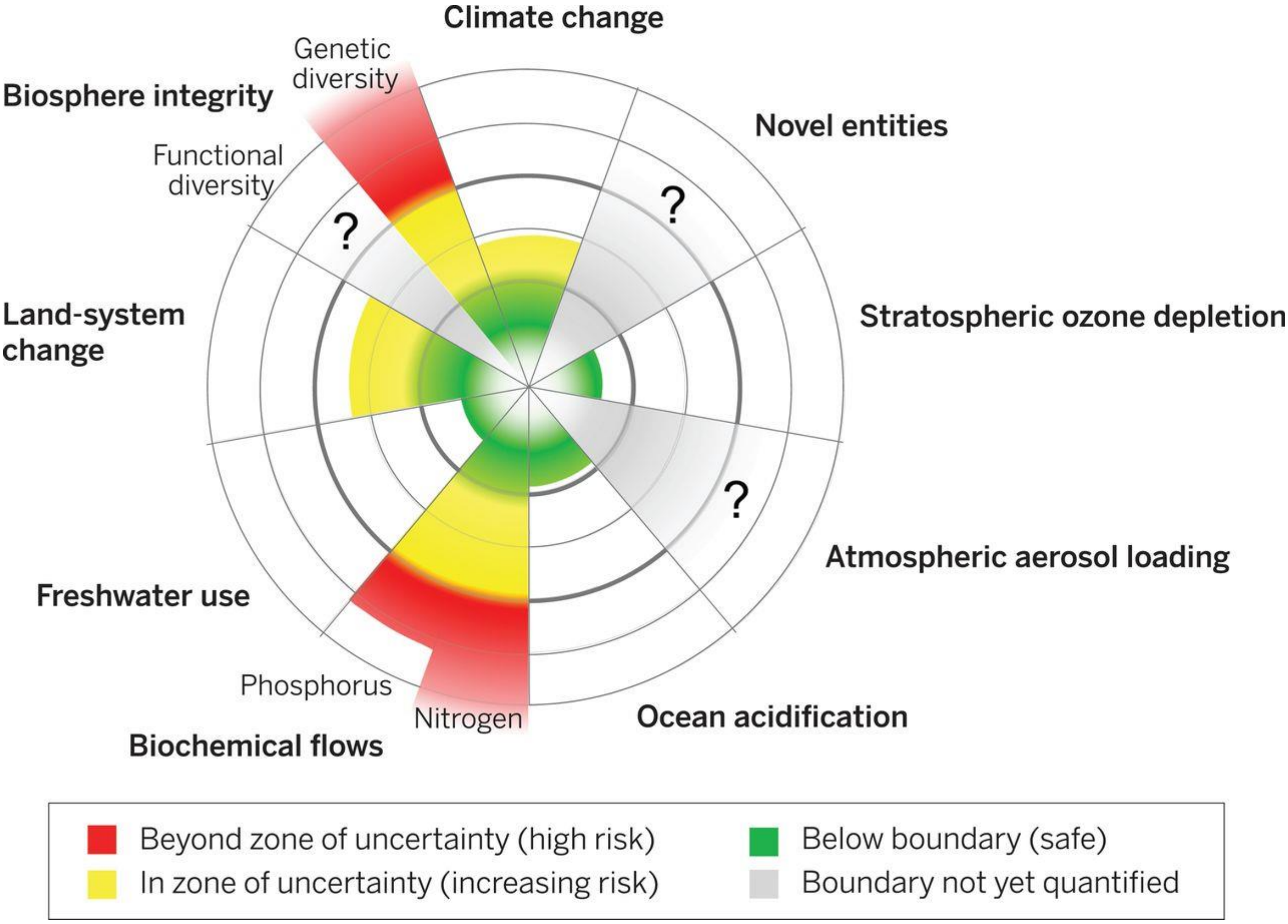


Figure 11.23. Status of variables controlling planetary boundaries (Steffen *et al* 2015) (Copyright granted)

The changes in global nutrient cycles have had both positive and negative effects. The increased use of N and P fertilizers has allowed for producing the food necessary to support the rapidly growing human population. However, significant fractions of the anthropogenically mobilized N and P in watersheds enter groundwater and surface water and are transported through freshwater to coastal marine systems. This has resulted in numerous negative human health and environmental impacts such as groundwater pollution, loss of habitat and biodiversity, an increase in frequency and severity of harmful algal blooms, eutrophication, hypoxia, and fish kills (Millennium Ecosystem Assessment 2004, Schindler 2016).

Figure 11.23 shows that the natural phosphorus and nitrogen biogeochemical are heavily overloaded. The expansion of agriculture has driven one of humanity's largest impacts on the environment. It has transformed habitats and is one of the greatest pressures on biodiversity: of the 28000 species evaluated to be threatened with extinction on the IUCN Red List, agriculture is listed as a threat for 24000 of them (https://www.iucnredlist.org/).

The increasing rate of nitrogen use by humans has led to an imbalance in the nitrogen content in the global environment. Human-induced nitrogen inputs into fertilizers and associated emissions from agriculture, fossil fuel burning, sewage and industrial waste have directly or indirectly far surpassed natural emissions, causing nitrogen pollution that has reached content levels that have overloaded the natural cycle (Sutton *et al* 2013). The agricultural sector accounts for 73% of N_2O emissions (EIA 2011). When excessive fertilizer is applied to crops, the microbes in the soil respond to excess bacteria food and emit exponentially more N_2O (Shcherbak et al. 2014). Nitrogen runoff from agricultural land has a high environmental impact on freshwaters, accelerating eutrophication. This happens because excess fertilizer that pollutes rivers, lakes, and oceans, increasing water treatment and health costs and killing fish (Broussard et al. 2012, Ma *et al* 2012; Troeh and Thompson 2005).

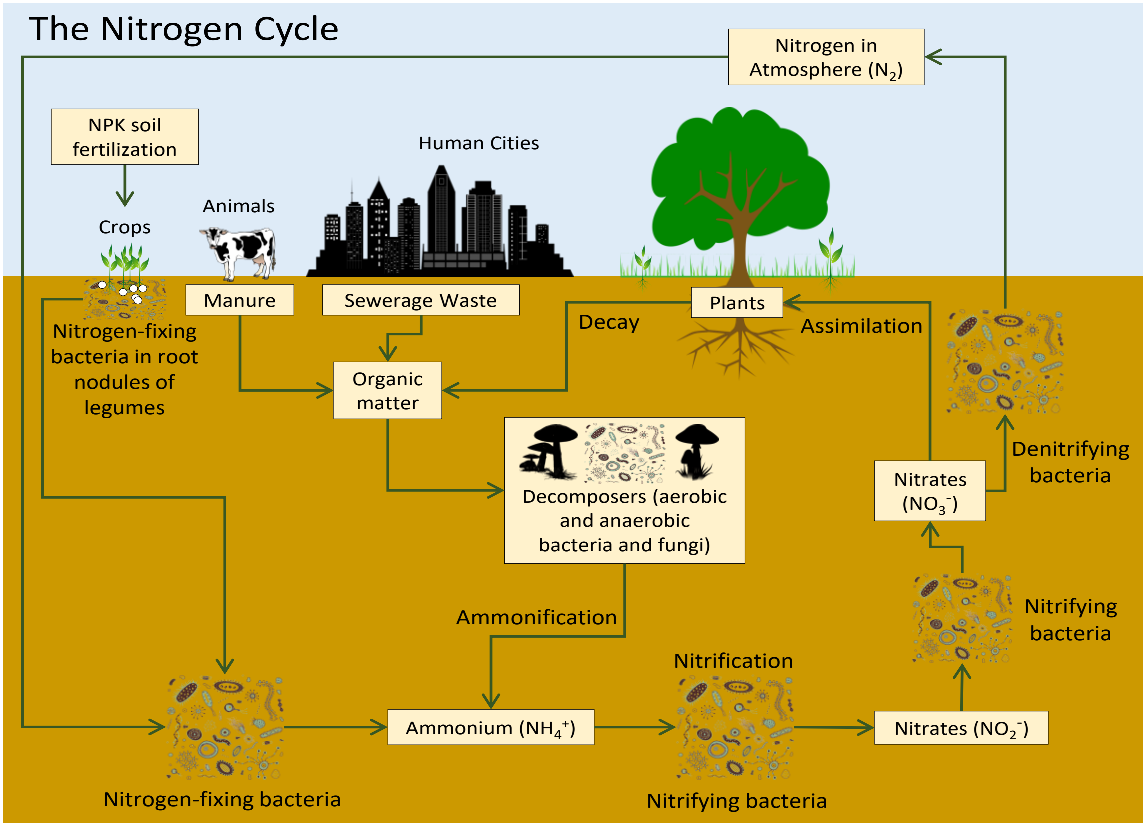


Figure 11.24: The nitrogen cycle
(Image: Simon Michaux)

Over half of phosphorus is lost from erosion on agricultural lands (Alewell et al. 2020), as well as from storm runoff, sewage released to waterways and landfill, and crop exports.

Modern agricultural systems require annual applications of phosphorous-rich fertilizer. However, unlike the natural biochemical cycle, which recycles phosphorous back to the soil 'in situ' via dead plant matter, modern agriculture harvest crops prior to their decay phase, then transporting them all over the world to food manufacturers and consumers. Studies on post-harvest losses of food and embodied water from the global food production and consumption chain, can be used as a basis for estimating phosphorous losses. This suggests that 55% of phosphorous in food is being lost from farm to fork. Around 50% of the phosphorus consumed and hence excreted by livestock is returned to agriculture globally (with significant regional imbalances). Because plants can only uptake small amounts of phosphate, a large majority of fertilizer ends up in unwanted places, like bodies of water, making these practices ecologically unsustainable. This is because of the chemical properties of phosphate, which interacts with soil particles in a way that makes it difficult for the plant to acquire, leaving a large portion of the element in the soil surface.

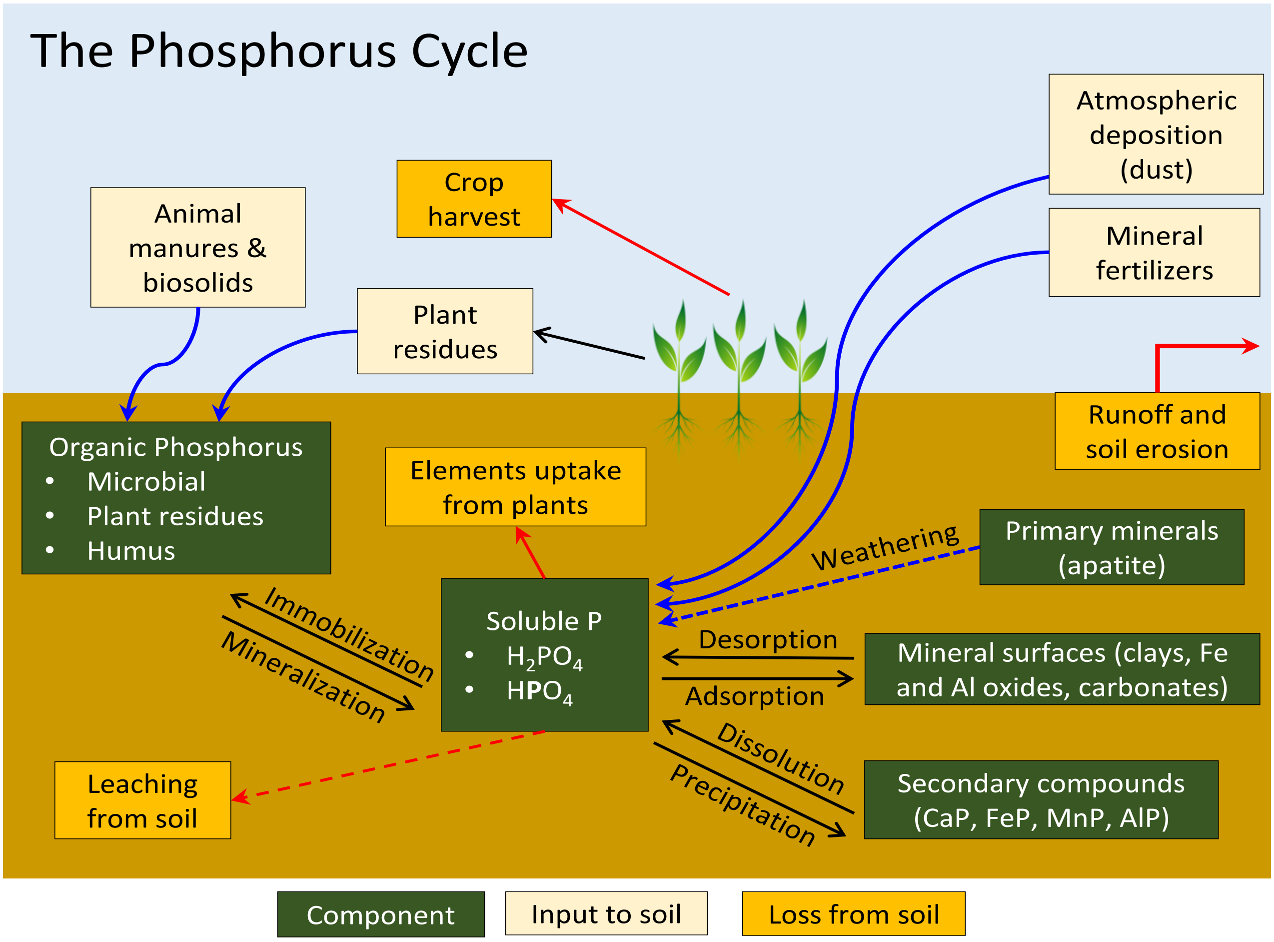


Figure 11.25: The phosphorus cycle
(Image: Simon Michaux)

The global phosphorus (P) cycle has also been altered by human activity. Mining of phosphate rock and subsequent production and use as fertilizer, detergent, animal feed supplement and other technical uses has more than doubled P inputs to the environment over natural, background P from weathering (Bouwman et al 2009).

Nutrient pollution in ground water - which is in use as a drinking water source - can be harmful, even at low levels. Too much nitrogen and phosphorus in the water causes algae to grow faster than ecosystems can handle. Significant increases in algae harm water quality, food resources and habitats, and decrease the oxygen that fish and other aquatic life need to survive. Large growths of algae (called algal blooms) can severely reduce or eliminate oxygen in the water, leading to illnesses and to death of large numbers of fish. Some algal blooms are harmful to humans because they produce elevated toxins and bacterial growth that can make people sick if they come into contact with polluted water, consume tainted fish or shellfish, or drink contaminated water.

Phosphorus pollution from the industrial agricultural industry is reaching dangerously high levels in freshwater basins around the world (Mekonnen and Hoekstra 2018). This study estimated the global amount of phosphorus from human activities that entered Earth's freshwater bodies from 2002 to 2010. Global human activity emitted 1.47 x 10^{12} grams (1.62 million U.S. tons) of phosphorus per year into the world's major freshwater basins.

China was the largest single regional source, contributing 30 % of the freshwater phosphorus load. India and the United States contributed 8% and 7% respectively. In terms of waste plume from a human activity, the largest contribution to the global phosphorus load came from domestic sewage at 54%, followed by agriculture at 38% and industry at 8%. It was found that the phosphorus load from agriculture grew by 27% over the study period, from 525 gigagrams (579,000 U.S. tons) in 2002 to 666 gigagrams (734,000 U.S. tons) in 2010.

Mekonnen and Hoekstra also assessed whether the industrial agricultural waste plume had surpassed the Earth's ability to dilute and assimilate excess levels of phosphorus in freshwater bodies. It was found that phosphorus load exceeded the assimilation capacity of freshwater bodies in 38% of Earth's land surface (excluding Antarctica). This area is associated with where 90% of the global human population live in densely populated areas or regions with intensive agriculture.

The problem has two sub-set signatures. One set is phosphorus overload in regions where there is not enough water to assimilate the phosphorus. The other signature set is the pollution load is so large that the water system can’t assimilate all the nutrients flowing into the local environment. The study's results indicate freshwater bodies in areas with high water pollution levels are likely to suffer from eutrophication, or an excess level of nutrients, due to high phosphorus levels. Eutrophication due to phosphorus pollution causes algal blooms, which can lead to the mortality of fish and plants due to lack of oxygen and light. It also reduces the use of the water for human purposes such as consumption and swimming light (Mekonnen and Hoekstra 2018).

The most severely polluted freshwater areas include Aral drainage basin, the Huang-He (Yellow) river in China, the Indus and Ganges rivers in India and the Danube river in Europe. Less-populated regions such as Australia and northern Africa also suffer from high water pollution levels, according to this study. These regions have smaller phosphorus loads compared to areas like China and Europe, but they have much less water available to accommodate their excess phosphorus.

Following more than half a century of generous application of inorganic high-grade phosphorus and nitrogen fertilizers, agricultural soils in Europe and North America are now understood to have surpassed ‘critical’ phosphorus levels, and thus only require light applications to replace what was lost in harvest. As most intensive industrial agriculture does not happen in Europe, the phosphorus balance has been becoming more stable since the 1950’s (Wironena *et al* 2018).

The gross phosphorus balance for the EU-28 decreased from an estimated average of 3.9 kg P per ha per year in the period 2004-2006 to 1.2 kg P per ha per year in the period 2013-2015. The inputs of the gross phosphorus balance consist mainly of mineral fertilizers, organic fertilizers and manure input, and other inputs like seeds and planting material (EuroStat 2018).

The widespread use of petrochemical fertilizers has overloaded the phosphorus cycle in the natural environment. Nutrient oversupply has led to a number of environmental hazards like algae blooms and fish kills.

11.5 Degradation of arable land as a consequence of environmental pollution the overuse of industrial petrochemical fertilizers

Strategic plans almost always predict expansion of the industrial ecosystem in some form. Due to predicted human population growth, future food demand is projected to require an increase in food production by 70 - 100 % by 2050 (FAO 2015a, United Nations 2019). Now, a new demand for arable land use is presented as a necessity, the production of feedstock for biofuels (Friedemann 2021).

Humans have already used half of all the biomass and forests over the previous 2000 years (Schramski *et al* 2015; Crowther *et al* 2015). In the twentieth century, despite most of energy consumption coming from fossil fuel sources, the industrial ecosystem consumed 10% of the planet's biomass (Smil 2016a; Houghton *et al*. 2009). Massive population growth in low-income countries where more wood-fuel and charcoal were consumed than ever before in history resulted in vast areas of deforestation (Smil 2018). An example of this is in Ethiopia, where in the late 19th century, 30% of the nation was covered by forest. Gradually this was reduced over time. Between 1990 to 2010, the country lost 18.6% of its forest lands (FAO 2011). Apart from using wood for energy, this is mainly due to dramatic increase in agricultural land. In 1991, agricultural land counted for 24.8%, which increased to 33.5% in 2019 (Negassa 2020 and Chernet 2021).

The United States (a major producer of food in the global economy), has lost approximately a third of its arable land in the last 70 years (Friedemann 2021). In 1949 there were 477 million acres of cropland (Nickerson and Borchers 2012) whereas in 2015, just 366.7 million (USDA 2019), a loss of 110.3 million acres.

Land degradation has impacted the natural environment outside of industrial agriculture (Friedemann 2021). Since the year 1990, 10 % of the remaining global wilderness was lost. At this rate, all wilderness would be gone by 2100 (Watson *et al* 2016). This has been caused by the waste plumes from several sources (FAO 2015a, United Nations 2019): unsustainable farming and grazing, pesticides, desertification, aridification, salinization, pollution, deforestation, and toxic elements from industrialization, mining, and microplastics production (Boots *et al* 2019). The net loss of natural land has been dominated by loss of tropical forests (3.3 million km^2), tropical grasslands (6.8 million km^2) and temperate grasslands (5.5 million km^2) (FAO 2015a, United Nations 2019). Quantification from satellite imagery of global forest change over the period 2000-2012 shows that tropical deforestation remains the predominant source of losses (Hansen *et al* 2013). Degrading land covers approximately 24 % of the global land area (35 million km^2) (FAO 2015a, United Nations 2019). The scale and nature of the changes are highly variable with type of land cover change, climate, and method of vegetation removal (e.g. land clearing fires, mechanical harvest). Land degradation will also disrupt community structure, wildlife settlement, endangered endemic plants, and ecosystem stability.

A United Nations study (FAO 2015b) concluded that 95% of our planet's land will be degraded by 2050. The arable land that is now used to grow food and graze animals on has degraded so much that the United Nations estimates there are only 60 years of harvests left worldwide, on average (Leahy 2018).

An alternative viewpoint is another study (Evans *et al* 2020). Evans *et al* found that although 93% of soils are thinning, only 16% of the world's farms have a lifespan of less than 100 years and another third may last 100–200 years (Evans *et al* 2020). Whichever of these studies is closer to the true state of the decline of arable land, both are showing that the available arable land for food production and bioenergy feedstock production is shrinking.

Mechanized plows introduced in the 1930s accelerated erosion by plowing the upper 15 – 20 cm of earth, exposing the soil to rain and wind (Friedemann 2021). Agricultural units like tractors and other farm machinery with lots of horsepower have accelerated the loss. On average, this has led to 90 times more soil lost than formed (Coombs 2007).

Soil erosion rates are much higher than soil formation rates. Soil is a finite resource, meaning its loss and degradation is not recoverable within a normal human lifespan. Soil erosion decreases agricultural productivity, degrades ecosystem functions, amplifies hydrogeological risk such as landslides or floods, causes significant losses in biodiversity, damage to urban infrastructure and, in severe cases, leads to displacement of human populations (FAO 2015a, United Nations 2019). Key figures on soil erosion from the United Nations Food and Agriculture Organization show that:

- It can take up to 1 000 years to produce just 2-3 cm of soil.
- 33% of the Earth's soils are already degraded and over 90% could become degraded by 2050 (FAO 2015a, United Nations 2019).
- The equivalent of one soccer pitch of soil is eroded every five seconds (FAO 2015a, United Nations 2019).
- Estimated rates of accelerated soil erosion on arable or intensively grazed lands are 100-1 000 times higher than natural erosion rates (FAO 2015a, United Nations 2019).
- Soil erosion can lead up to 50% loss in crop yields (FAO 2015a, United Nations 2019).

Although soil erosion has a direct impact on farmers, it also has effects outside of agriculture. It has implications for our environment and health including on water quality, the energy sector, urban infrastructure, and our landscapes. For example, sediments associated with soil particles displaced by wind and water can lead to off-site soil and water pollution. Soil erosion affects all people who need to eat food.

As the global population continues to grow, having already increased 227 % between 1965 and 2018 (UN World Population Data 2017,), there is greater demand for food. And the strain on land, which is a limited resource, has also grown. Global cropland area per capita decreased continuously over the period between 1965 and 2016: from about 0.45 hectare per capita in 1961 to 0.21 hectare per capita in 2016

Land degradation of arable land has been advanced as the single most pressing current global risk for future global stability (Stocking 2001). Land degradation is defined as the temporary or permanent decline in the productive capacity of the land, and the diminution of the productive potential, including its major land uses (e.g., rain-fed arable, irrigation, forests), its farming systems (e.g., smallholder subsistence), and its value as an economic resource.

As can be observed in Figure 11.26, all areas around the world currently being used for food production are reducing per capita human population (Source: OurWorldinData.org). One of the reasons for this is the increasing yield productivity, which means each unit area of arable land will produce more crops. The degradation of arable land data would be only part of the data in Figure 11.26. So, as food producing areas are undergoing land degradation, the productivity of agricultural methods used in those lands has been increasing in yield. The demand for food has also been increasing with human population, which has been increasing pressure on a declining area of land.

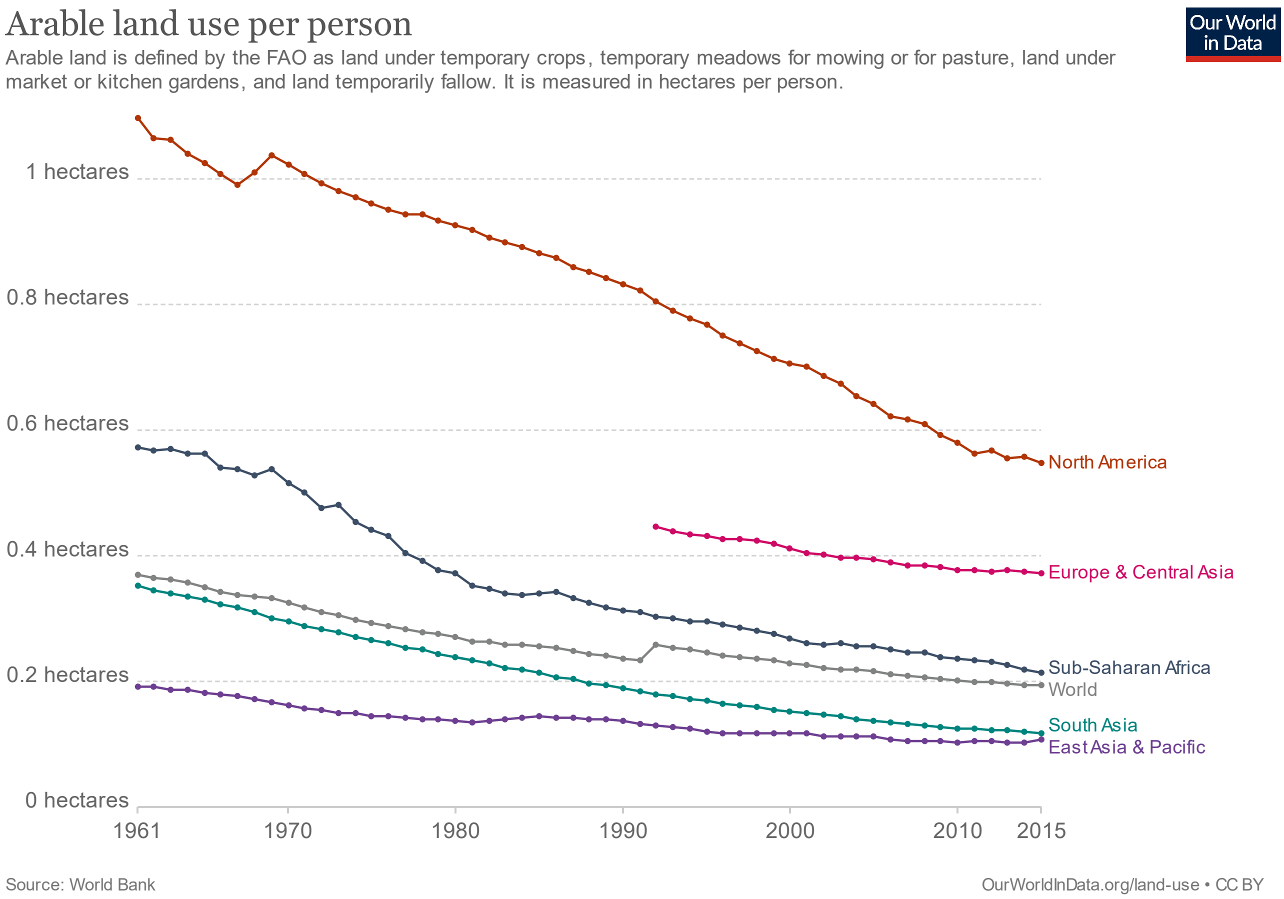


Figure 11.26: The degradation of arable land by region (Source: OurWorldinData.org)

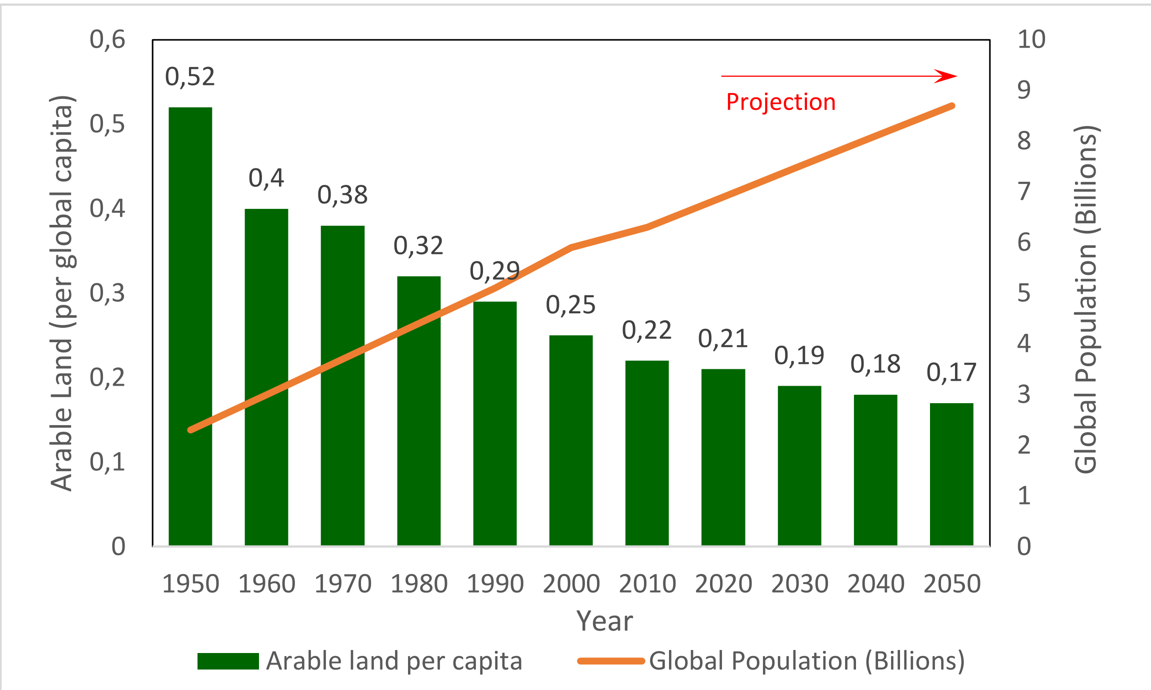


Figure 11.27: Decreasing arable land per capita globally compared with global human population growth. (Source: The World Bank & Fraser Mackenize 2011)

Figure 11.27 shows the inverse correlation between arable land per capita and population growth. The world has lost a third of its arable land due to erosion or pollution in the past 40 years (with current arable land loss at a rate of 0.5% each year), with potentially disastrous consequences as global demand for food has greatly increased. The University of Sheffield's Grantham Centre for Sustainable Futures (Cameron & Osborne 2015) has calculated that nearly 33% of the world's adequate or high-quality food-producing land has been greatly reduced in productivity at a rate that far outstrips the pace of natural processes to replace diminished soil erosion rates from ploughed fields average 10-100 times greater than natural rates of soil formation. This has resulted in vast tracts of land that are now longer suitable to grow crops.

There is an observable link between the ubiquitous use of NPK petrochemical fertilizer, the viability of industrial agriculture and the degradation of arable land. Currently, intensive agriculture is unsustainable – under the intensive farming system current crop yields are maintained through the heavy use of fertilizers, which require high energy inputs to supply inorganic nitrogen via the industrial Haber-Bosch process (Appl 1982).

For each bushel of wheat sent to market, 0.8 cubic meters of soil is made infertile (Reed *et al* 2015).

The use of petrochemical fertilizers and pesticides (in particular NPK, Nitrogen Phosphorous Potassium) has had an enormous influence on the degradation of arable land. There are many causes of which the loss of arable land is the consequence. The activity of industrial agriculture engages in almost all of them directly and indirectly. The use of petrochemicals has made the Green Revolution possible. Phosphate rock is a vital ingredient of those petrochemical fertilizers.

This has the net effect of sterilizing the microbe population (residing in the organic matter) of soil and producing lifeless 'dirt'. A possible outcome could be a widespread manifestation of the dust bowl of the 1930's in North America (Cameron and Osborne 2015). Modern industrial agriculture is increasing the rate of loss and is reducing soils to their bare mineral components. By employing this chemical technology, the rate of the soils capability to take up minerals and elements in a form useful for the growth of plants is degraded in a cumulative fashion.

Soil is lost rapidly but replaced over millennia and this represents one of the greatest global threats for agriculture. This is considered a serious risk in context of takes about 500 years to form 2.5 cm of topsoil under normal agricultural conditions (Cameron & Osborne 2015). The same 2.5 cm of topsoil can take several thousand years to form depending on what kinds of minerals are below in the subsoil (Bogard 2017). The fastest rate of soil formation occurs in hot, wet areas, and the slowest in areas that are cold and dry. It takes centuries because below the soil there is rock that needs to break down into smaller pieces (SSA 2020).

The erosion of soil has largely occurred due to the loss of structure by continual disturbance for crop planting and harvesting. If soil is repeatedly turned over, it is exposed to oxygen and its carbon is released into the atmosphere, causing it to fail to bind as effectively. This loss of integrity impacts soil's ability to store water, which neutralizes its role as a buffer to floods and a fruitful base for plants. Degraded soils are also vulnerable to being washed away by weather events fueled by global warming. Deforestation, which removes trees that help knit landscapes together, is also detrimental to soil health (Reed *et al* 2015).

At the rate the world's soils are degrading, by 2050, it is predicted that soil erosion is likely to lead to 30% less food being grown (Bogard 2017).

Farmers were obliged by law to comply with conservation planning regulations and procedures. Compliance involved using research outputs such as the 'Universal Soil Loss Equation' which calculated rates of soil loss for various planned land uses, comparing these with a benchmark known as the 'tolerable soil loss,' a rate at which it was said that future production would not be jeopardized. Some of the science underpinning these procedures is now known to be flawed (Stocking 2001).

11.6 The Green Revolution net outcome

Agriculture before the green revolution was able to supply food to the global population but was approaching limitations in capacity. Agriculture in the pre petrochemical profile would have struggled to feed a growing human population. The world's population had doubled by 1923 and doubled again by 1973. Paul R. Ehrlich, in his 1968 book The Population Bomb, stated that "India couldn't possibly feed two hundred million more people by 1980" and "Hundreds of millions of people will starve to death in spite of any crash programs" (Erlich 1968).

What later would be termed the Green Revolution, was a technological evolution of industrial agricultural production, where the use of petrochemical (using oil and gas) would produce fertilizers and pesticides using among other minerals, phosphate. This innovation was allowed for the significant increase in food production. This allowed the supply of food to areas that were previously thought to be subject to serious and permanent food shortages, thus the lives of billions of people were saved.

Ehrlich's warnings failed to materialize when India became self-sustaining in cereal production in 1974 (six years later) as a result of the introduction of Norman Borlaug's dwarf wheat varieties (Pollock 2007). The petrochemical based industrial agriculture had greatly increased food supply in a very short time. Human population was able to grow unchecked.

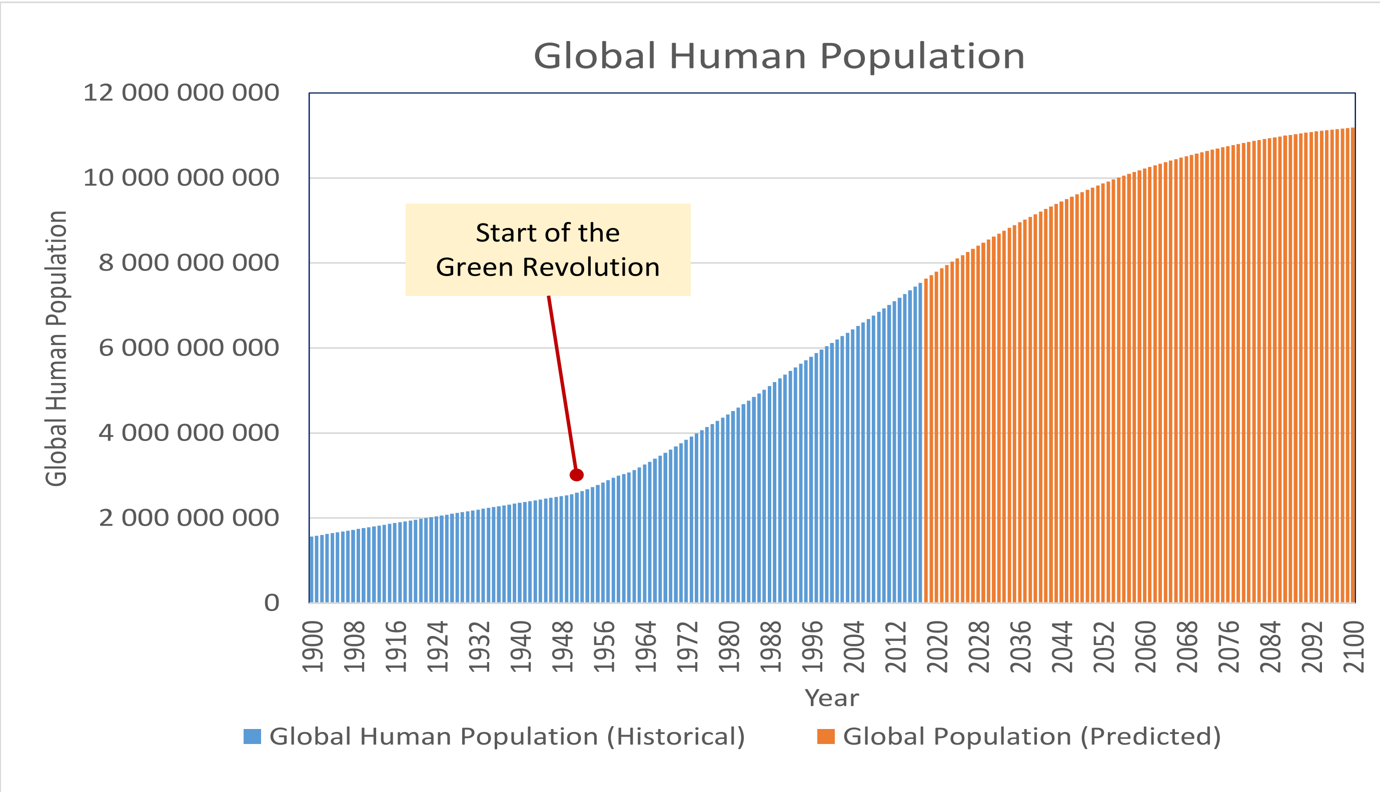


Figure 11.28: (left in blue columns) Historic human global population 1994 to 2017. (right in red columns) Projected human global population growth (United Nations, Department of Economic and Social Affairs, Population Division 2017).

There is an underlying problem, however. To continue to supply the human population with food at the desired quantity and rate, industrial agriculture would be required to continue to improve in sophistication. The effectiveness of petrochemical fertilizers and pesticides are requiring increasingly larger applications per unit volume of soil to maintain production targets. This suggests that this technology is a short term solution in its current form.

Feeding a population of 9 billion people in 2050 will rely upon the availability of plant nutrients commensurate with the necessary increase in productivity, the deployment of new plant and farming technologies and the cultivation of more marginal land (Blanco 2011).

An untended consequence of the Green Revolution has been that petrochemical fertilizers and pesticides destroy soil biota as well as accelerate nutrient loss from topsoil via soil erosion (Friedemann 2021). This unusual situation is perhaps best described by the following quote:

> *"this puts us in the odd position of consuming finite fossil fuels—geologically one of the rarest and most useful resources ever discovered—to provide a substitute for dirt, the cheapest and most widely available agricultural input imaginable."*
>
> David R. Montgomery (Montgomery 2007)

The Green Revolution agricultural technology has indeed provided food for billions of people over several decades, but it has come at a cost. All proposed solutions to meet the land degradation issue all propose a combination of new generation fertilizers in conjunction with a return to a more natural balance of the phosphorus (and nitrogen) cycles (Cameron and Osborne 2015). This involves the rebuilding of soil in areas that have now been sterilize, in a fashion where the soils humus organic component is increase to 20-25%. This is something that is not easily obtainable in areas of land that been sterilized to the point where there are almost no micro-organisms in the soil.

The net position that the global ecosystem now finds itself in is:

- A human population that is more than double what it was at the start of the Green Revolution. Between 1960 and 2010, global human population has grown by approximately 3.9 billion people, or approximately 228% in size, with a predicted expansion of a further another 3.7 billion people by 2050. This means that in 2050, there will be an extra 7.1 billion people demanding food production compared to when the Green Revolution started to make a significant impact (1960). This will require an increase food production by 70 - 100 % on top of 2015 production levels by 2050

- A food production system that is dependent on petrochemical fertilizers that are in turn dependent on finite non-renewable natural resources like natural gas and phosphate rock.

- Arable land, which is needed to produce food, is degrading at a rate 50-100 times greater than natural rates of soil formation. Enormous sections of fertile arable land are now unsuitable for the growing of food. In the same time period (1960 to 2010), global scale land degradation of arable land decreased by 33 %.

- Over 90 % of the globally available arable land could become degraded by 2050.

- To naturally regenerate arable land will take a long time. It can take up to 1000 years to produce just 2-3 cm of soil.

- The alternative to producing food with industrial fertilizers is the reestablishment of small scale organic farming practices (Buckley 2010).

- Plants conditioned to grow with the support of industrial fertilizers may not be viable in organic farming practices.

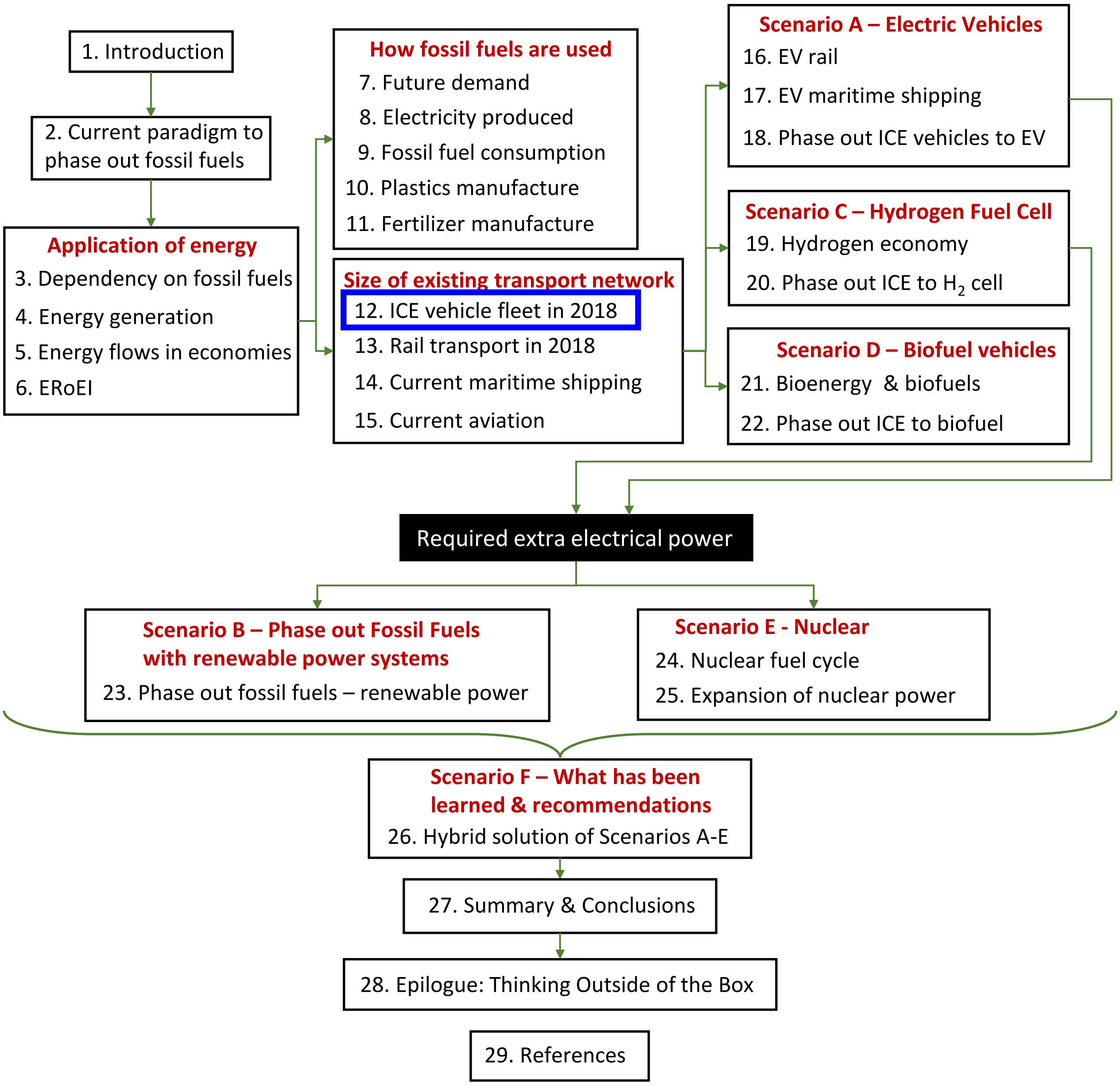
- The net position is at in 2050industrial agriculture may not be effective enough to supply the human population with enough food. To reestablish organic farming methods, sustainably stable and healthy arable land is required.

It is believed that as difficult as the environmental situation is, it is not quite at the tipping point yet and there is time to allow the environment to adjust if the rate of use of petrochemicals is radically optimized.

More work needs to be done to understand the cause and effect linkages between the industrial scale use of industrial agriculture, petrochemical fertilizers, industrial herbicides 6 pesticides and environmental pollution.

12 SIZE, SCOPE AND SPECIFICATION OF THE CURRENT ICE VEHICLE TRASNPORT SYSTEM

The largest task to phase out fossil fuels, is to develop an alternative technology to substitute petroleum fueled Internal Combustion Engine (ICE) vehicles. This task is addressed in Section 18. However, to do this task, data on the size of the global vehicle fleet is required. The number of vehicles, and their operating class is needed, as well as the annual distance traveled for the whole transport fleet. These numbers are needed for the United States, Europe (EU-28), China and in a Global context.



Assessment of the Extra Capacity Required of Alternative Energy Electrical Power Systems to Completely Replace Fossil Fuels

The Internal Combustion Engine (ICE) transport system has been the primary supporting technology for the current global industrial ecosystem, and it has been developing for more than a century to become the size and scope it is today. ICE technology is used to power vehicles of many different types, which all serve a number of purposes. The fundamental method of transport in developed economies is the self-propelled vehicle. This takes the form of passenger cars, trucks, and buses.

The purpose of this section is to estimate the size and scope of the global fleet of self-propelled vehicles and the distance they travelled in the year 2018.

12.1 Number of vehicles in global transport fleet

Appendix J shows a compilation of the number of vehicles in each nation state and associated references. This produced a number of vehicles that includes cars, vans, buses, and freight and other trucks; but excludes motorcycles and other two-wheelers. Summed together gives an estimate of the size of the global feet. Some of this information was current as of 2019 and some of it is as old as 2011. Many of the data points were last updated in 2015. An average data date of 2016 with an estimated global transport fleet of 1.416 billion vehicles (Table 12.1). The real value in 2021 will be a little higher. So, this report will use this figure as a conservative estimate.

Table 12.1. Total number of vehicles in global fleet (Source: Appendix J)

Country or Region	Motor vehicles per 1000 people	Total vehicle fleet	Proportion (%)	Refence/Source	Date of Estimate
Global	205	**1 416 528 615**		Appendix J	
United States	811	268 913 221	18,98 %	U.S. Dept of Transportation (2017)	2017
European Union	543	261 019 964	18,43 %	ACEA (2018)	2015/2016
China	179	232 312 300	16,40 %	National Bureau of Statistic of China 2019	2019
Rest of World		654 283 130	46,19 %		

Not all vehicles are the same in size, performance, or consumption. Trucks for example are far fewer than cars but consume more fuel to perform their tasks. Cars transport people, while trucks transport freight, often over long distances.

12.1.1 The size and form of the U.S. Vehicle Fleet

The classification of transportation has many sub-classifications. Figures 12.1 and 12.2 shows how the U.S. transportation energy sector was split by sources and/or fuels in 2018.

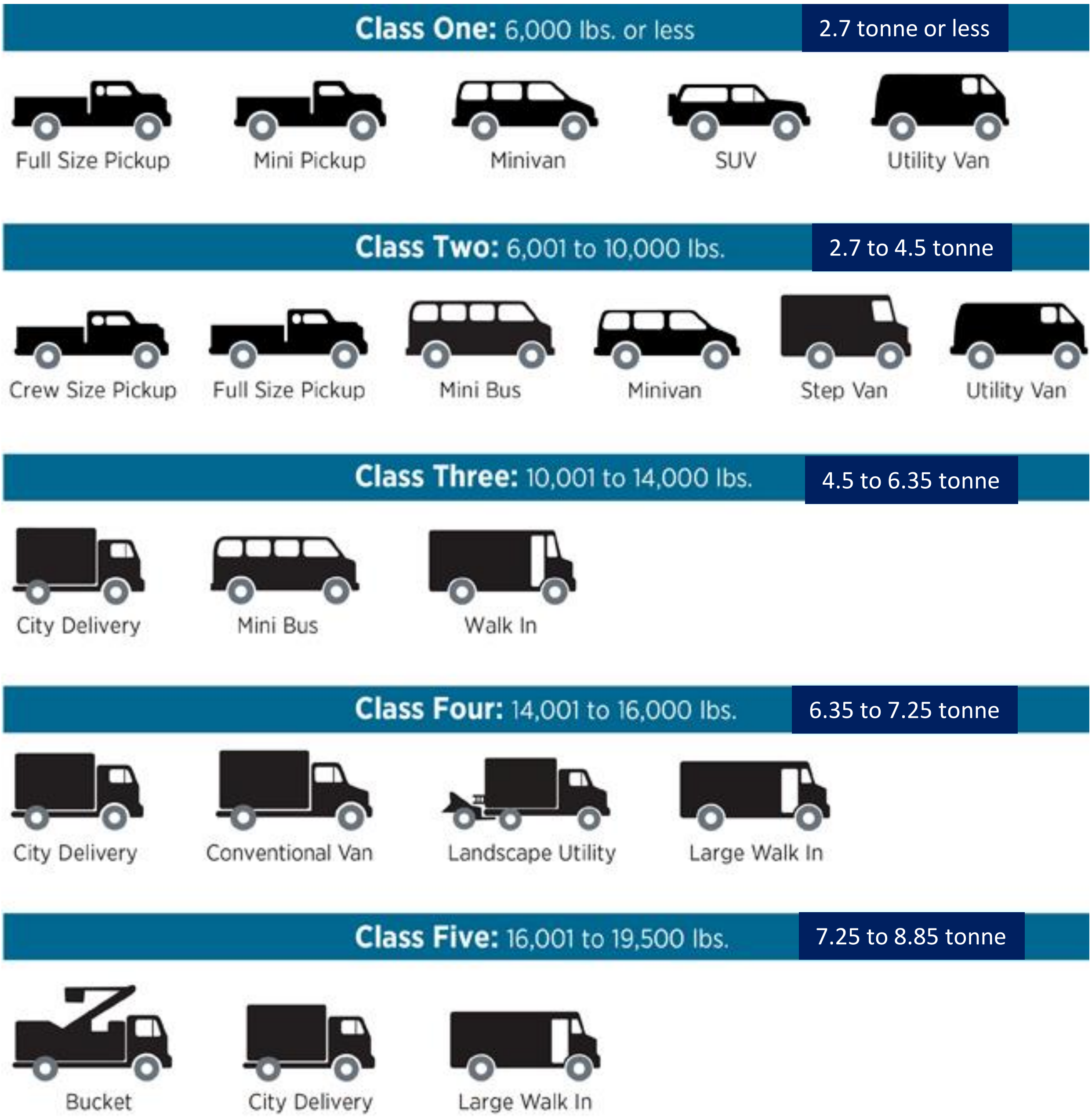


Figure 12.1. Vehicle type by class in the United States, Class 1-5
(Source: U.S. Department of Transportation, Bureau of Transportation Statistics)
(Copyright License: https://www.eia.gov/about/copyrights_reuse.php)

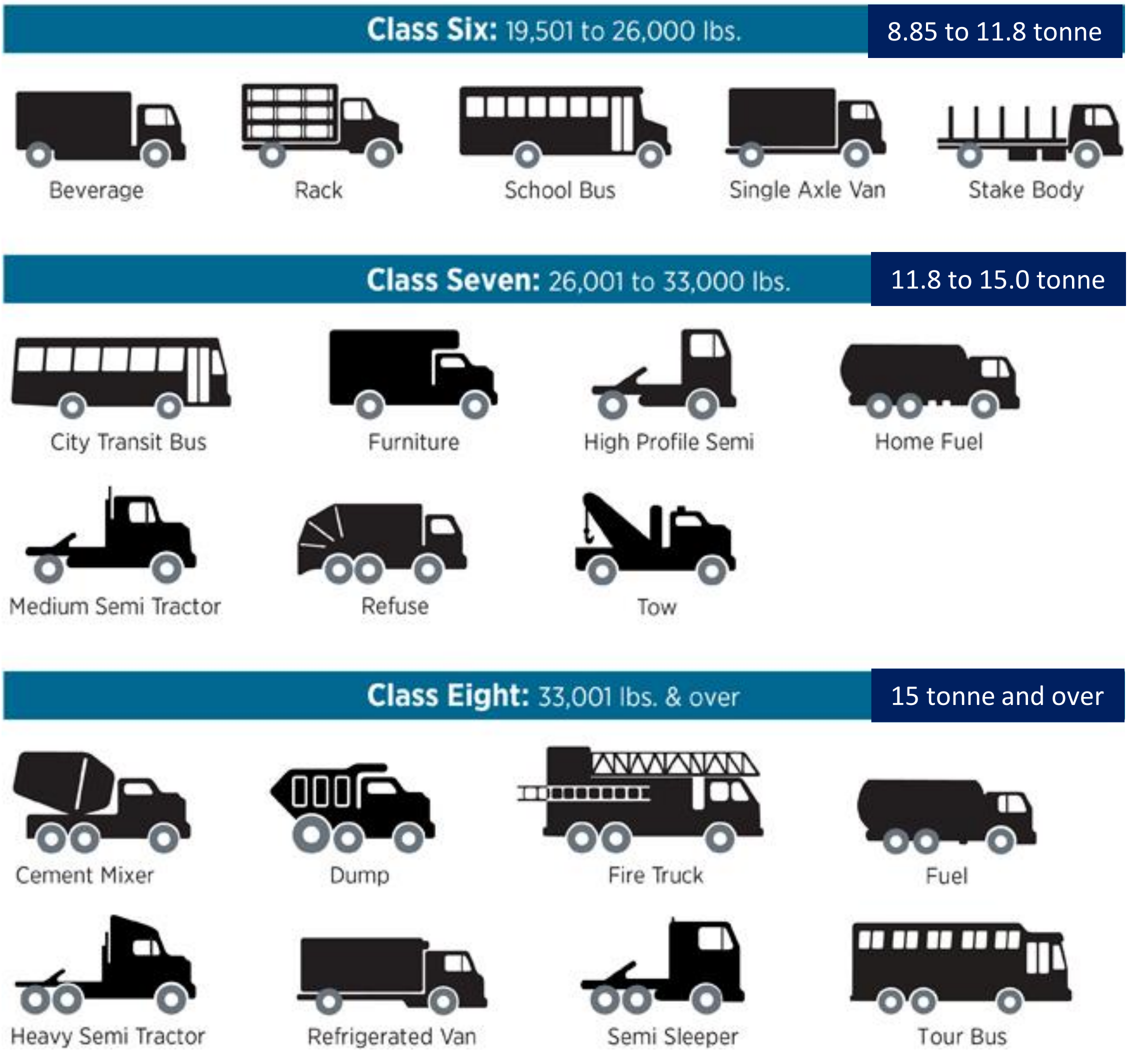


Figure 12.2. Vehicle type by class in the United States, Class 6-8
(Source: U.S. Department of Transportation, Bureau of Transportation Statistics)
(Copyright License: https://www.eia.gov/about/copyrights_reuse.php)

Figure 12.3 shows the recorded portions of self-propelled vehicles by class in the U.S. in 2018. Table 12.2 shows the number of vehicles by class and also the number of kilometers driven by each vehicle class in the United States.

Many developments of transport technology to be an alternative to ICE vehicles in the past have focused on just passenger cars. This is inappropriate as passenger cars represent only part of the number of vehicles and have travelled only a fraction of the kilometers. All vehicle classes need to be quantified in number and physical work done if a substitution system is to be viable.

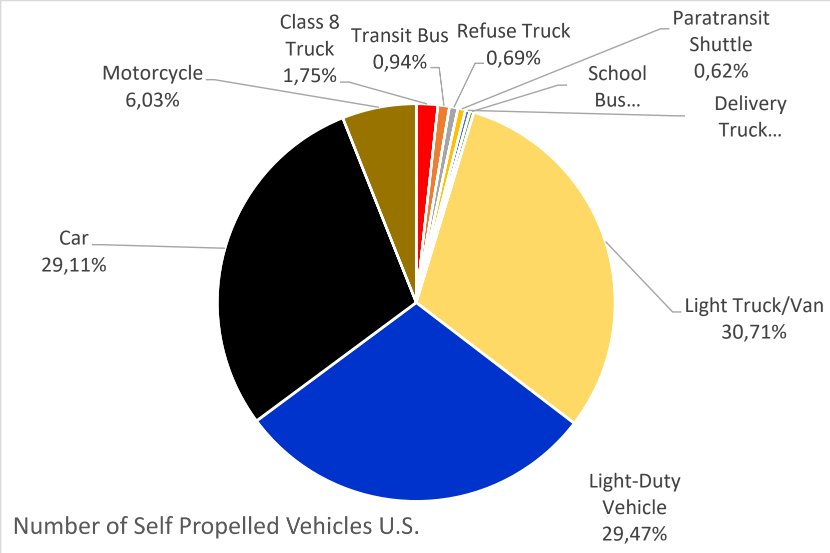


Figure 12.3. Self-Propelled Vehicles by Mode in the U.S. in 2018
(Source: U.S. Department of Transportation, Bureau of Transportation Statistics: National Transportation Statistics)

Figure 12.4 shows the total miles travelled over time in the United States. Figure 12.5 shows the miles traveled by vehicle class in the year 2018.

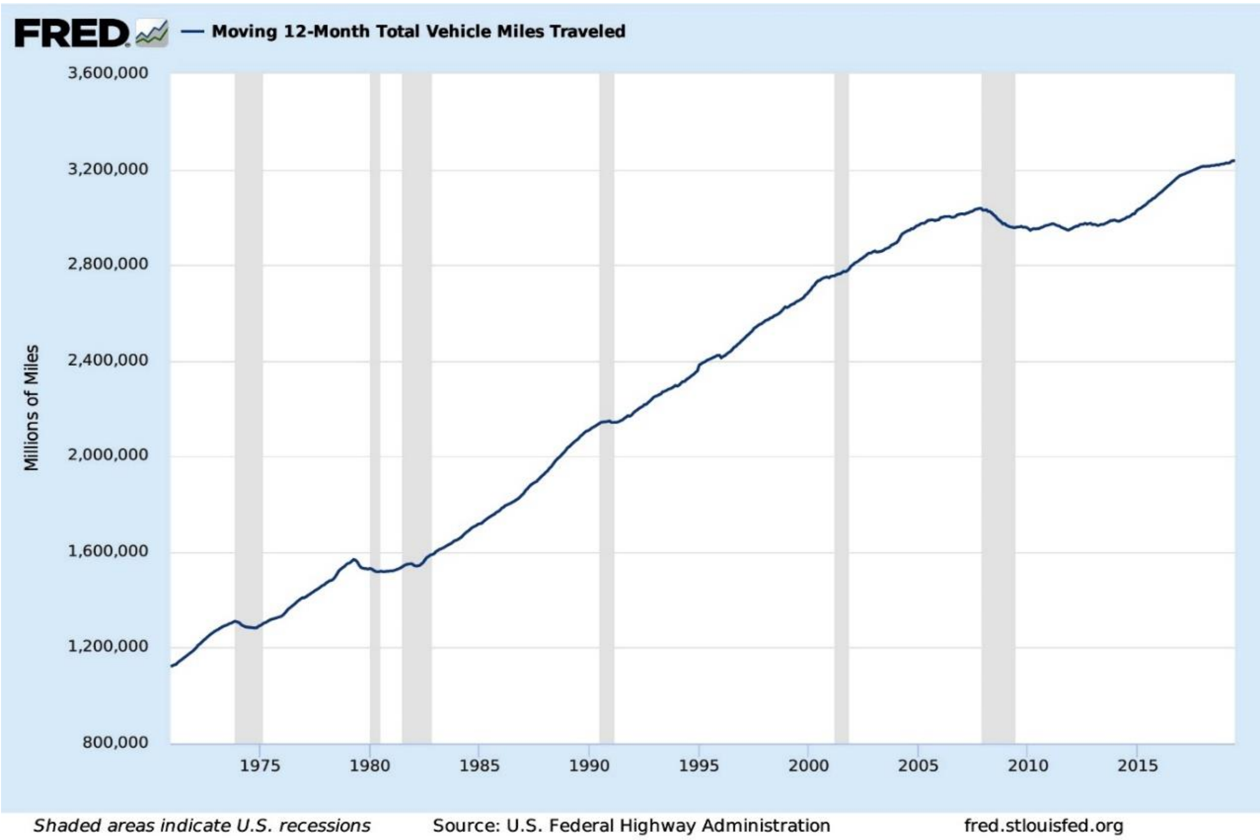


Figure 12.4. Moving 12-Month Total Vehicle Miles Traveled (M12MTVUSM227NFWA)
(Source: U.S. Dept. of Transport, Federal Reserve Bank of St Louis Economic Research 2019)

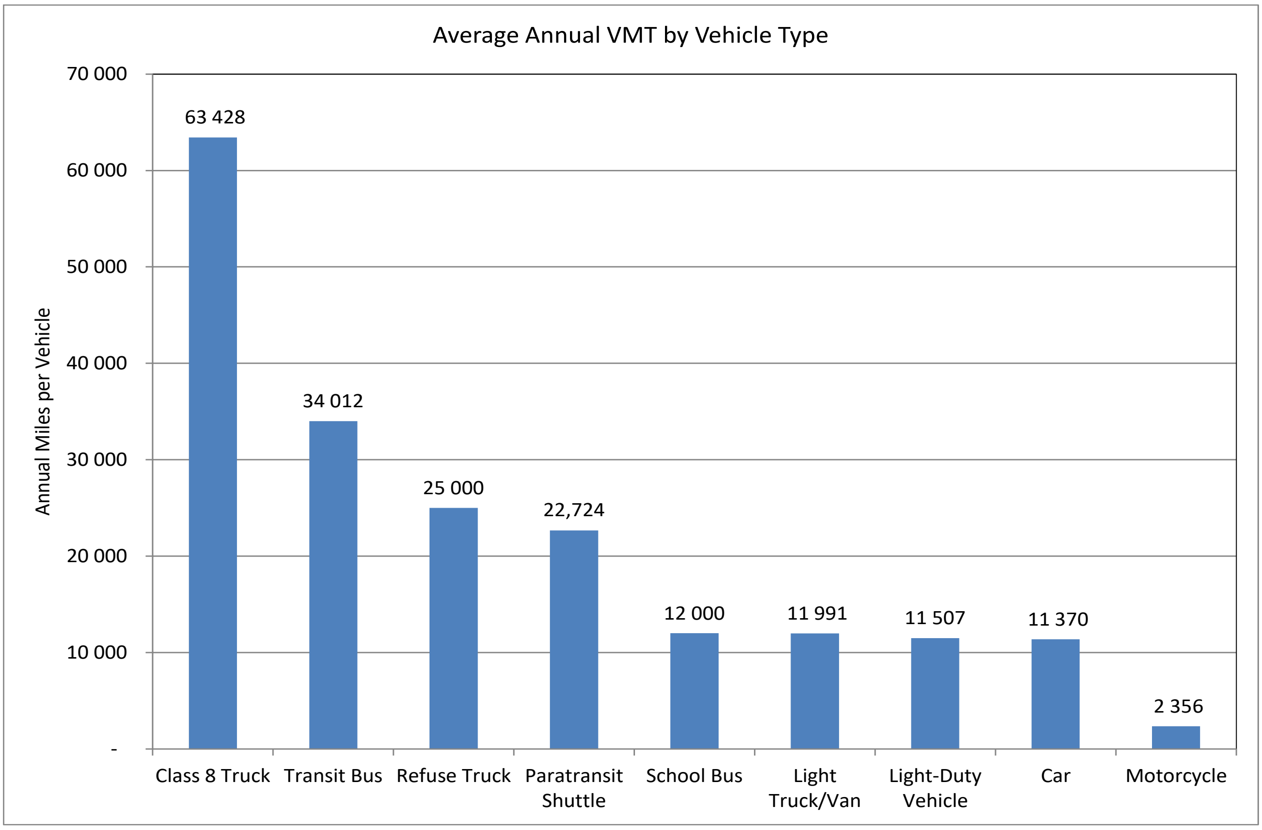


Figure 12.5. Average Annual Vehicle Miles Traveled (VMT) by Vehicle Class in the United States (Source: US Dept. of Energy 2019, Worksheet available at www.afdc.energy.gov/data/, Updated 11/28/2018) (Copyright License: https://creativecommons.org/licenses/by-nc-sa/4.0/)

Data Sources:

- Federal Highway Administration. Highway Statistics 2016, Table VM-1. Accessed 11/20/18 at http://www.fhwa.dot.gov/policyinformation/statistics/2016/
- Calculated from statistics found in American Public Transit Association's Public Transportation Fact Book 2017. Accessed 06/16/2014 at: https://www.apta.com/resources/statistics/Documents/FactBook/2017-APTA-Fact-Book.pdf
- Gordon, Deborah, Juliet Burdelski, and James S. Cannon. Greening Garbage Trucks: New Technologies for Cleaner Air. Inform, Inc. 2003. ISBN #0-918780-80-2.
- American School Bus Council. National School Bus Fuel Data. Accessed 11/21/18 at http://www.americanschoolbuscouncil.org/issues/environmental-benefits

Notes:

- Light-duty vehicles are sales-weighted combination of cars, wagons, vans, SUVs, and pickups. Vehicles with short wheelbases (<121 in.) are generalized as cars and vehicles with long wheelbases are generalized as light trucks.
- Delivery trucks are single-unit trucks with 2 axles and 6 or more tires.
- Class 8 trucks are combined tractor/trailer trucks, also known as long-haul or Class 8.

Table 12.2. Total number of km driven in the United States in 2018
(Source: U.S. Department of Transportation, Bureau of Transportation Statistics: National Transportation Statistics)

Vehicle Class	Number of Self Propelled Vehicles	Proportion of U.S. Fleet in 2018 (%)	Average annual miles driven by class in 2018 (miles)	Average annual km driven by class in 2018 (km)	Total miles driven in 2018 (miles)	Total km driven in 2018 (km)
Class 8 Truck	4 694 851	1,75 %	63 428	102 077	297 785 023 606	479 238 392 763
Transit Bus	2 517 520	0,94 %	34 012	54 737	85 625 901 695	137 801 488 504
Refuse Truck	1 850 465	0,69 %	25 000	40 234	46 261 619 737	74 450 837 120
Paratransit Shuttle	1 678 668	0,62 %	22 679	36 498	38 070 503 372	61 268 517 223
Delivery Truck	959 133	0,36 %	12 958	20 854	12 428 444 244	20 001 635 985
School Bus	888 223	0,33 %	12 000	19 312	10 658 677 187	17 153 472 873
Light Truck/Van	82 569 993	30,71 %	11 991	19 298	990 096 783 911	1 593 405 825 638
Light-Duty Vehicle	79 237 170	29,47 %	11 507	18 519	911 782 117 028	1 467 370 625 372
Passenger Car	78 293 789	29,11 %	11 370	18 298	890 200 375 687	1 432 638 190 179
Motorcycle	16 223 409	6,03 %	2 356	3 792	38 222 352 737	61 512 895 012
Total	268 913 221	100,0 %			3 321 131 799 203	5,34,E+12
	269 million vehicles					5.3 trillion km travelled in 2018

Where:

- Total number of vehicles in 2018 in the U.S. fleet was 269 million vehicles
- Total number of km driven by U.S. fleet in 2018 was 5.34 x 10^{12} km (5.34 trillion km).

12.1.2 Estimated distance travelled of vehicle classes in international transport fleets

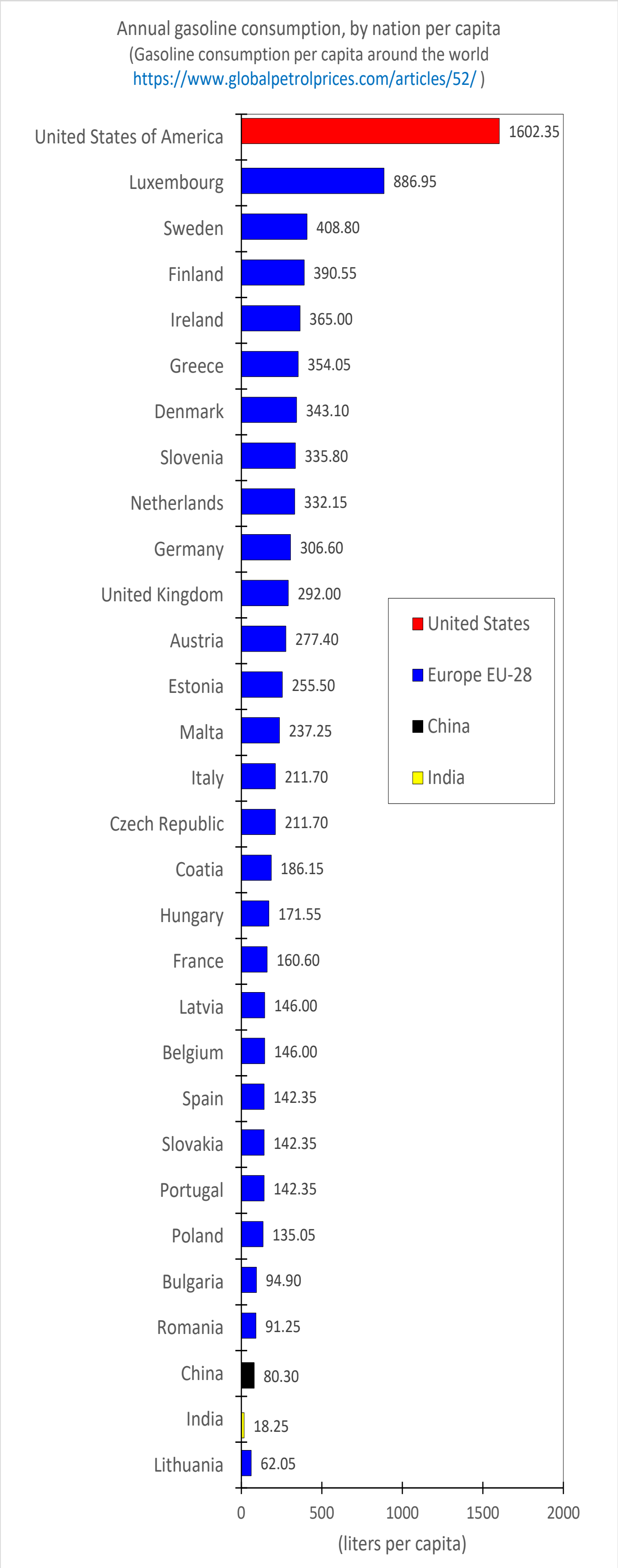
A number of calculations done later in this report in Section 18 require the estimated annual distance travelled by the different vehicle classes in the international transport fleets for the year 2018. This data is collected in the United States but not elsewhere. To resolve this, a set of ratio's are required to scale the U.S data to all other ecosystems studied. The following set of calculations were used to estimate a ratio in which to apply to Europe, China and the Rest of the World transport fleets, by comparing them to the United States. This data is shown in Figures 12.6 to 12.9.

1. The average daily gasoline consumption per capita for 151 nations, (the 151 largest consumption rate). This was adjusted to calculate the annual consumption (in Appendix J).
   (Source: Gasoline consumption per capita around the world https://www.globalpetrolprices.com/articles/52/)

2. The human population data for each nation state was collected.
   (Source: UN World Population Data 2017)

3. The number of vehicles in each nation state transport fleet was collected (in Appendix J)
   (Source: Appendix J, & ACEA 2018 for EU-28)

The annual national consumption of gasoline was calculated by multiplying the per capita consumption by the human population. The average gasoline consumed annually per vehicle, for each nation state was calculated by dividing the total annual gasoline consumption by the total number of vehicles in the national transport fleet (including cars, trucks, buses, etc.).



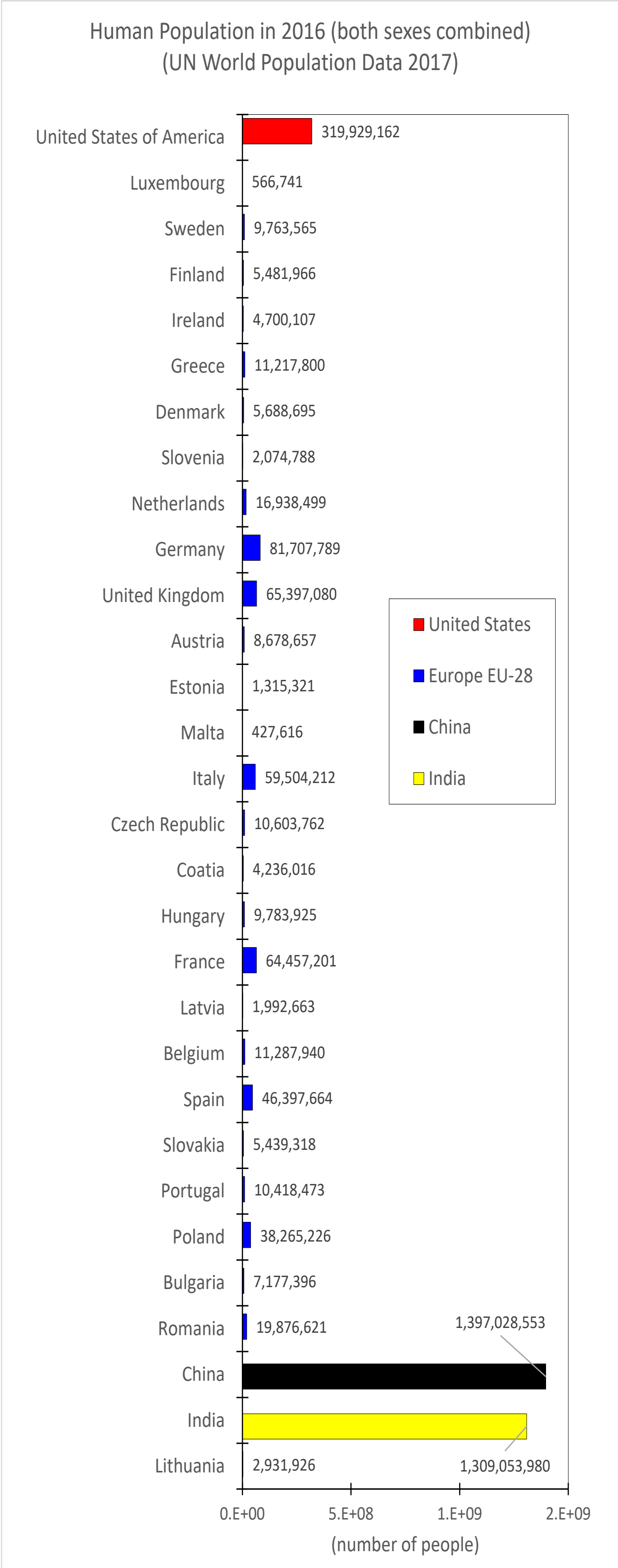


Figure 12.6. Annual gasoline consumption per population capita, by nation (LHS), Human population of each nation (RHS) United States, Europe EU-28, China, and India

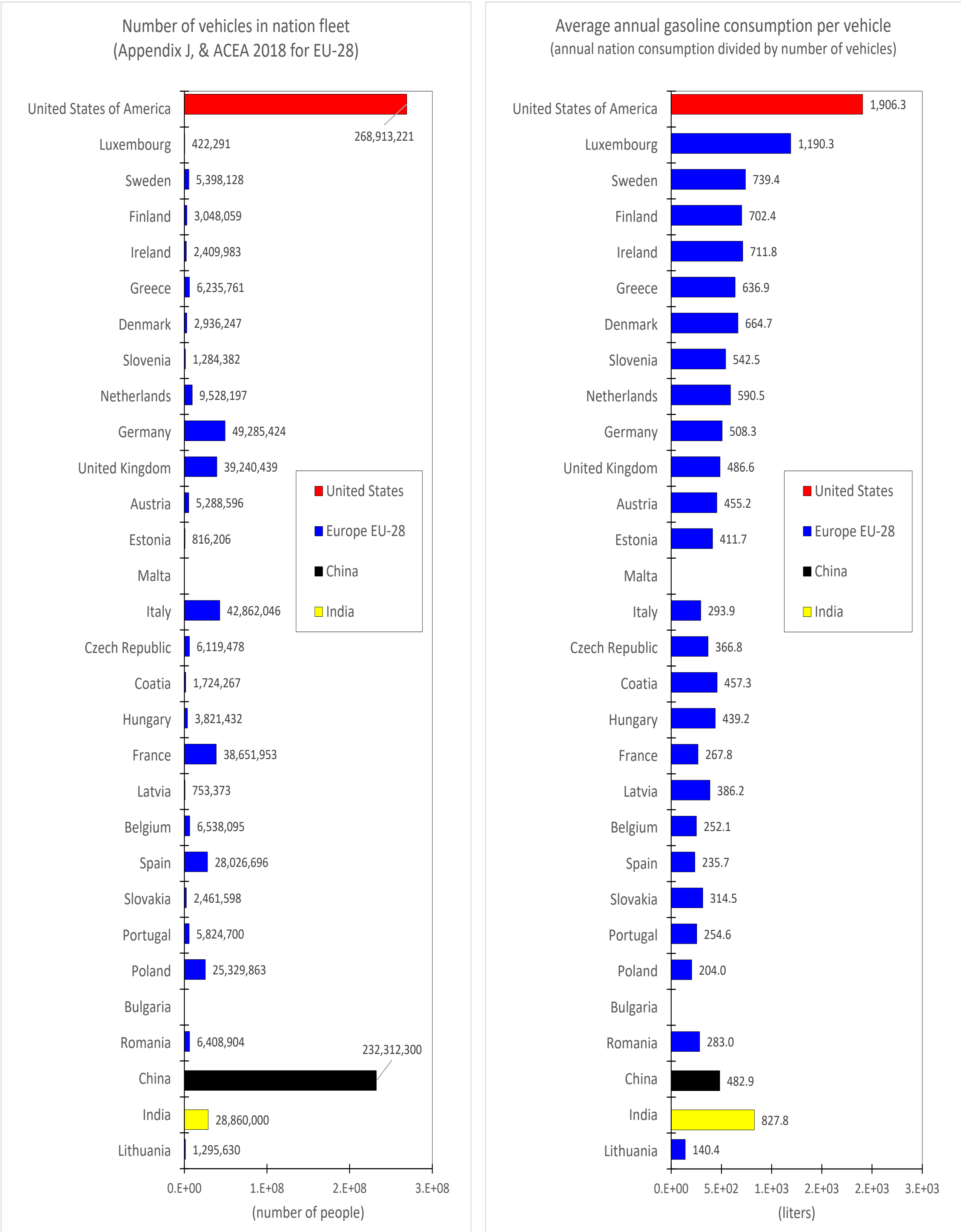
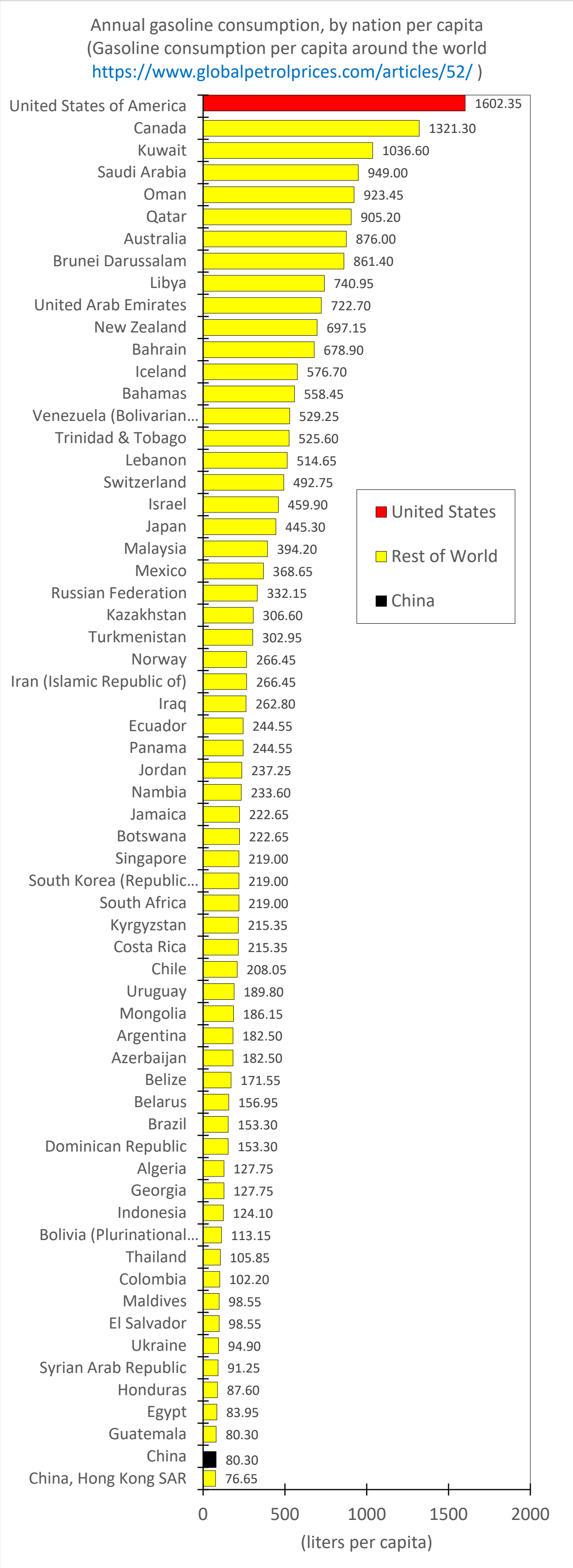


Figure 12.7. Number of vehicles in national transport fleet (LHS), Average annual gasoline consumption per vehicle (RHS) United States, Europe EU-28, China, and India



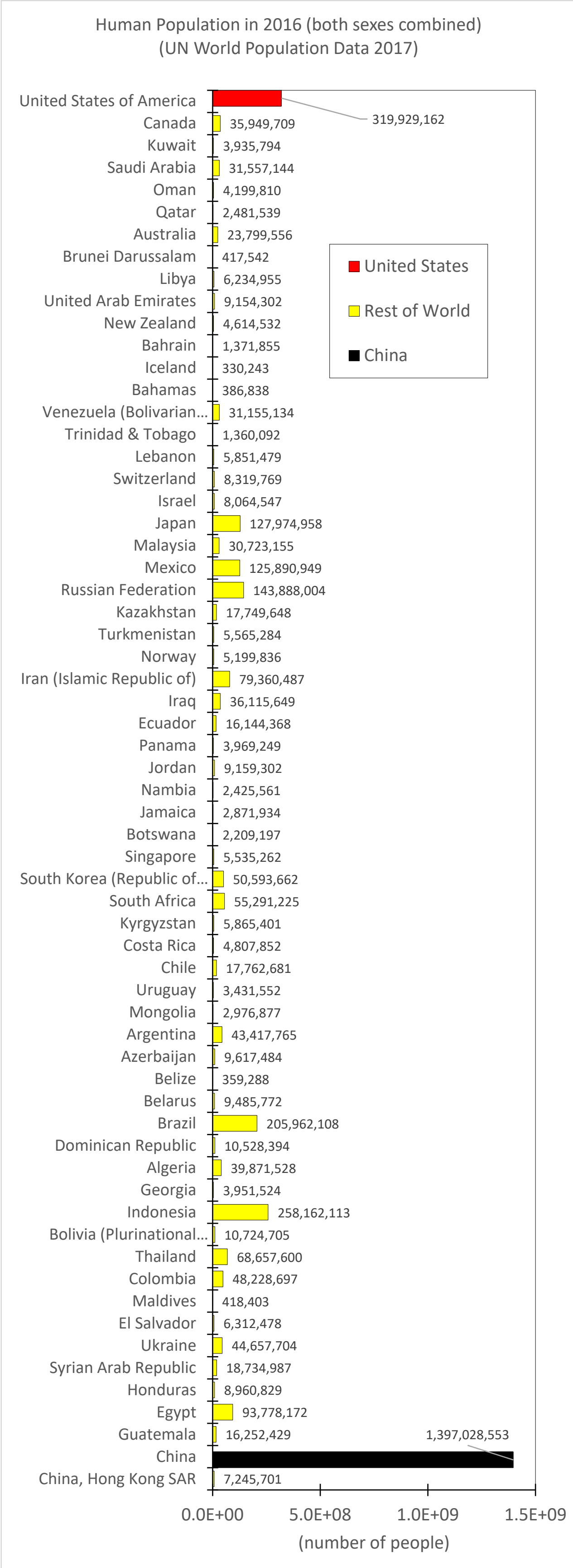


Figure 12.8. Annual gasoline consumption per population capita, by nation (LHS), Human population of each nation (RHS) United States, China, and the Rest of World

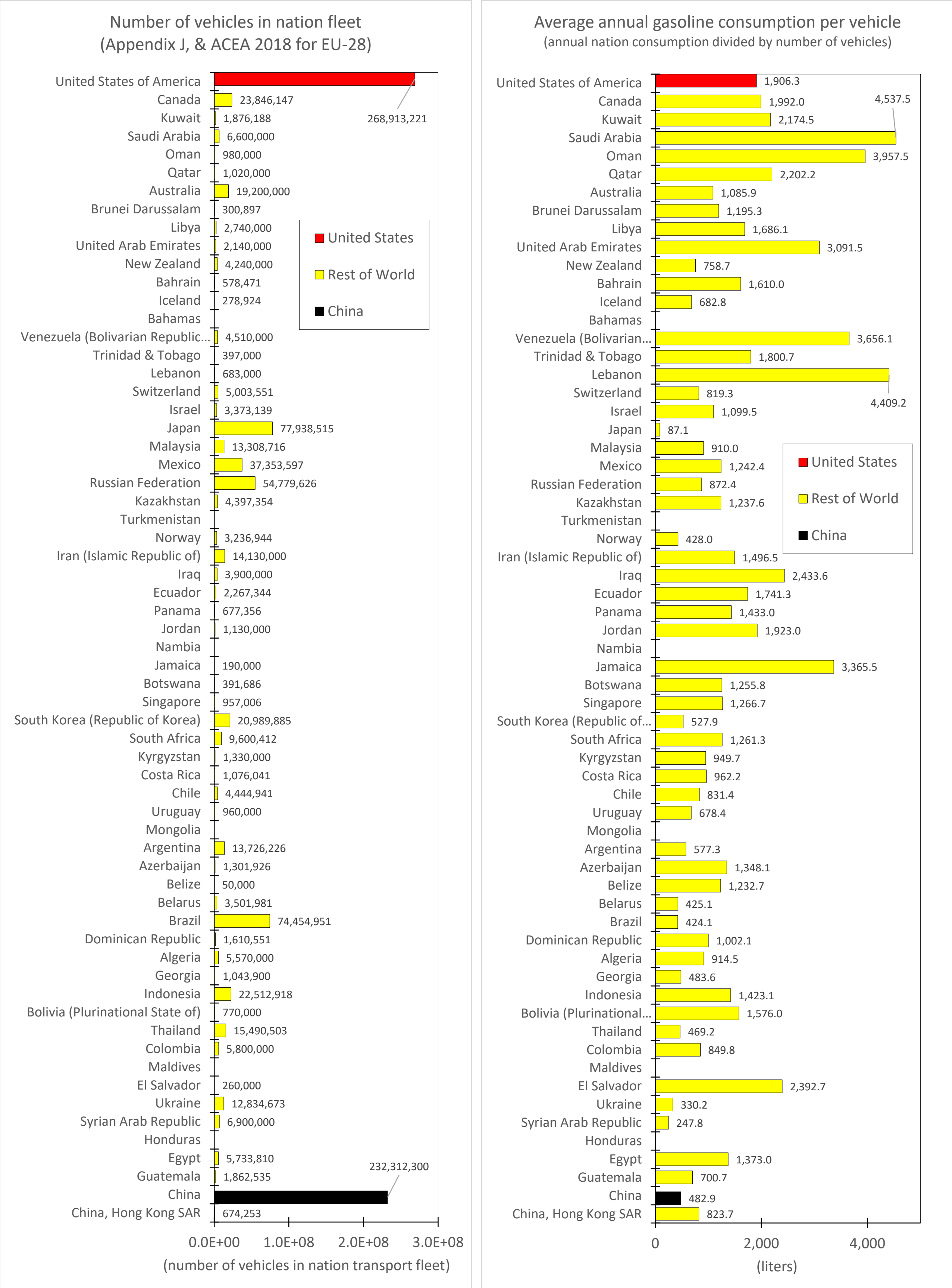


Figure 12.9. Number of vehicles in national transport fleet (LHS), Average annual gasoline consumption per vehicle (RHS) United States, China, and the Rest of World

Using the average vehicle annual consumption of gasoline, for each nation state (Figure 12.7 RHS and Figure 12.9 RHS) was used to develop a ratio between the United States and Europe (EU-28), China and the Rest of the World transport fleets. This is to develop an estimate to compare the activities by vehicles in each of these regions. There are measurements in the United States, but in other regions, an estimated based on the United States is required. The outcome is shown in Table 12.3.

Table 12.3. Estimated ratio between USA and other nations for average annual vehicle consumption (Source: Bottom of Table J6 in Appendix J)

Nation/Region	Average annual gasoline consumption per vehicle (liters)	Ratio (USA:Nation)
United States of America	1906.3	1
Europe EU-28	400.3	0.21
China	482.9	0.25
Rest of World	1185.1	0.62

These ratios in Table 12.3 are applied to the number of km travelled by vehicle class in the United States to estimate what those same vehicle classes travelled (on average) in Europe, China, and the Rest of the World (RoW). The outcome of this is shown in Table 12.4.

Table 12.4. Estimated average annual distance travelled for each vehicle class in Europe, China, and Rest of World, using the USA and the ratios in Table 12.3

Vehicle Class	Average km driven by class in 2018 U.S. Fleet (Ratio 1:1) (km)	Average km driven by class in 2018 EU-28 Fleet (Ratio 1 : 0.21) (km)	Average km driven by class in 2018 Chinese Fleet (Ratio 1 : 0.25) (km)	Average km driven by class in 2018 RoW Fleet (Ratio 1 : 0.62) (km)
Class 8 Truck	102,077	21,436	25,857	63,460
Transit Bus	54,737	11,495	13,865	34,029
Refuse Truck	40,234	8,449	10,192	25,013
Paratransit Shuttle	36,498	7,665	9,245	22,690
Delivery Truck	20,854	4,379	5,282	12,965
School Bus	19,312	4,056	4,892	12,006
Light Truck/Van	19,298	4,053	4,888	11,997
Light-Duty Vehicle	18,519	3,889	4,691	11,513
Passenger Car	18,298	3,843	4,635	11,376
Motorcycle	3,792	796	960	2,357

While it is recognized that this is a crude assumption, this was the best estimate the author could assemble, for the average distance travelled by each vehicle class, and the total km traveled in the national fleet of these regions. Assembling the number of vehicles in the global fleet proved to be difficult. This kind of data is not routinely collected in many countries. Only one country records the distance traveled. The United States Department of Transport quote up to date information on the number of vehicles, the different numbers by class and the miles driven by each vehicle class.

To estimate the total distance traveled by all the different classes of vehicles in a global context, the patterns and proportions seen in the United States was projected onto a 1.416 billion car fleet (Appendix J). This is a crude estimate, but it will suffice for the purpose of this report.

Once an overall number of vehicles is established, the proportions of vehicle class and the distance traveled by them can be estimated.

In 2018, the transport fleet in the United States was 268 913 211 vehicles (269 million vehicles). This shows that the U.S. transport fleet was 18.98% of the global transport fleet. The estimate number of km driven by the different vehicle classes in the United States in 2018 is shown in Table 12.2.

12.1.3 Estimated fleet size and kilometers driven by each vehicle class in European transport fleet

The annual distance traveled by vehicles in the United States is much higher than the annual distance travelled by vehicles in Europe. In 2018, the transport fleet in the European Union (EU-28) was reported as 261 019 964 vehicles (261 million vehicles). This shows that the EU transport fleet was 18.43% of the global transport fleet. The estimate number of km driven by the different vehicle classes in the European Union in 2018 is shown in Table 12.5.

Table 12.5. Estimated total number of km driven by vehicles in the European Union in 2018 (Source: ACEA 2018)

Vehicle Class	Number of Self Propelled Vehicles in 2018 European Union Fleet (Data Source: ACEA 2018)	Proportion of EU-28 Fleet (%)	Average annual km driven by class in EU-28 in 2018 (km)	Total km driven by class in 2018 EU-28 Fleet (km)
Class 8 Truck	5,716,322	2.19%	2.14E+04	1.2E+11
Bus	657,714	0.25%	1.15E+04	7.6E+09
Light Truck/Van	27,413,946	10.50%	4.05E+03	1.1E+11
Passenger Car	222,683,327	85.31%	3.84E+03	8.6E+11
Motorcycle	4,548,655	1.74%	7.96E+02	3.6E+09
Total	261,019,964			1.10E+12
	261 million vehicles			Travelled 1.115 trillion km in 2018

Where:

- Total number of vehicles in the EU fleet is 261 million vehicles
- Total number of km driven by EU fleet is 1.1 x 10^{12} km.

12.1.4 Estimated fleet size and kilometers driven by each vehicle class in the Chinese transport fleet

In 2018, the transport fleet in the China was 232 312 300 vehicles (232 million vehicles). This shows that the Chinese transport fleet was 16.4% of the global transport fleet. The estimate number of km driven by the different vehicle classes in China in 2018 is shown in Table 12.6.

Table 12.6 shows the same outcomes as Table 12.2 but for the China. The number of vehicles and how many in which vehicle class was collected from the National Bureau of Statistic of China in 2019 http://www.stats.gov.cn/tjsj/ndsj/2019/indexch.htm. The definitions of what comprises of a vehicle class were stated according to the People's Republic of China public safety industry standard, from the same website (http://www.jxjdcjc.com/ueditor/php/upload/file/20170818/1503017721116112.pdf).

The Chinese department of transport did not record the number of kilometers travelled. As this is needed, these values were estimated by projecting the average numbers for km travelled by vehicle class in 2018, as quoted by the U.S. Dept. of Transport.

Where:

- Total number of vehicles in the Chinese fleet is 232 million vehicles (National Bureau of Statistic of China 2019)

- Total number of km driven by Chinese fleet is 1.34 $x10^{12}$ km. This number was projected from data collected per car class and number collected by the U.S. Department of Transport.

Table 12.6. Number of vehicles in the Chinese fleet 2018, by class, and estimated km driven

(Source: National Bureau of Statistic of China in 2019 http://www.stats.gov.cn/tjsj/ndsj/2019/indexch.htm)

Vehicle Class in China	Vehicle Mass According to Chinese Classification (Appendix J)	Number of Vehicles in China in 2018 (number)	Proportion of Vehicle Class in 2018 (%)	Vehicle Class in U.S. Dept of Transport Classification System	Proportion of vehicles in Chinese fleet, reclassified with U.S. dept transport Classification System	Average km traveled in 2018 by Vehicle Class in Chinese Transport system (km)	Estimated total km driven by class in 2018 Chinese Fleet (projected from US dept of Transport) (km)
Passenger Vehicle		**205,554,100**	88.5 %	Passenger Car	203,689,500	4,635	9.4412E+11
Large		1,583,300					
Medium Size		754,000					
Small		201,352,200					
Mini		1,864,600		Motorcycle	1,864,600	960	1.79E+09
Goods Vehicle		**25,678,200**	11.1 %				
Heavy Duty	>= 12000 kg	7,095,300		Class 8 Truck	7,095,300	25,857	2.93E+11
Medium	4500 >= Medium < 12000	1,243,900		Transit Bus + School Bus + Refuse Truck + Paratransit Shuttle + Delivery Truck	1,243,900	12,028	1.50E+10
Light	< 4500 kg	17,285,300		Light Truck/Van + Light-Duty Vehicle + Other Vehicle Type	18,419,000	4,790	8.82E+10
Mini	=< 1800 kg	53,700					
Other Vehicle Type		**1,080,000**	0.5 %				
	Total	232,312,300			232,312,300		1.34E+12
		232.3 Trillion Vehicles			232.3 Trillion Vehicles		1.34 Trillion km

12.1.5 Estimated fleet size and kilometers driven by each vehicle class in Rest of World (RoW) transport fleet

The rest of the world transport fleet (RoW) size is estimated by subtracting from the global fleet size (1.416 billion), the U.S. fleet (269 million), the European fleet (261 million) and the Chinese fleet (232 million). This gives a number of 654 283 130 vehicles (see Table 12.7).

The number of kilometers travelled in the RoW proportion, by each vehicle class can be estimated by taking the estimated fraction proportion of vehicle class in the United States, as recorded by the U.S. Department of Transport, and projecting the numbers from Table 12.2, onto a transport fleet to represent the RoW fleet, of 654 million vehicles, by applying the ratios and data in Tables 12.3 and 12.4. Table 12.7 below shows this outcome.

Table 12.7. Rest of World (RoW) total number of km driven in 2018

Vehicle Class	Number of Self Propelled Vehicles in U.S. in 2018 (number)	Proportion of U.S. Fleet in 2018 (%)	Estimated number of Self Propelled Vehicles in 2018 RoW Fleet (number)	Average km traveled in 2018 by Vehicle Class in Rest of World Transport system (km)	Estimated total km driven by class in RoW Global Fleet (km)
Class 8 Truck	4,694,851	1.75%	11,422,874	63,460	7.2E+11
Transit Bus	2,517,520	0.94%	6,125,289	34,029	2.1E+11
Refuse Truck	1,850,465	0.69%	4,502,300	25,013	1.1E+11
Paratransit Shuttle	1,678,668	0.62%	4,084,306	22,690	9.3E+10
Delivery Truck	959,133	0.36%	2,333,632	12,965	3.0E+10
School Bus	888,223	0.33%	2,161,104	12,006	2.6E+10
Light Truck/Van	82,569,993	30.71%	200,898,093	11,997	2.4E+12
Light-Duty Vehicle	79,237,170	29.47%	192,789,122	11,513	2.2E+12
Passenger Car	78,293,789	29.11%	190,493,814	11,376	2.2E+12
Motorcycle	16,223,409	6.03%	39,472,597	2,357	9.3E+10
Total	268,913,221	100.0 %	654,283,130		8.085.E+12
			654 million vehicles		Travelled 8.1 trillion km in 2018

The data collected in Tables 12.2 (United States fleet), Table 12.5 (European fleet), Table 12.6 (Chinese fleet) and Table 12.7 (Rest of the World fleet) was combined into Table 12.8. In Table 12.9, the pertinent information is further distilled, showing the estimated number of vehicles and the estimate distance travelled by each vehicle class in the global fleet.

12.1.6 Predicted size of the future global vehicle fleet

This report is using an estimate of what the global vehicle fleet currently is, where a rough approximation is calculated in Appendix J. This however is an underestimation. The current industrial paradigm is one of continued economic growth in all sectors. Using the EIA International Energy Outlook 2019 (EIA 2019 Sept b), the size of the future vehicle fleet is estimated (but is not used for this report). The purpose of this section is to demonstrate that while these outcomes for extra power capacity required to charge a completely EV vehicle fleet are significantly larger than current thinking allows for, they are most certainly an underestimation of what will be needed. It is predicted that from 2018 to 2050, the light-duty vehicle fleet transitions from primarily gasoline and diesel vehicles; by 2050, electricity and natural gas powers over one-third of the light-duty vehicle fleet in the Reference case.

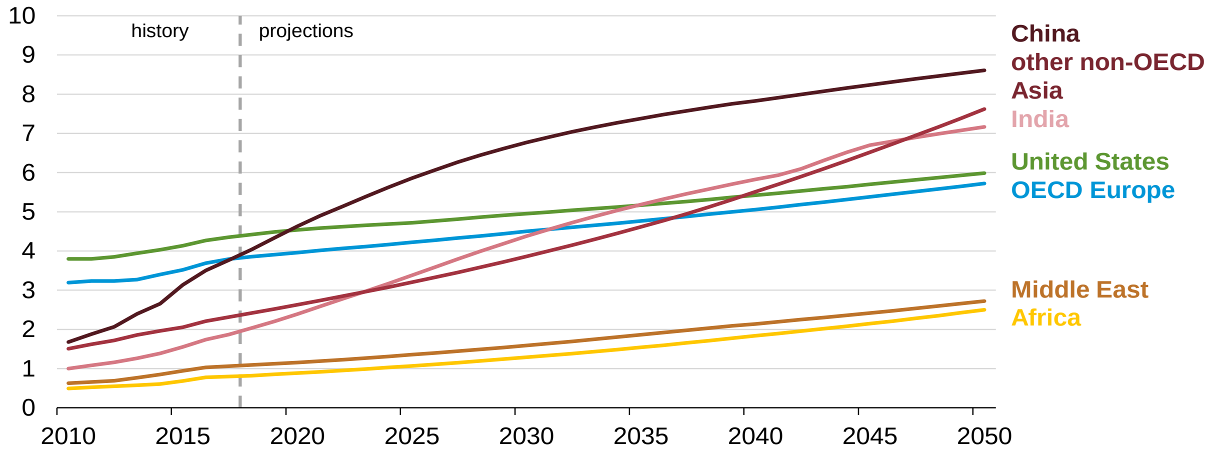


Figure 12.10. Passenger vehicle travel (select regions) trillion vehicle miles traveled
(Source: EIA International Energy Outlook 2019 with projections to 2050)

Figure 12.10 shows the predicted growth in passenger vehicles. Figure 12.11 shows the predicted growth in light-duty vehicles.

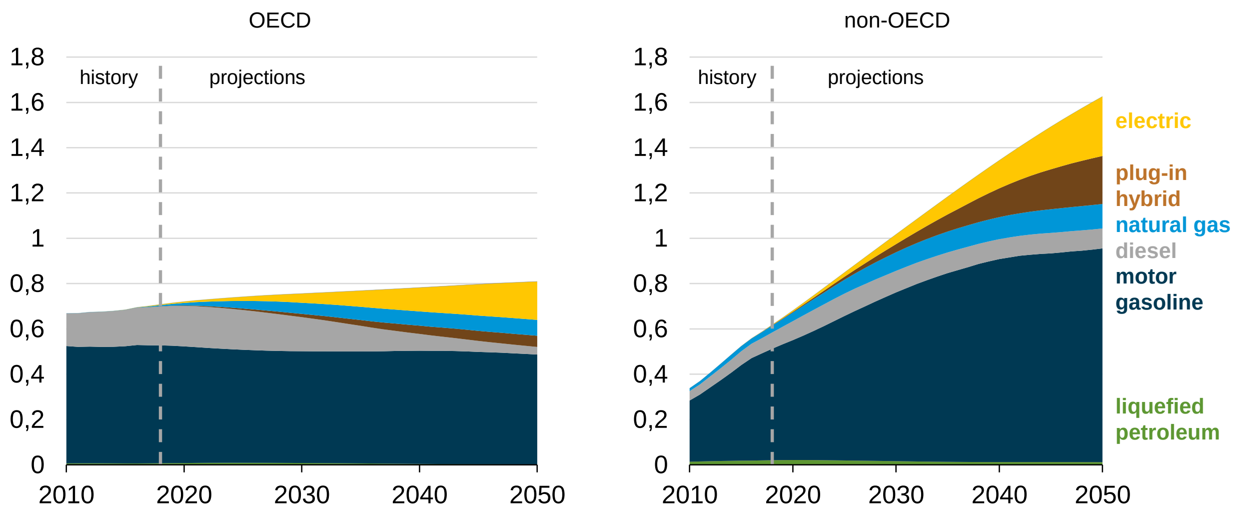


Figure 12.11. Light-duty vehicle stock billion vehicles
(Source: EIA International Energy Outlook 2019 with projections to 2050)

Much of the decline in diesel consumption in OECD countries comes as Europe gradually transitions from diesel powered light-duty vehicles to electric vehicles. Because stocks reflect existing vehicles, the rate of growth in vehicle stocks is lower than that of new vehicle sales. Many regions, including non-OECD Europe and Eurasia, the Middle East, and Africa, maintain mostly petroleum-fueled light-duty fleets throughout the projection period. These regions continue to operate largely gasoline and diesel vehicle fleets because of many reasons, such as cost, and infrastructure. The worldwide transportation sector is predicted to account for 59% of total end-use sector liquid fuels (residual fuel oil, diesel, motor gasoline, and jet fuel) consumption in 2050 (Figure 12.12). This is about the same as in 2018. Within the transportation sector, the use of refined petroleum and other liquid fuels is predicted to continue to increase through 2050, but its share decreases from 94% to about 82% as alternative fuel use slowly increases.

Motor gasoline, including biofuel additives such as ethanol, remains the primary fuel for transportation purposes, accounting for 32% of the world's transportation-related energy use in 2050 (Figure 12.13). A continuing global rise in air travel demand leads to jet fuel consumption more than doubling from 2018 to 2050. This 2019 prediction has already been destabilized due to the Covid-19 pandemic that was declared in 2020. This has resulted in a significant drop of 43% in global aviation transport (IATA 2021). This highlights the difficulties in making future predictions.

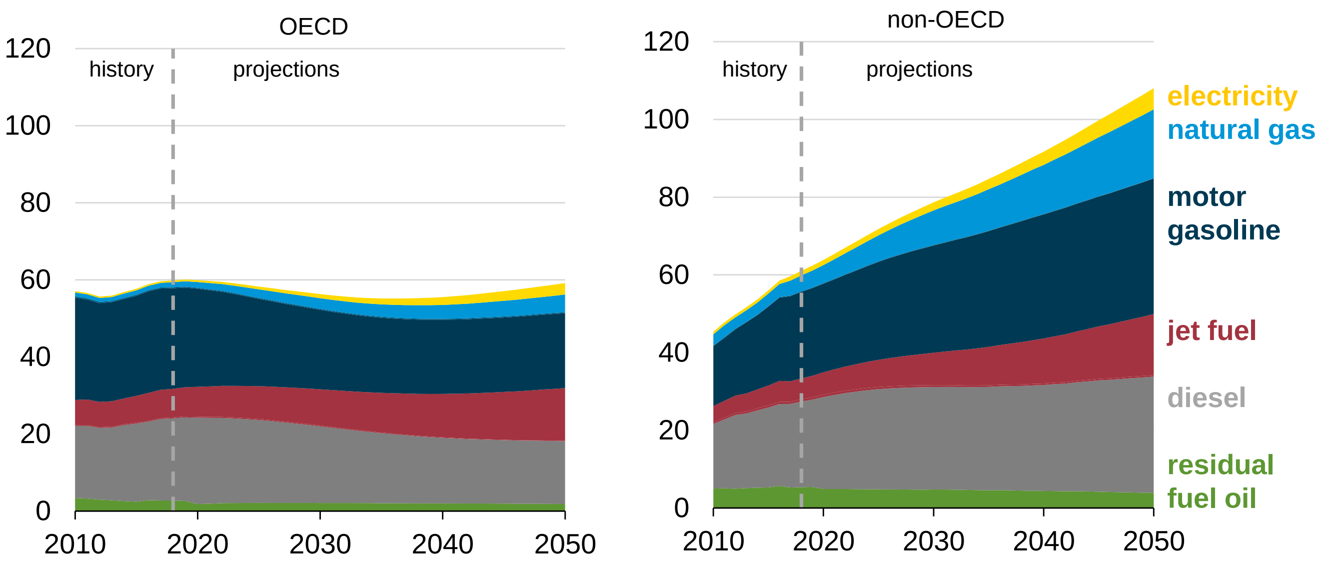


Figure 12.12. Transportation energy consumption British thermal units
(Source: EIA International Energy Outlook 2019 with projections to 2050)
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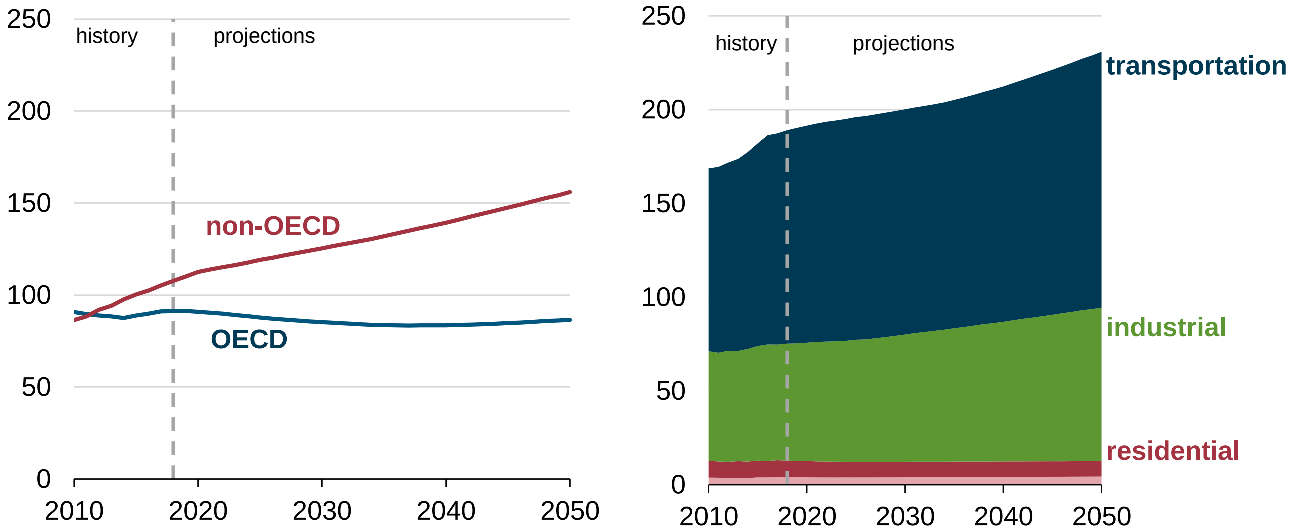

Figure 12.13. Petroleum and other liquids consumption British thermal units
(Source: EIA International Energy Outlook 2019 with projections to 2050)
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Table 12.8. Number of vehicles and estimated km driven in U.S., EU-28, China, and RoW fleets

U.S.

Vehicle Class	Number of Self Propelled Vehicles in U.S. in 2018 (number)	Total km driven by class in U.S. in 2018 (km)
Class 8 Truck	4,694,851	4.8E+11
Transit Bus	2,517,520	1.4E+11
Refuse Truck	1,850,465	7.4E+10
Paratransit Shuttle	1,678,668	6.1E+10
Delivery Truck	959,133	2.0E+10
School Bus	888,223	1.7E+10
Light Truck/Van	82,569,993	1.6E+12
Light-Duty Vehicle	79,237,170	1.5E+12
Passenger Car	78,293,789	1.4E+12
Motorcycle	16,223,409	6.2E+10
Total	268,913,221	5.34.E+12

EU-28

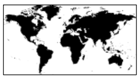
Vehicle Class	Number of Self Propelled Vehicles in EU-28 in 2018 (number)	Total km driven by class in EU-28 in 2018 (km)
Class 8 Truck	5,716,322	1.23E+11
Bus	657,714	7.56E+09
Light Truck/Van	27,413,946	1.11E+11
Passenger Car	222,683,327	8.56E+11
Motorcycle	4,548,655	3.62E+09
Total	261,019,964	1.10.E+12

China

Vehicle Class	Number of Self Propelled Vehicles in China in 2018 (number)	Total km driven by class in China in 2018 (km)
Class 8 Truck	7,095,300	2.93E+11
Transit Bus + School Bus + Refuse Truck + Paratransit Shuttle + Delivery Truck	1,243,900	1.50E+10
Light Truck/Van + Light-Duty Vehicle + Other Vehicle Type	18,419,000	8.82E+10
Passenger Car	203,689,500	9.44E+11
Motorcycle	1,864,600	1.79E+09
	232,312,300	1.34.E+12

Vehicle Class (Rest of World)	Number of Self Propelled Vehicles in RoW in 2018 (number)	Total km driven by class in RoW in 2018 (km)
Class 8 Truck	11,422,874	7.25E+11
Transit Bus	6,125,289	2.08E+11
Refuse Truck	4,502,300	1.13E+11
Paratransit Shuttle	4,084,306	9.27E+10
Delivery Truck	2,333,632	3.03E+10
School Bus	2,161,104	2.59E+10
Light Truck/Van	200,898,093	2.41E+12
Light-Duty Vehicle	192,789,122	2.22E+12
Passenger Car	190,493,814	2.17E+12
Motorcycle	39,472,597	9.30E+10
Total	654,283,130	8.08.E+12

Table 12.9. Number of vehicles and estimated km driven in global fleet (combined from Table 12.6) (World Map Image by Clker-Free-Vector-Images from Pixabay)

Vehicle Class 	Number of Self Propelled Vehicles in Global Fleet in 2018 (number)	Total km driven by class in Global Fleet in 2018 (km)
Class 8 Truck	28,929,348	1.62E+12
Transit Bus + Refuse Truck + Paratransit Shuttle + Delivery Truck + School Bus	29,002,253	8.03E+11
Light Truck/Van + Light-Duty Vehicle	601,327,324	7.89E+12
Passenger Car	695,160,429	5.40E+12
Motorcycle	62,109,261	1.60E+11
Total	1,416,528,615	1.587.E+13

1.416 billion vehicles   Travelled 15.87 trillion km in 2018

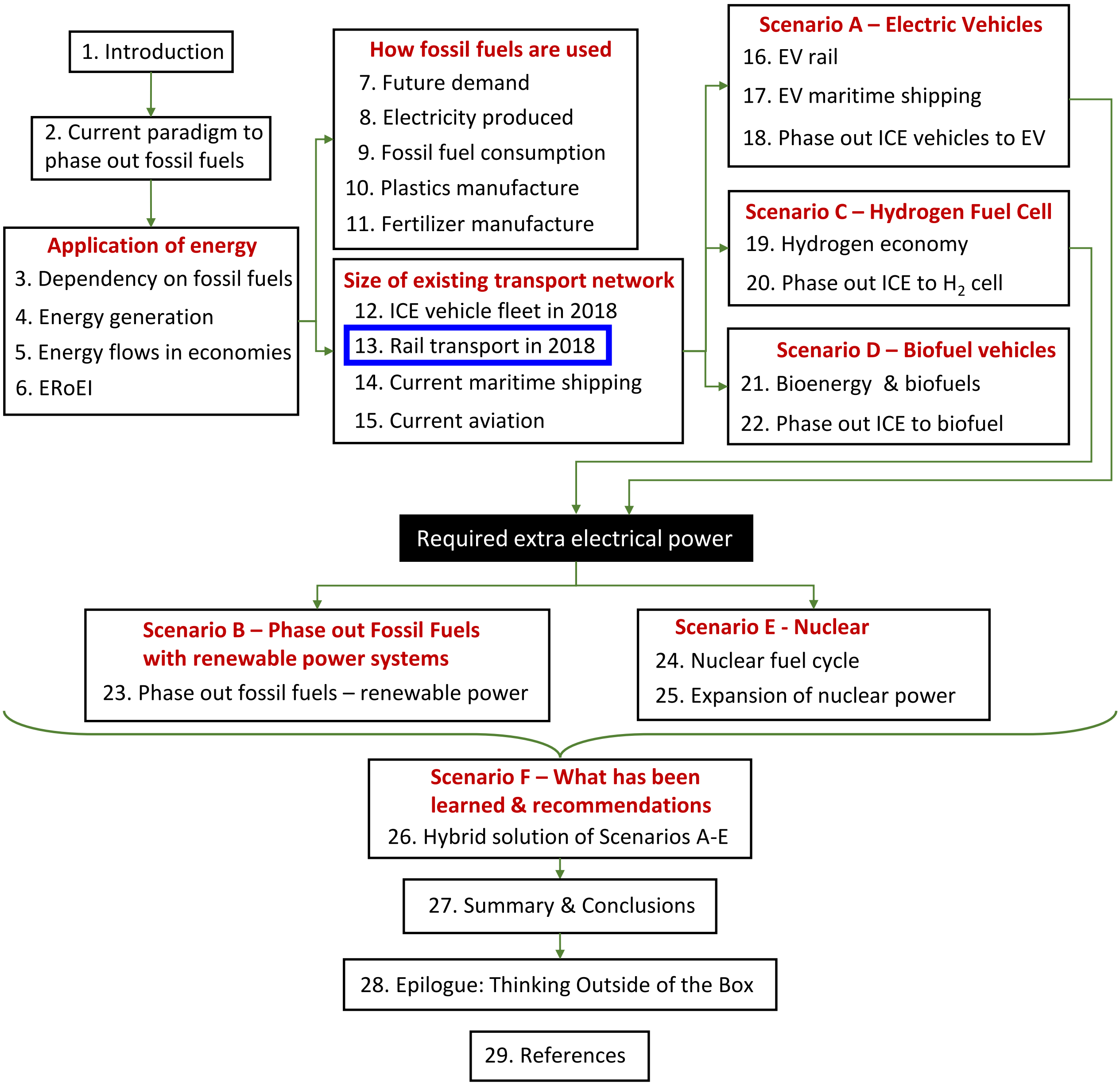
Where:

- Estimated total number of vehicles in the global fleet was 1.416 billion vehicles. While this number is an average of several studies with an average date of 2016 (Appendix J), this number will be used to estimate the number in 2018 global fleet.

- Estimated total number of km driven by global fleet was 1.587 x10^{13} km (15.87 trillion km).

13 SIZE AND SCOPE OF CURRENT RAIL TRANSPORT OF PASSENGERS AND FREIGHT

The industrial ecosystem is underpinned by the transport of goods and people. Rail has been a very effective method to transport large quantities of freight and large numbers of passengers over long distances. A large proportion of rail transport (both passenger and freight) is powered by diesel fueled ICE engines. To phase out fossil fuel systems, the size and scope of those diesel fueled rail locomotives would need to be quantified some numbers collected. Also, if urban planning would become more reliant on rail as ICE vehicles are phased out, then the scope of electrification of the existing diesel fueled rail networks would need to be understood.



Assessment of the Extra Capacity Required of Alternative Energy Electrical Power Systems to Completely Replace Fossil Fuels

Passenger rail transport activity comprises urban and non-urban passenger movements and is typically measured in passenger-kilometers per year. Such activity has increased significantly over the past twenty years, but is concentrated in a few regions, China, India, Japan, European Union, and Russia together account for more than 90% of passenger rail activity worldwide (IEA 2019).

In the European Union, historically the first region to build an international rail network, rail activity has risen slowly but steadily in recent decades, both in the case of urban and non-urban transport. Part of its passenger activity has shifted from conventional to high-speed rail. By 2016, high-speed rail accounted for roughly one-quarter of non-urban passenger-kilometers. There is great interest in high speed rail systems development, but most passenger rail activity currently takes place on conventional trains. That being stated, growth in rail transport development activity is most significant in metro and high-speed rail networks.

On a global scale, rail accounts for a minor share of urban passenger transport. On a country basis, Japan and Korea have the highest shares of rail in urban transport.

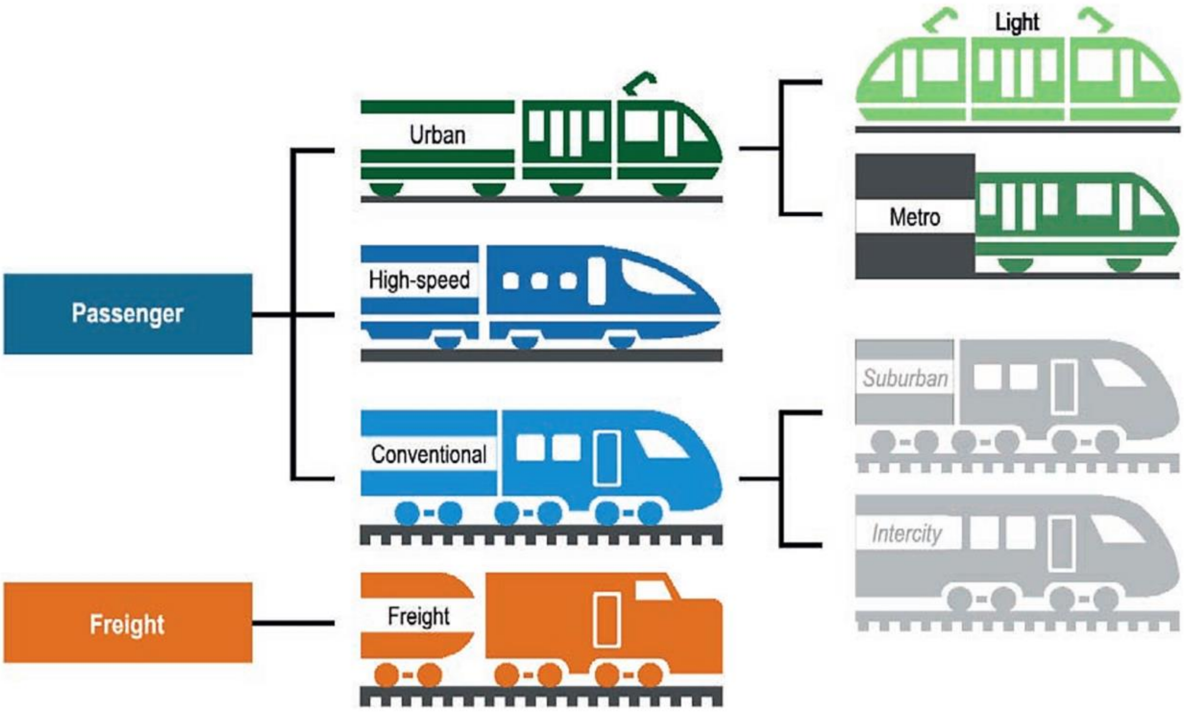


Figure 13.1. Classification of various railway services and infrastructure (Source: IEA 2019)
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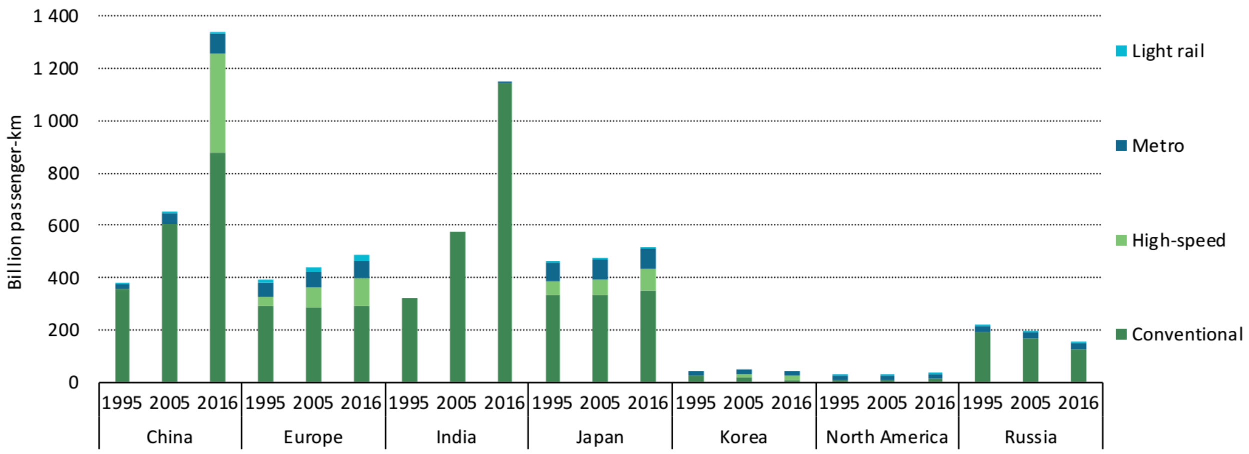
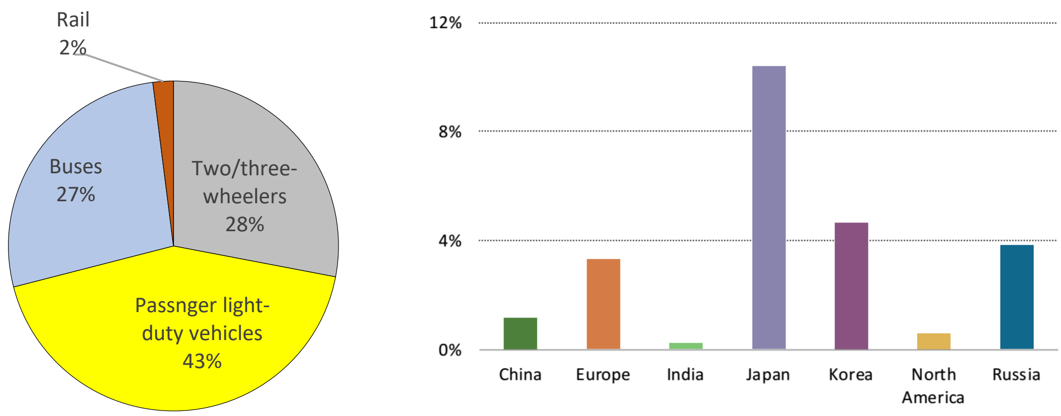


Sources: IEA assessment based on UIC (2018a); UITP (2018a); ITDP (2018), National Bureau of Statistics of China (2018); Indian Railways (2018a); Japan Ministry of Land, Infrastructure and Tourism (2018); AAR (2017) and Russian Federation State Statistics Service (2018).

Figure 13.2. Passenger activity by rail type (Source: IEA 2019)
(Copyright License: https://www.iea.org/media/copyright/Termsandconditions_2019update_FINAL.docx.pdf)



Note: The figures include metro and light rail systems within city limits and do not include suburban and commuter rail networks.
Source: IEA (2018a).

Figure 13.3. Modal shares of urban transport activity in passenger-kilometers (LHS) and as a share of urban rail in total urban passenger activity by country (RHS), 2017 (Source: IEA 2019)
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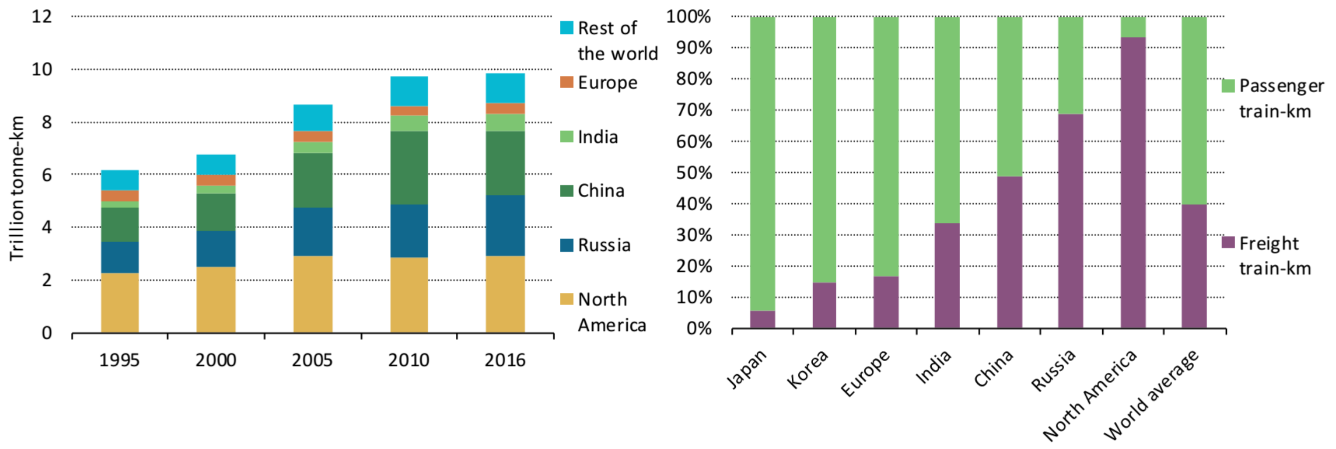
Freight transport activity by rail, measured in tonne-kilometers per year, increased overall at an average pace similar to that of passenger rail over the past two decades. Activity growth from 1995-2005 was very rapid, but slowed between 2005 and 2010, and remained almost constant between 2010 and 2015. Freight rail activity has risen steadily over the last twenty years. High freight rail transport activity is normally related to the existence of large landlocked resources that can be effectively exploited if traded over long distances. This pattern is seen in both on a domestic basis and as export-oriented industrial clusters that require the transport of significant quantities of goods or large volumes of commodities. The ratio of freight rail activity relative to passenger rail activity varies significantly from country to country (IEA 2019). This report will only use the global estimates in Scenario A (Section 18), B (Section 23) and C (Section 20).



Note: In the figure on the left, freight volumes in Japan and Korea are too small to be visible so their freight activity is included in the rest of the world category. The most significant countries in the rest of the world are Australia, Brazil and South Africa.

Sources: IEA assessment, based on UIC (2018a); National Bureau of Statistics of China (2018); Eurostat (2018); Indian Railways (2018a); (Japan Ministry of Land, Infrastructure and Tourism (2018); AAR (2017) and Russian Federation State Statistics Service (2018).

Figure 13.4. Freight rail activity in selected countries, 1995-2016 (LHS) and share of passenger and freight trains in total train-kilometers, 2016 (RHS), (Source: IEA 2019)
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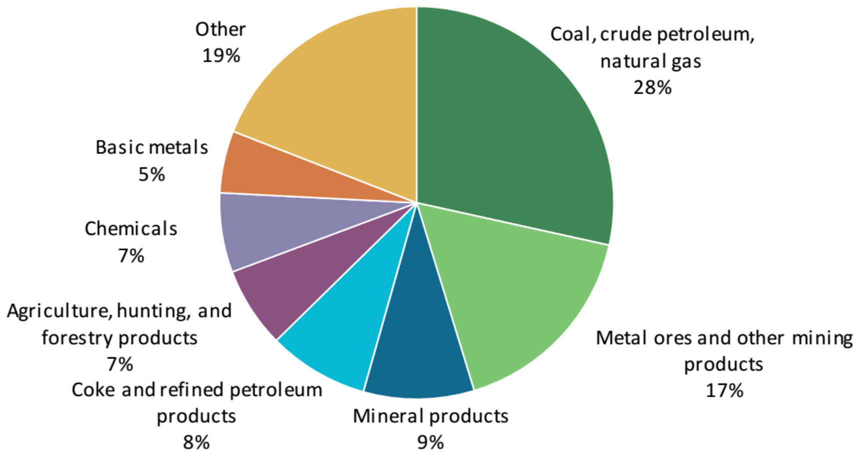
Coal and mineral products have been, to date, the most common type of freight transported by rail around the world. The lower reliance on freight rail in Europe, Japan and Korea reflects industrial structures which rely to a lesser extent on the primary sector and the shorter distances between the main industrial clusters and major ports (IEA 2019).



Note: Materials measured in tonnes.

Sources: (AAR, 2017), National Bureau of Statistics China (2017); Indian Railways (2018a); Statistics Canada (2016); Globaltrans (2017); UIC (2018); SAFF/SIADE (2017); Ukrstat (2018); Transnet (2016); Agencia Reguladora del Transporte Ferroviario (2016).

Figure 13.5. Shares of materials transported by freight railways worldwide, 2016 (Source: IEA 2019)
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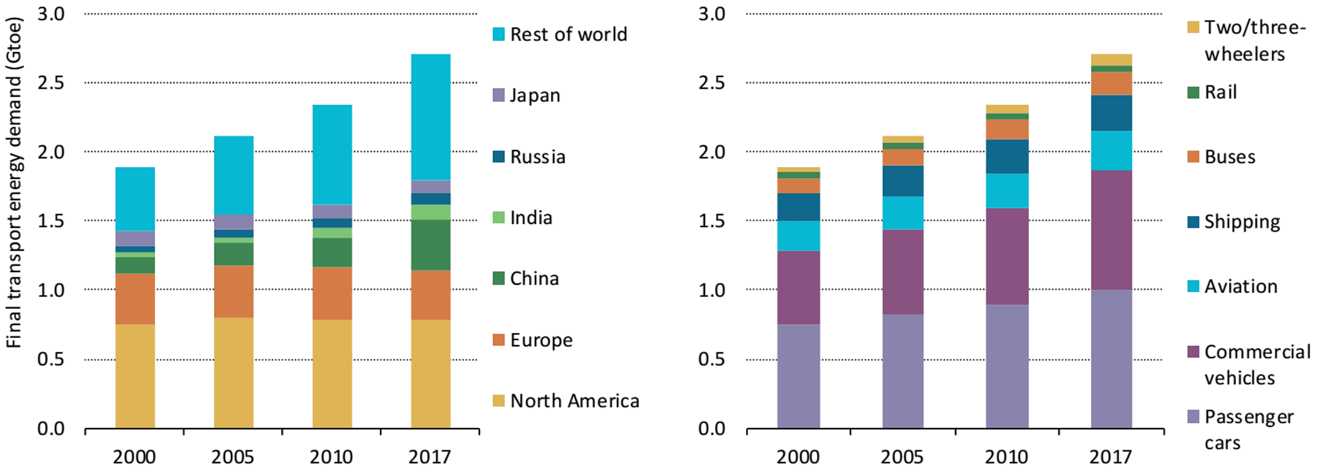
Table 13.1 Number of diesel freight locomotives (see Appendix K)

Rank	Country	Number of Diesel Locomotives	Date of Assessment (average 2016)	Reference
	Global Estimate	**104 894**		
1	Europe EU-28	22 100	2014	Railway Statistics 2014 Report by the International Union of Railways
2	China	21 000	2018	Statistica.com https://www.statista.com/statistics/276290/china-railways-train-fleet-by-type-of-carriage/
3	United States	20 366	2015	Statistica.com https://www.statista.com/statistics/495660/locomotive-and-transit-railcars-in-selected-countries-worldwide/
4	Russia	18 250	2015	Railway Statistics 2014 Report by the International Union of Railways
5	India	6086	2018	Statistica (2020): Number of locomotives in the railway fleet across India in financial year 2018, by type, https://www.statista.com/statistics/1029182/india-rolling-stock-number-by-type/#:~:text=The%20Indian%20Railways%20had%20a,sectors%20worldwide%20under%20single%20management.
6	Brazil	4 955	2016	SCI (2017): Diesel locomotives – Global market trends, Forecast, Fleet, Suppliers, and Procurement Projects, https://www.sci.de/fileadmin/user_upload/MC_Studien_Flyer/Flyer_Diesel_Locomotives.pdf
7	Ukraine	4 371	2020	Railway Statistics 2014 Report by the International Union of Railways
8	Canada	2 400	2015	Statistica.com https://www.statista.com/statistics/495660/locomotive-and-transit-railcars-in-selected-countries-worldwide/
9	Australia	1 850	2013	ENVIRON (2013): Locomotive Emissions Project Scoping Study of Potential Measures to Reduce Emissions from New and In-Service Locomotives in NSW and Australia, Prepared by NSW EPA, ENVIRON Australia Pty Ltd, https://www.epa.nsw.gov.au/~/media/EPA/Corporate%20Site/resources/air/locoemissrep.ashx
10	Kazakhstan	1 300	2019	Gadimova, N. (2019): Kazakhstan Modernizes Its Railway Fleet Thanks To French Locomotives, Caspian News, https://caspiannews.com/news-detail/kazakhstan-modernizes-its-railway-fleet-thanks-to-french-locomotives-2019-5-29-49/
11	South Africa	988	2014	Barrow, K., (2014 March): Transnet South Africa orders 1064 locomotives, International Rail Journal, https://www.railjournal.com/locomotives/transnet-south-africa-orders-1064-locomotives/
12	Belarus	825	2014	Railway Statistics 2014 Report by the International Union of Railways
13	United Kingdom	244	2015	Railway Statistics 2014 Report by the International Union of Railways
14	Argentina	81	2016	SCI (2017): Diesel locomotives – Global market trends, Forecast, Fleet, Suppliers, and Procurement Projects, https://www.sci.de/fileadmin/user_upload/MC_Studien_Flyer/Flyer_Diesel_Locomotives.pdf
15	Colombia	78	2016	SCI (2017): Diesel locomotives – Global market trends, Forecast, Fleet, Suppliers, and Procurement Projects, https://www.sci.de/fileadmin/user_upload/MC_Studien_Flyer/Flyer_Diesel_Locomotives.pdf

On a global basis, the transport and industry sector each account for 29% of final energy use, the residential sector for 22% with the remainder used in commercial and public services, agriculture and others (IEA 2019). Within transport demand, the European Union and North America are the source of the world's highest energy requirements, but emerging economies, such as China, India, South Africa and Brazil are developing quickly (Figure 13.6). Railways today consume close to 2% of transport final energy use, a modest share relative to road, maritime and air transport, especially since rail constitutes a much higher share of transport activity (8% of total passenger-kilometers and 7% of total tonne-kilometers) (IEA 2019).

The key reason for the gap discrepancy between its share of rail activity and rail energy use is rail's much better energy efficiency, compared with road transport and aviation (Figure 13.7). When expressed as final energy use per passenger-kilometer or tonne-kilometer, the energy intensity of rail generally significantly outperforms other transport modes given its unique characteristics.



Note: Gtoe = gigatonnes of oil equivalent.

Sources: IEA Mobility Model (IEA, 2018a), using assessments based on UIC (2018a); UITP (2018d); ITDP (2018); National Bureau of Statistics of China (2018); Eurostat (2018); Indian Railways (2018a); Japan Ministry of Land, Infrastructure and Tourism (2018); AAR (2017) and Russian Federation State Statistics Service (2018).

Figure 13.6. Final energy use in transport by region and mode, 2000-17 (Source: IEA 2019)
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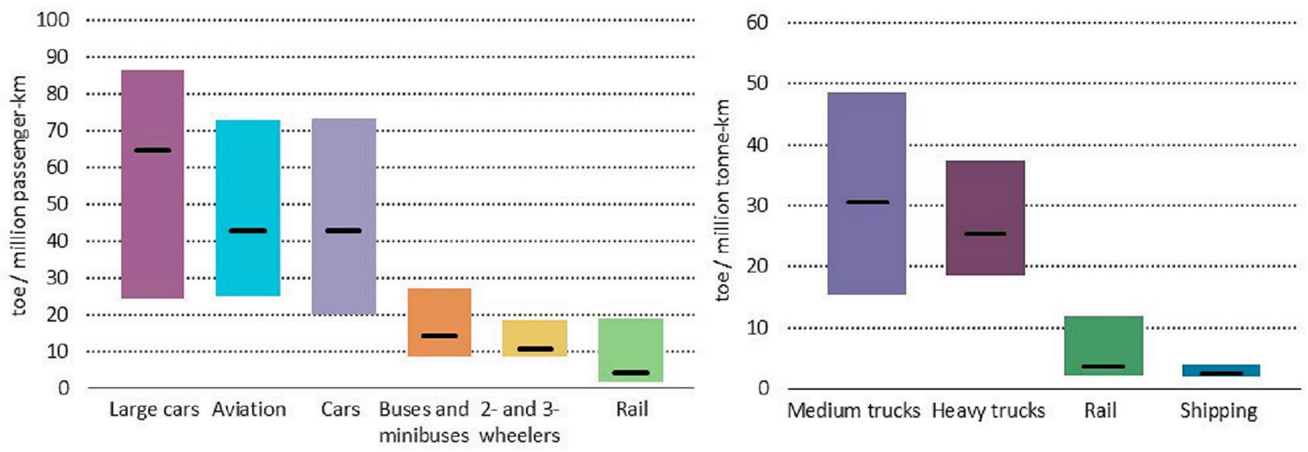

Notes: toe = tonne oil equivalent. The boxes in this figure indicate the range of average energy intensity in various countries, while the horizontal lines represent the world averages.

Sources: IEA Mobility Model (IEA, 2018a), using assessments based on UIC (2018a); UITP (2018d); ITDP (2018a); National Bureau of Statistics of China (2018); Eurostat (2018); Indian Railways (2018a); Japan Ministry of Land, Infrastructure and Tourism (2018); AAR (2017) and Russian Federation State Statistics Service (2018).

Figure 13.7. Energy intensity of different transport modes, 2017, (Source: IEA 2019)
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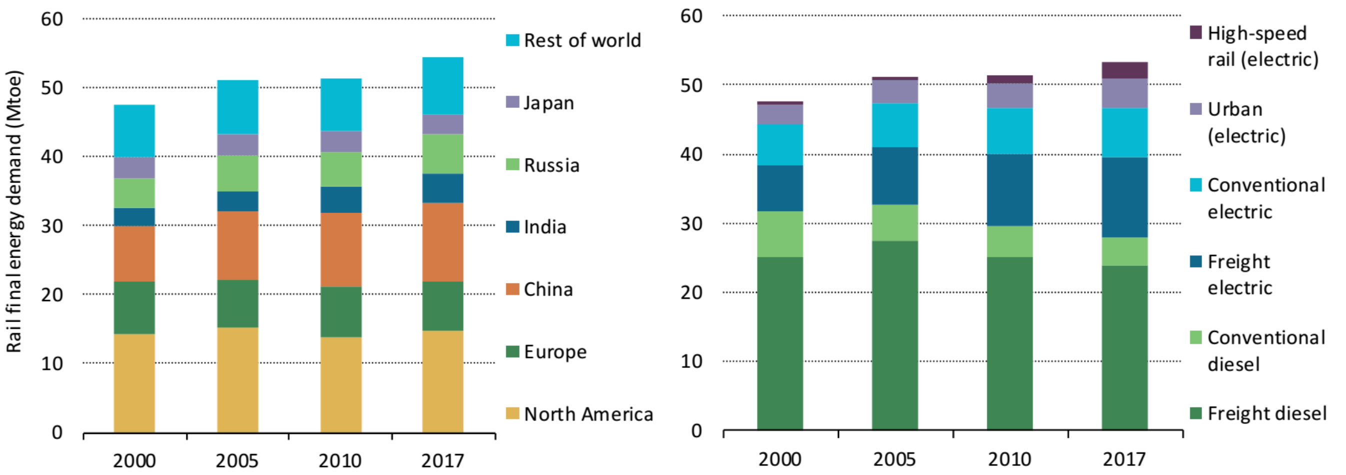

Note: Mtoe = million tonnes of oil equivalent.

Sources: IEA assessment based on UIC (2018a); UITP (2018d); National Bureau of Statistics of China (2018); Eurostat (2018); Indian Railways (2018a); Japan Ministry of Land, Infrastructure and Tourism (2018); AAR (2017) and Russian Federation State Statistics Service (2018).

Figure 13.8. Final energy demand in rail transport by region and type, 2000-17, (Source: IEA 2019)
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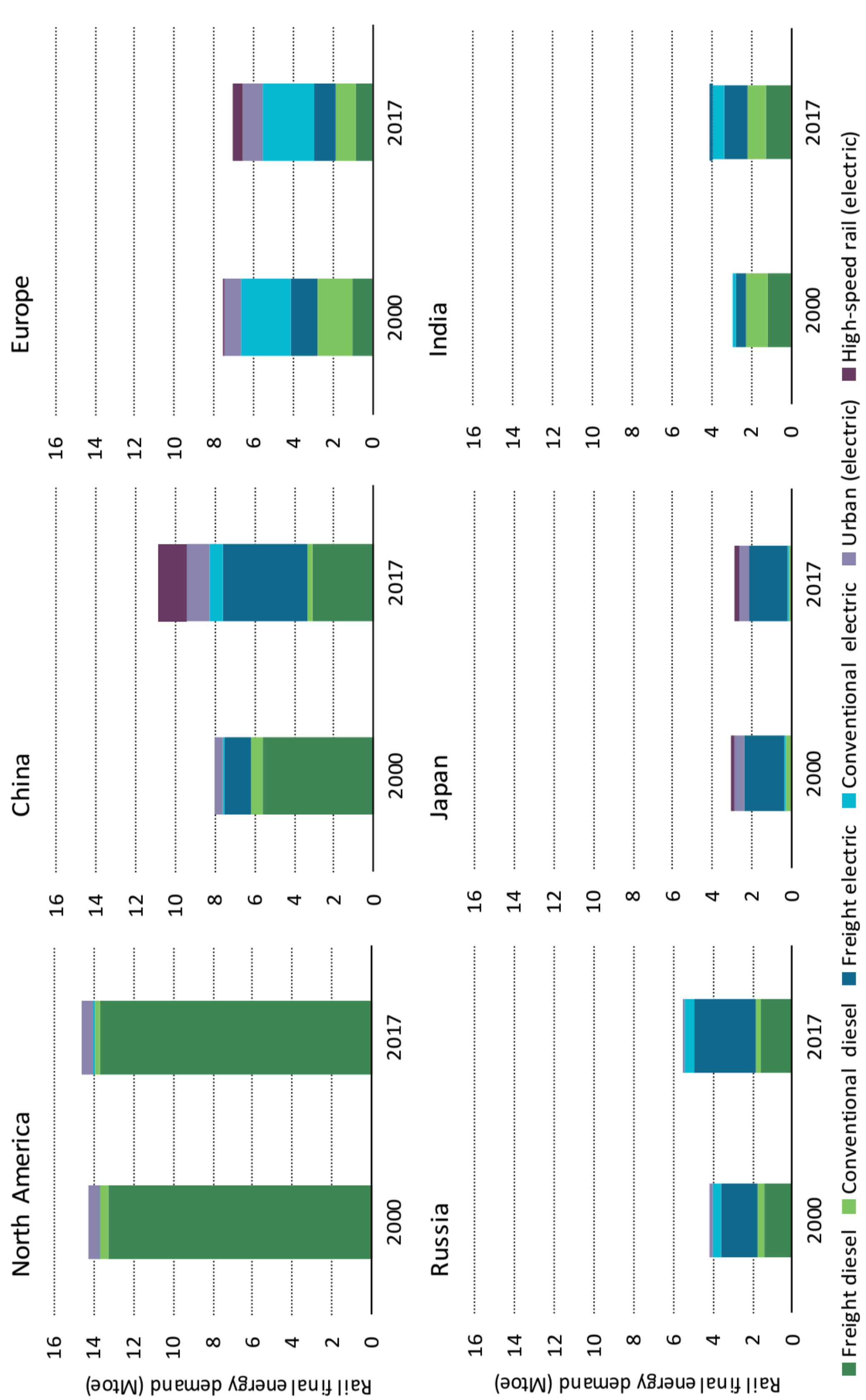
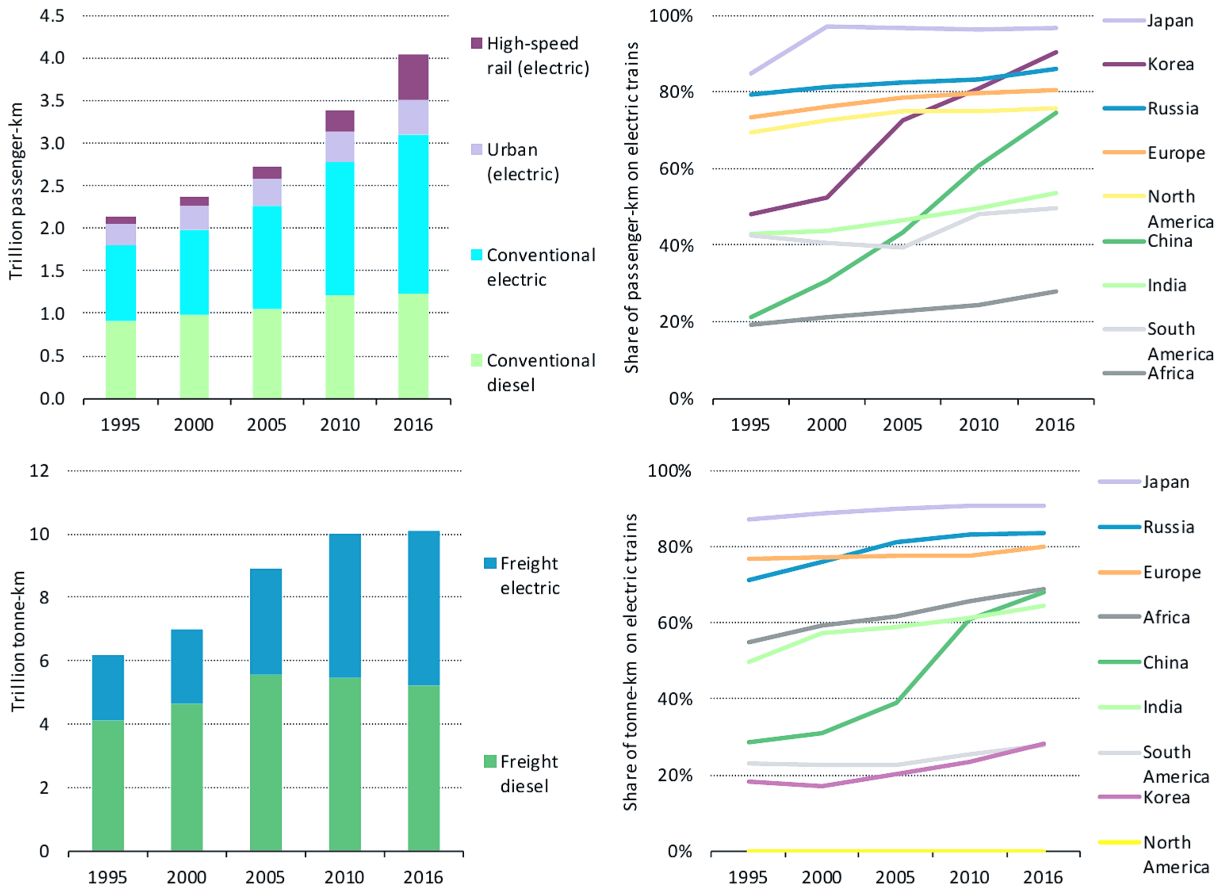


Notes: Mtoe = million tonnes of oil equivalent. The data shown are the result of a bottom-up analysis of data provided by the cited sources, calibrated using data from the top-down analysis of the IEA World Energy Balances database (IEA, 2018b). Small divergences may arise between the latter and the data used for the figure due to different modelling methodologies.

Sources: IEA Mobility Model (IEA, 2018a) using assessments based on UIC (2018a); UITP (2018b); National Bureau of Statistics of China (2018); Eurostat (2018); Indian Railways (2018a); Japan Ministry of Land, Infrastructure and Tourism (2018); AAR (2017) and Russian Federation State Statistics Service (2018).

Figure 13.9. Final energy demand in rail transport by region and type, 2000 and 2017, (Source: IEA 2019) (Copyright License: https://www.iea.org/media/copyright/Termsandconditions_2019update_FINAL.docx.pdf)

Currently, electricity accounts for 47% of rail energy use, amounting to 290 terawatt-hours (TWh) (or 25 million tonnes of oil equivalent [Mtoe]), while diesel accounts for 53%, roughly equivalent to 29 Mtoe, or 0.6 mb/d (Figure 13.8, RHS). About 55% of electricity use in rail transport is for passenger services, and most of the diesel (85%) is for freight services. Countries with the highest shares of electricity use for rail transport tend to be those with the most passenger rail activity. For example, in the European Union, Japan and Korea, passenger trains account for well over 80% of train-kilometers and use electricity, whereas in the United States, passenger trains account for only 7% of train-kilometers and of which only 1% are fuelled by electricity (IEA 2019), as shown in Figures 13.9 and 13.10.



Sources: IEA Mobility Model (IEA, 2018a) using assessments based on UIC (2018a); National Bureau of Statistics of China (2018); Eurostat (2018); Indian Railways (2018); Japan Ministry of Land, Infrastructure and Tourism (2018); AAR (2017) and Russian Federation State Statistics Service (2018).

Figure 13.10. Passenger and freight rail transport activity by fuel type (left) and share of activity on electric trains (right), 1995-2016, (Source: IEA 2019)
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Major factors influencing the energy intensity of rail transport (expressed in terms of energy per passenger-kilometer or per tonne-kilometer) include:

- Changes in the specific energy consumption of trains (energy/train-kilometer).

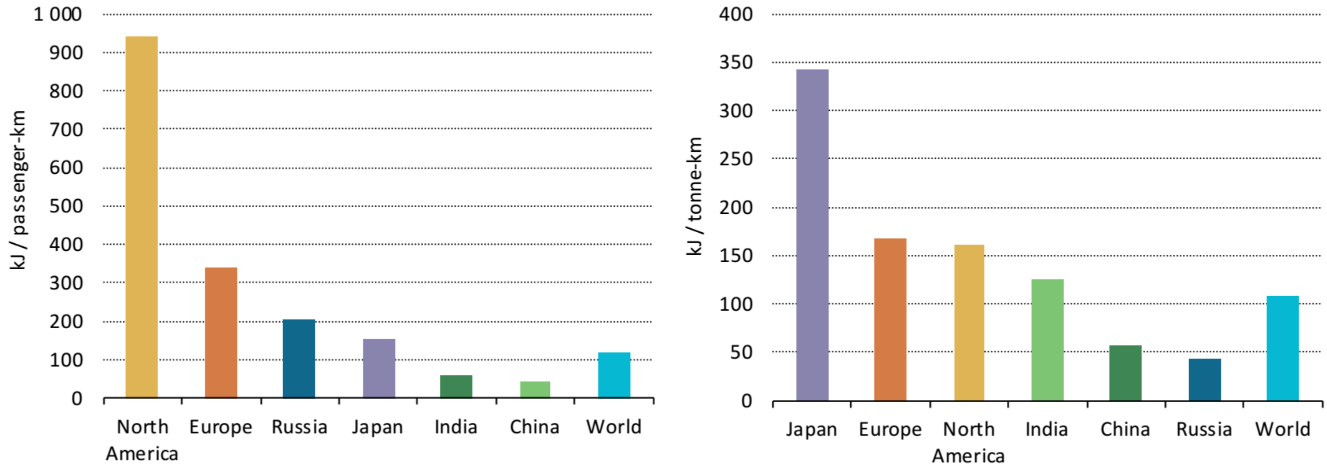
- Variations in train capacities and their utilization rates (leading to different rates of passenger-kilometer per train-kilometer, or tonne-kilometer per train-kilometer).

The specific energy consumption of trains depends largely on powertrain types and train size. More energy is needed to move larger volumes of people and goods, especially at low speed and in the absence of regenerative braking.

Electric trains are generally less energy intensive than diesel trains because electric motors have much higher thermodynamic efficiencies (EV efficiency 73%, see Section 11.9) than internal combustion engines. Electric motors are also much better placed to enable regenerative braking, minimizing inertial losses (especially relevant in the case of frequent stops). As a result, countries with large shares of trains running on electricity tend to have lower energy demand per train-kilometer for similar sized trains.

The combined effect on the energy intensity of rail services of changes in specific energy consumption, capacities and utilization rates on the energy intensity of rail services is summarized in Figure #. Trains in the United States consume three-times more energy per passenger-kilometer than those in Europe because of their low occupancy and the low rate of electrification.

Energy use for rail freight also shows a strong dependency on how the train is loaded. Russia is the most energy-efficient freight rail system, due to a high share of electric traction and high loads. The United States has the highest freight loading, giving it the best energy efficiency per tonne-kilometers of trains using diesel (essentially the only fuel used for freight rail in the United States). Emerging economies of China, Brazil, India and South Africa have comparable characteristics of specific energy use and train loads. The European Union and Japan are less energy efficient per tonne-kilometer, due to significantly smaller loads.



Sources: IEA Mobility Model (IEA, 2018a) using assessments based on UIC (2018a); National Bureau of Statistics of China (2018); Eurostat (2018); Indian Railways (2018a); Japan Ministry of Land, Infrastructure and Tourism (2018); AAR (2017) and Russian Federation State Statistics Service (2018).

Figure 13.11. Energy intensities of passenger (LHS) and freight (RHS) rail, 2016, (Source: IEA 2019) (Copyright License: https://www.iea.org/media/copyright/Termsandconditions_2019update_FINAL.docx.pdf)

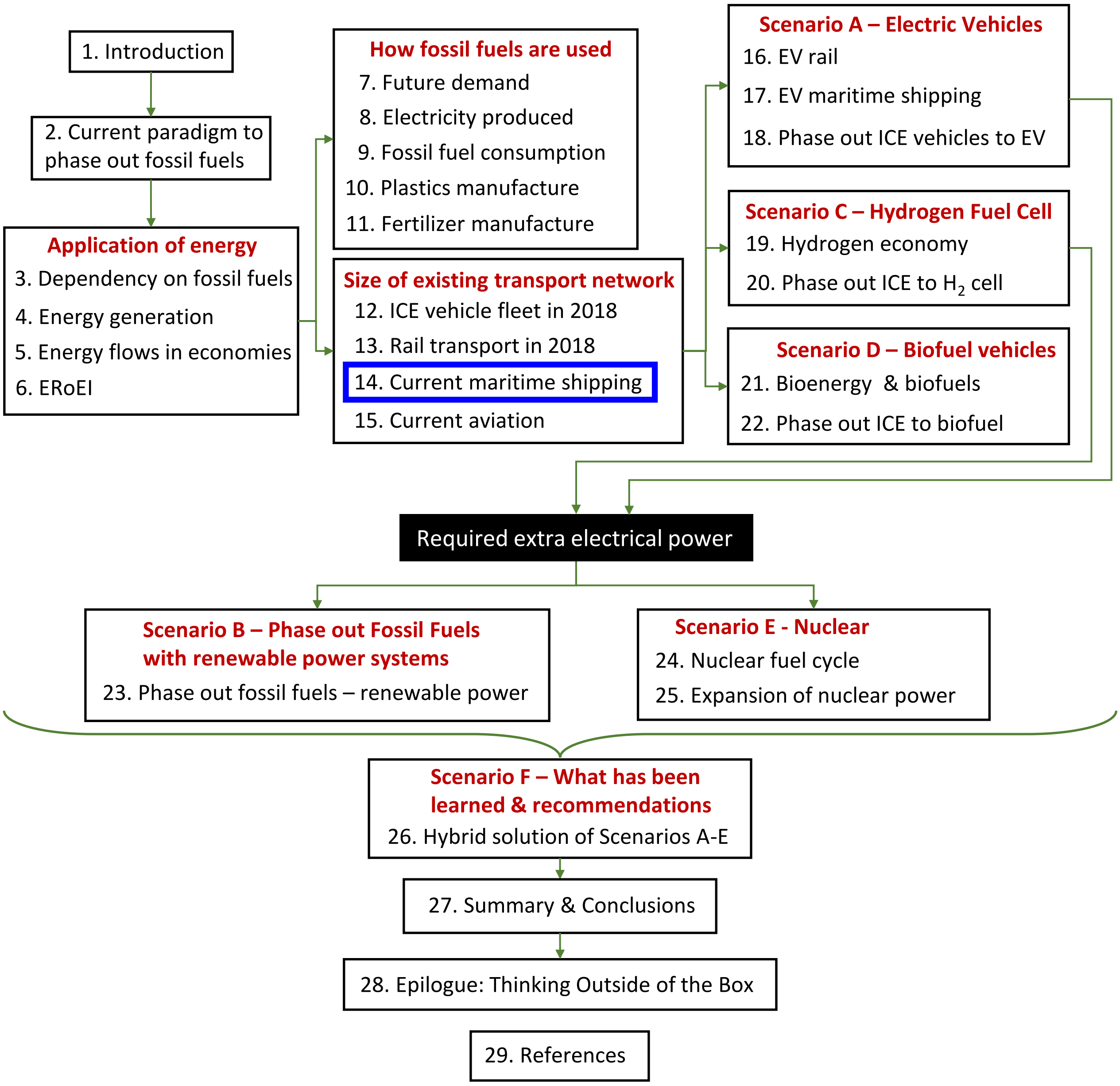
13.1 Summary of Rail Transport Statistics in 2018

- The energy intensity for passenger rail transport as an estimated global average is 112 kJ/passenger-km (IEA 2019).
- The energy intensity for passenger rail transport in Europe is 340 kJ/passenger-km (IEA 2019).
- Global number of million passengers carried per year was 32 355 in 2018
- Global number of passenger-kilometers was 3 823 billion passenger-kilometers in 2018

- The energy intensity for freight as an estimated global average is 108kJ/tonne-km (IEA 2019).
- The energy intensity for freight in Europe is 166kJ/tonne-km (IEA 2019).
- Global tonne-kilometers of rail freight transport per year was 11 067 billion tkm in 2018
- Global tonnes carried in rail freight transport per year was 12 545 tonnes in 2018

14 SIZE AND SCOPE OF CURRENT MARITIME SHIPPING TRANSPORT OF FREIGHT

The maritime transport shipping fleet delivers a vital service to the global industrial ecosystem. The movement of goods and commodities internationally cannot happen in the needed quantities without shipping. The purpose of Section 14 is to quantify the size and scope of the maritime shipping fleet. Later in Section 16, this information will be used to develop what a EV propulsion system that is alternative to fossil fuel ICE.



Assessment of the Extra Capacity Required of Alternative Energy Electrical Power Systems to Completely Replace Fossil Fuels

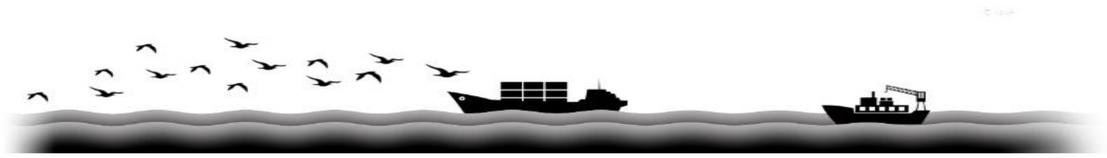
Maritime shipping of cargo is a vital part of the global industrial ecosystem. As raw materials are extracted on one continent (for example Africa, Middle East, South America, South Africa, etc.), then are used for manufacture on another continent (for example China in Asia), then used and consumed on yet other continents (for example Europe, North America, etc.). These material flows are so large, that they can only be transported in bulk volumes by large maritime shipping.

Figure 14.1. A large container ship vessel
(Image by minka2507 from Pixabay)

Figure 14.2. Commodity freight shipping vessel
(Image by LisaMus from Pixabay)

This system of material flows, where demand and supply are global in nature. It is not useful to consider individual country fleets in the context of this report. So just a global calculation will be done.

A more detailed statistics and data presentation for maritime shipping transport fleet in Appendix N – Maritime Shipping Statistics & Data.



14.1 Maritime terms definitions

- **Gross tonnage** (GT, G.T. or gt) is a nonlinear measure of a ship's overall internal volume. Gross tonnage is different from gross register tonnage. Neither gross tonnage nor gross register tonnage should be confused with measures of mass or weight such as deadweight tonnage or displacement. Gross tonnage (GT) is a function of the volume of all of a ship's enclosed spaces (from keel to funnel) measured to the outside of the hull framing. The numerical value for a ship's GT is always smaller than the numerical values of gross register tonnage (GRT).

- A **nautical mile** is a unit of measurement used in air, marine, and space navigation, and for the definition of territorial waters. Historically, it was defined as one minute (160 of a degree) of latitude along any line of longitude.

- In maritime tonnage, **deadweight tonnage** is a measurement of total contents of a ship including cargo, fuel, crew, passengers, food, and water aside from boiler water. It is expressed in long tons of 2,240 lbs (1 016.04 kg).

- Shipping containers come in different sizes, but most are the standard **twenty-foot equivalent units** (**TEU**)—rectangular prisms 6.1 meters (20 feet) long and 2.4 meters wide. The first small container ships of the 1960s carried mere hundreds of TEUs; now Maersk’s Triple-E class ships load 18,000 TEUs, and OOCL Hong Kong holds the record, at 21,413 TEU’s.

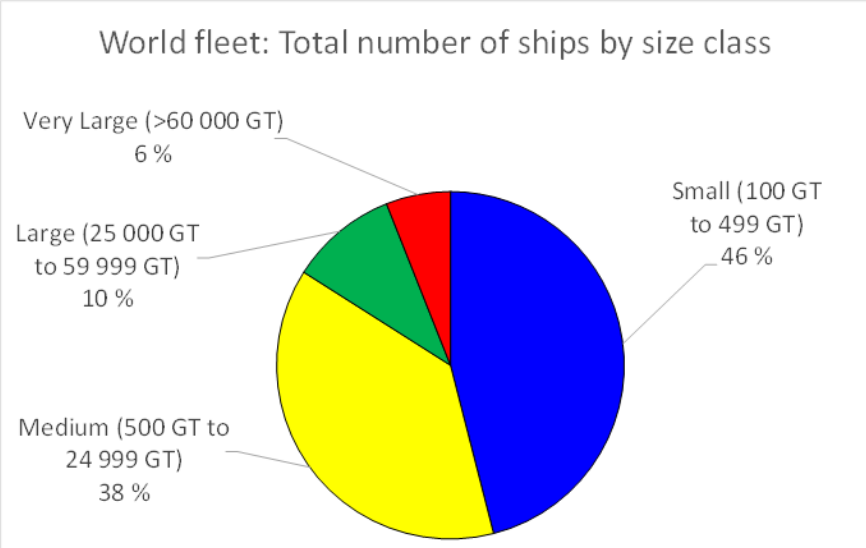
- **Tonne-mile** is defined as the distance covered by a quantity of cargo. For example, 1,000 tonnes carried 500 miles equals 500,000 tonne miles. A measure of demand for capacity. Calculated as the amount of freight times the transport in nautical miles.

- **Tonne-km** is defined as the distance covered by a quantity of cargo. For example, 1,000 tonnes carried 500 kilometers equals 500,000 tonne km. A measure of demand for capacity. Calculated as the amount of freight times the transport in nautical miles.

Table 14.1. shows the number and size of vessels in global maritime fleet

Table 14.1. World Fleet: total number of ships by type and size
(Source: The World Merchant Fleet in 2018 Statistics from Equasis) (World Map Image by Clker-Free-Vector-Images from Pixabay)

Ship Type	Small		Medium		Large		Very Large		Total	
	(number)	(%)	(number)	(%)	(number)	(%)	(number)	(%)	(number)	(%)
General Cargo Ships	4,346	8.1 %	11,659	26.1 %	245	2.0 %			**16,250**	13.9 %
Specialized Cargo Ships	8	0.0 %	227	0.5 %	61	0.5 %	5	0.1 %	**301**	0.3 %
Container Ships	19	0.0 %	2,213	5.0 %	1,538	12.8 %	1,441	22.8 %	**5,211**	4.5 %
Ro-Ro Cargo Ships	30	0.1 %	629	1.4 %	565	4.7 %	247	3.9 %	**1,471**	1.3 %
Bulk Carriers	316	0.6 %	3,788	8.5 %	6,119	51.1 %	1,706	27.0 %	**11,929**	10.2 %
Oil and Chemcial Tankers	1,931	3.6 %	7,241	16.2 %	2,642	22.0 %	1,943	30.8 %	**13,757**	11.8 %
Gas Tankers	36	0.1 %	1,116	2.5 %	362	3.0 %	481	7.6 %	**1,995**	1.7 %
Other Tankers	396	0.7 %	698	1.6 %	12	0.1 %			**1,106**	0.9 %
Passenger Ships	4,094	7.6 %	2,793	6.2 %	277	2.4 %	184	2.9 %	**7,348**	6.3 %
Offshore Vessels	2,727	5.1 %	5,297	11.9 %	149	1.2 %	294	4.8 %	**8,467**	7.2 %
Service Ships	2,744	5.1 %	2,750	6.1 %	27	0.2 %	6	0.1 %	**5,527**	4.7 %
Tugs	17,848	33.1 %	1,041	2.3 %					**18,889**	16.2 %
Fishing Vessels	19,359	35.9 %	5,244	11.7 %	3	0.0 %			**24,606**	21.1 %
Total	**53,854**	100.0 %	**44,696**	100.0 %	**12,000**	100.0 %	**6,307**	100.0 %	**116,857**	100.0 %



Ships are grouped by size into four categories:
(Source: The World Merchant Fleet in 2018 Statistics from Equasis)

- Small Ships 100 GT to 499 GT
- Medium ships 500 GT to 24 999 GT
- Large ships 25 000 GT to 59 999 GT
- Very large ships greater than 60 000 GT

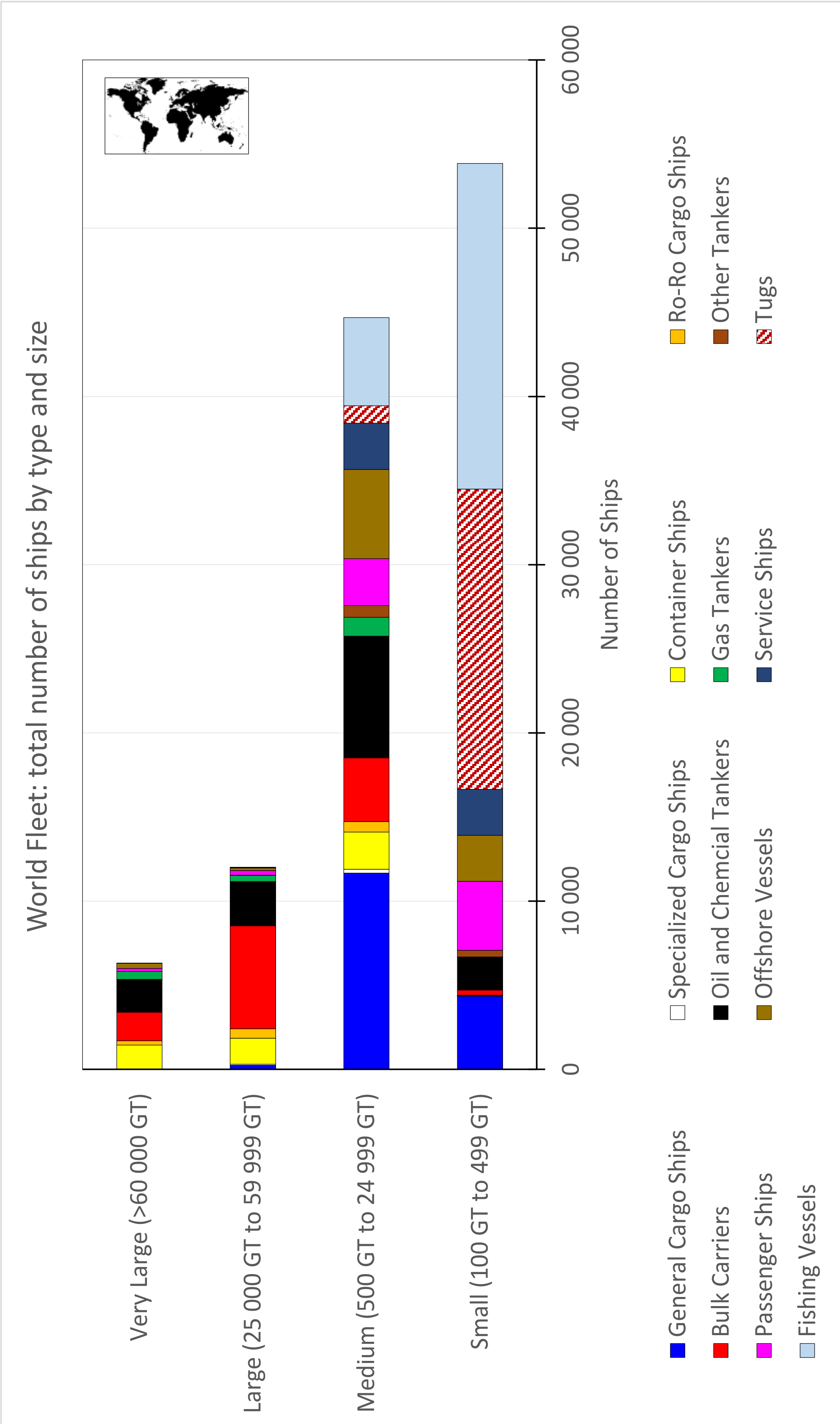
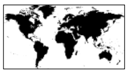


Figure 14.3. World Fleet: total number of ships by type and size
(Source: The World Merchant Fleet in 2018 Statistics from Equasis)
(World Map Image by Clker-Free-Vector-Images from Pixabay)

Table 14.2. Deadweight tonnes by commodity in 2018 (World Map Image by Clker-Free-Vector-Images from Pixabay) (Source: UNCTAD 2019 Review of maritime transport 2019, United Nations Conference on Trade and Development)

Ship Type 	**Dead-Weight Tons (1000's tonnes)**	**Dead-Weight Tons (%)**
General Cargo Ships	73,951	3.84%
Container Ships	253,275	13.15%
Bulk Carriers	818,921	42.52%
Oil and Chemcial Tankers	606,492	31.49%
Gas Tankers	64,407	3.34%
Passenger Ships	6,922	0.36%
Offshore Vessels	78,269	4.06%
Other	23,946	1.24%
Total	1,926,183	100.0 %

14.1.1 Shipping route distance and estimated time at sea

To calculate the fuel consumption for the maritime shipping fleet, it was necessary to document several examples of shipping routes and their distances. The four basic classifications of speed were (Source: Fuel Consumption by Containership Size and Speed https://transportgeography.org/?page_id=5955):

1. **Normal** (20-25 knots; 37.0 – 46.3 km/hr). Represents the optimal cruising speed a containership and its engine have been designed to travel at. It also reflects the hydrodynamic limits of the hull to perform within acceptable fuel consumption levels. Most containerships are designed to travel at speeds around 24 knots.

2. **Slow steaming** (18-20 knots; 33.3 – 37.0 km/hr). Running ship engines below capacity to save fuel consumption but at the expense an additional travel time, particularly over long distances (compounding effect). This is likely to become the dominant operational speed as more than 50% of the global container shipping capacity was operating under such conditions as of 2011.

3. **Extra slow steaming** (15-18 knots; 27.8 – 33.3 km/hr). Also known as super slow steaming or economical speed. A substantial decline in speed for the purpose of achieving a minimal level of fuel consumption while still maintaining a commercial service. It can be applied on specific short-distance routes.

4. **Minimal cost** (12-15 knots; 22.2 – 27.8 km/hr). The lowest speed technically possible, since lower speeds do not lead to any significant additional fuel economy. The level of service is however commercially unacceptable, so it is unlikely that maritime shipping companies would adopt such speeds.

Figure 14.4 shows the results of a study to estimate fuel consumption (in tonnes of diesel fuel oil, or bunker oil) for the different ship sizes at different speeds. The speed of ship selected in Table 14.3 below was based on the most cost effective and economical speed that large ships use in current industrial practice.

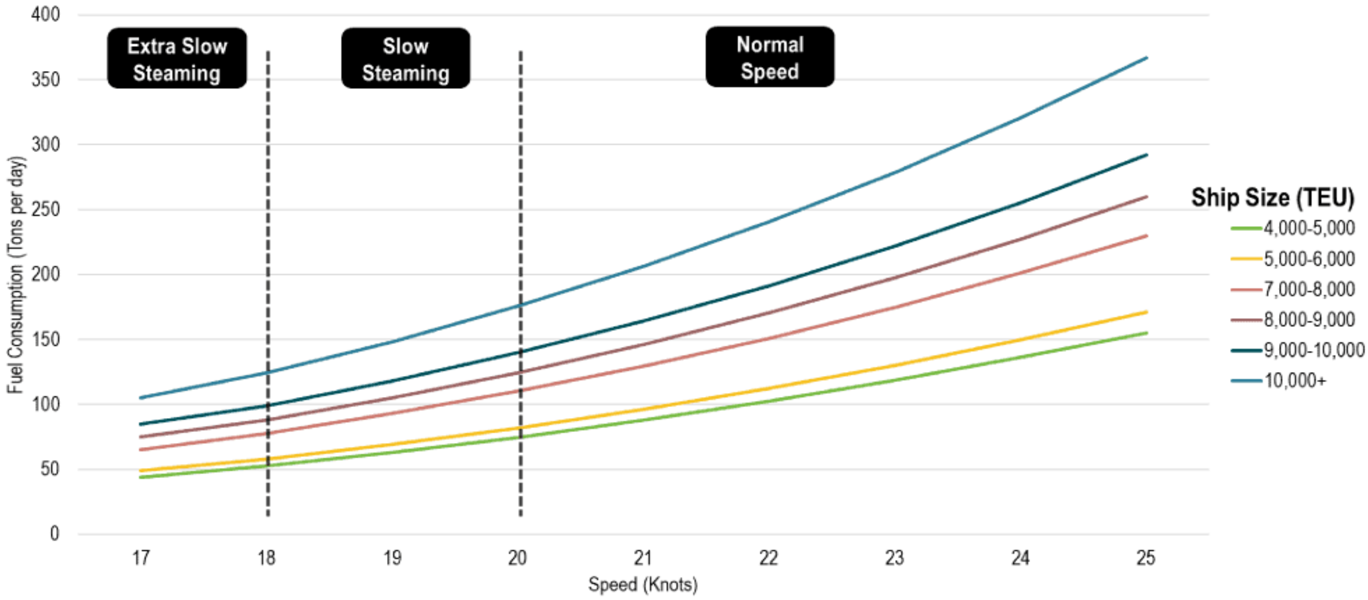


Figure 14.4. Fuel Consumption by Containership Size and Speed
(Source: adapted from Notteboom & Carriou 2009)

Table 14.3 shows the distance of several examples of shipping routes, and days at sea at the selected speed of 20 knots.

Table 14.3. Shipping route distance and estimated time at sea
(Source: Ports.com, Shipping Trade Route Calculator)
(http://ports.com/sea-route/port-of-shanghai,china/port-of-hamburg,germany/)

Origin	Destination	Distance in Nautical Miles (nm)	Distance in kilometers (km)	Estimated time at sea (days)	Speed of Ship (knots)
Port of Shanghai (China)	Port of Hamburg (Germany)	12 277	22 737	25,6	20
Port of Hamburg (Germany)	Port of Melbourne (Australia)	13 372	24 765	27,8	20
Port of Hamburg (Germany)	Port of Osaka (Japan)	12 999	24 074	27,1	20
Port of Hamburg (Germany)	Port Hong Kong	11 416	21 142	23,8	20
Port of Amsterdam (Netherlands)	Port Los Angelas (United States)	10 279	19 037	21,4	20
Port of Amsterdam (Holland)	Port of Singapore	9 378	17 368	19,6	20
Port of Shanghai (China)	Port Los Angelas (United States)	19 270	35 688	40,1	20
Port of Shanghai (China)	Port of Cape Town (South Africa)	9 250	17 131	19,3	20

Table 14.4 shows a summary of data collected (Appendix N).

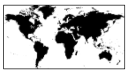
Table 14.4. Number of ships in global maritime fleet by size and their fuel consumption (Appendix N)

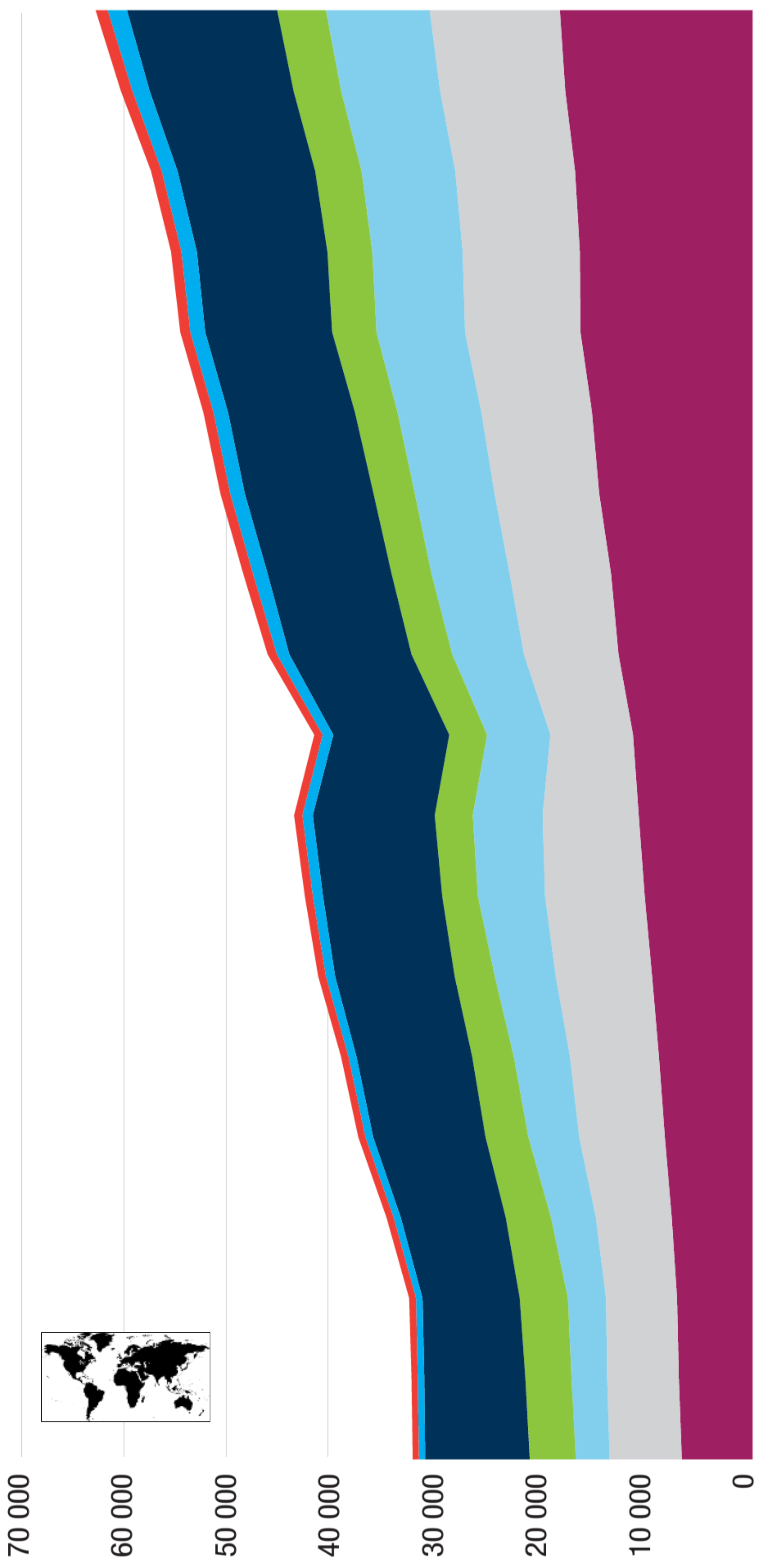
Size Classification 	Number of ships in Global Fleet (Source: The World Merchant Fleet in 2018 Statistics from Equasis)	Ship Size (TEU)	Gross Tonnage (GT)	Fuel Consumption @ 20 knots (tonnes per day)	Source
Small (100 GT to 499 GT)	53 854		300	8,6	IHS Markit 2018
Medium (500 GT to 24 999 GT)	44 696	1000	12 300	27	Maloni et al 2013
Large (25 000 GT to 59 999 GT)	12 000	4000-5000	54 000	75	Transport Geography
Very Large (>60 000 GT)	6 307	10000+	196 000	175	Transport Geography

14.2 World seaborne trade in cargo tonne-miles and tonne-km

The scope of maritime freight shipping transport in 2018 was 60 414 billion tonne miles, or 97 206 billion tonne kilometers (97.2 Trillion tonne kilometers). This is a value calculated by the tonnes of freight moved multiplied by the distance travelled (UNCTAD 2018). Shown in Figure 14.5 and Table 14.5.

Table 14.5. World seaborne trade in cargo tonne-miles -2018 (billions of tonne-miles) (Source: UNCTAD 2018) (World Map Image by Clker-Free-Vector-Images from Pixabay)

Commodity 	World seaborne trade in cargo tonne-miles in 2018 (billions of tonne-miles)	World seaborne trade in cargo tonne-miles in 2018 (billions of tonne-km)	Proportion in 2018 (%)
Chemicals	1,111	1788	1.8 %
Gas	1,766	2,841	2.9 %
Oil	13,809	22,219	22.9 %
Other dry cargo	4,497	7,236	7.4 %
Containers	9,535	15,342	15.8 %
Minor dry bulk	11,967	19,255	19.8 %
Main bulks	17,729	28,526	29.3 %
	60,414	97,206	100.0 %



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Chemicals	580	589	620	632	650	676	713	747	759	783
Gas	576	591	611	662	717	735	833	913	956	958
Oil	9 614	9 303	8 938	9 665	10 348	10 654	10 984	10 981	11 211	10 679
Other dry cargo	4 233	4 245	4 414	4 150	3 920	3 818	3 712	3 257	3 517	3 481
Containers	3 111	3 279	3 512	4 124	4 687	5 158	5 601	6 178	6 431	5 815
Minor dry bulks	6 638	6 573	6 538	6 965	7 876	8 170	8 852	9 160	8 817	7 586
Main Bulks	6 509	6 793	6 937	7 448	8 061	8 626	9 245	9 941	10 476	11 006

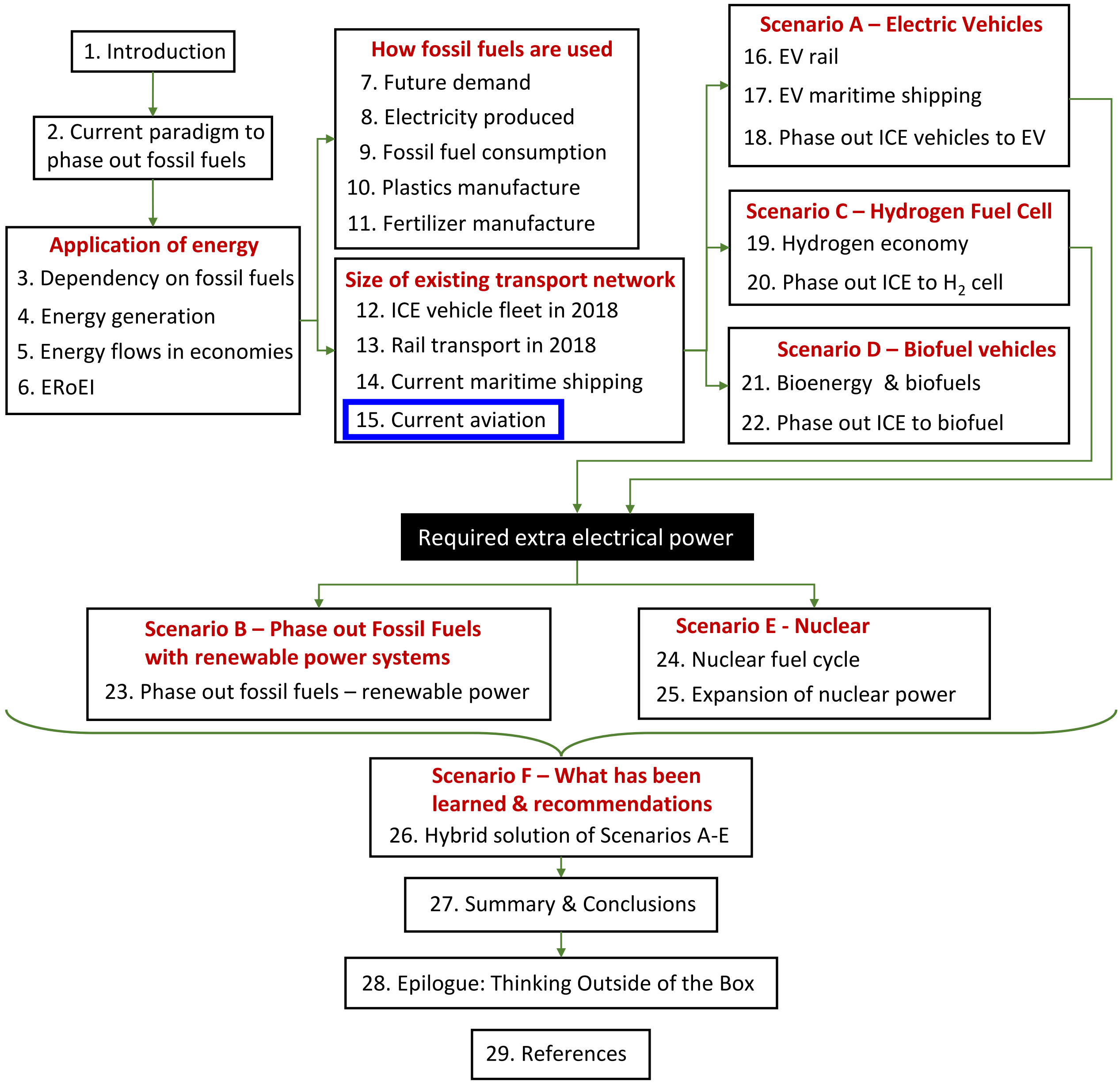
	2010	2011	2012	2013	2014	2015	2016	2017[a]	2018[b]
Chemicals	848	888	903	925	920	961	993	1 058	1 111
Gas	1 148	1 344	1 333	1 337	1 381	1 421	1 462	1 595	1 766
Oil	11 255	11 420	11 831	11 657	11 659	11 993	12 657	13 216	13 809
Other dry cargo	3 723	3 645	3 795	3 923	4 065	4 139	4 242	4 384	4 497
Containers	6 588	7 206	7 352	7 712	8 157	8 290	8 635	9 117	9 535
Minor dry bulks	8 705	9 312	9 624	10 172	10 617	10 775	11 018	11 510	11 967
Main Bulks	12 336	13 019	14 099	14 764	15 828	15 897	16 314	17 217	17 729

Source: UNCTAD secretariat calculations, based on data from Clarksons Research, 2018a.
[a] Estimated.
[b] Forecast.w

Figure 14.5. World seaborne trade in cargo tonne-miles, 2000-2018 (billions of tonne-miles) (Source: UNCTAD 2018) (World Map Image by Clker-Free-Vector-Images from Pixabay) (Copyright License: https://creativecommons.org/licenses/by-nc-sa/4.0/)

15 SIZE AND SCOPE OF CURRENT AVIATION TRANSPORT OF PASSENGERS AND FREIGHT

The aviation industry is a vital part of the international transport network. Jet turbines represent a very sophisticated application of high quality refined petroleum. The purpose of Section 15 is to quantify the size and scope of the global aviation fleet. Appendix O shows a more complete data set for the global commercial aviation industry in 2018.



Assessment of the Extra Capacity Required of Alternative Energy Electrical Power Systems to Completely Replace Fossil Fuels

The majority of the physical work done in the commercial aviation fleet is conducted by turbojet powered aircraft, which consumes jet fuel (see Section 3.3.16). The remaining small portion is conducted by turboprop aircraft, which consume petroleum gasoline. For each 42 gallon barrel of oil extracted, only 4 gallons (9.5%) of jet fuel is refined (EIA –Refining of crude oil). In the year 2018, 2 260 million barrels of jet fuel was consumed (Table 15ER in Section 9, OECD Data Statistics Database), where the jet turbine engine has a power efficiency of 36-48%.

The Airbus A350 and the Boeing 777 are becoming the standard passenger transport aircraft. The A350-900, is a wide-body aircraft manufactured by Airbus. This jetliner accommodates between 300 and 350 passengers in a standard three-class configuration, with maximum seating of 440 passengers (https://www.airbus.com/aircraft/passenger-aircraft/a350xwb-family.html). The A350-900 has an operational range of 15 000 km, maximum take-off weight of 280.00 tonnes, and a maximum fuel capacity of 141 000 liters. The overall aircraft length is 66.80 m, and a wingspan of 64.75 m (Airbus.com). This aircraft is propelled with two Trent XWB jet turbines.

Figure 15.1. LHS - An Airbus A350 (Image by tpicture from Pixabay)
RHS - A Boeing 777 (Image by WikimediaImages from Pixabay)

The main types of planes that carry cargo include Boeing 737, Airbus 340, Airbus 320, and Boing 747. Boeing 737 has an operating range of up to 4,650 km and is fitted with 2 central cargo bays. This plane has a capacity of 2 tonnes and a volume of 13 – 15 m^3. It is considered small aircraft compared to other types. Airbus 340 is another type that is used for air freight in Europe, and it is mainly used to transport bulk and large cargo.

15.1 Size of the aviation fleet

The reported number of aircraft in the commercial aviation fleet in 2018 was 30 379 (ICAO 2018, Reed Business Information RBI), as shown in Table 15.1. Table 15.2 below shows the physical tasks conducted by aircraft in the commercial fleet. Appendix O shows a more complete data set for the global commercial aviation industry in 2018.

Table 15.1. Commercial transport fleet of ICAO Member States at the end of each year

(Source: ICAO 2018, Reed Business Information RBI)

Year	Turbojet		Turboprop		Total Aircraft
	Number	Percentage	Number	Percentage	All Types
2009	20 332	87,4 %	2 932	12,6 %	23 264
2010	20 904	87,5 %	976	12,5 %	21 880
2011	21 543	87,7 %	3 009	12,3 %	24 552
2012	22 255	88,1 %	2 997	11,9 %	25 252
2013	22 893	88,1 %	3 061	11,9 %	25 954
2014	23 587	88,5 %	3 066	11,5 %	26 653
2015	24 259	88,7 %	3 093	11,3 %	27 352
2016	25 060	88,9 %	3 117	11,1 %	28 177
2017	26 100	89,3 %	3 136	10,7 %	29 236
2018	27 183	89,5 %	3 196	10,5 %	30 379

Note: Active and parked aircraft are included;

Note: Aircraft having a maximum take-off mass of less than 9 000kg are not included

Table 15.2. World Scheduled Passenger and Cargo Traffic 2018 (Source: World Air Transport Statistics 2019)
(World Map Image by Clker-Free-Vector-Images from Pixabay)

 Global	International		Domestic		Global System	
	2018	% Change	2018	% Change	2018	% Change
Passengers Carried (thousands)	1,811,324	7.0 %	2,566,346	6.8 %	4,377,670	6.9 %
Freight Tonnes carried (thousands)	42,450	2.9 %	20,037	2.9 %	62,487	2.9 %
Passenger-Kilometeres (millions)	5,332,852	7.2 %	2,996,924	7.6 %	8,329,776	7.4 %
Available Seat-Kilometres (millions)	6,569,395	6.7 %	3,605,433	7.2 %	10,174,828	6.9 %
Passenger Load Factor	81.2 %	0.4 %	83.1 %	0.3 %	81.9 %	0.4 %
Freight and Mail Tonne-Kilometres (millions)	299,328	3.4 %	33,005	3.8 %	332,333	3.4 %
Available Freight Tonne-Kilometres (millions)	416,834	4.8 %	115,166	6.7 %	532,000	5.2 %
Freight Load Factor	55.0 %	-0.8 %	28.7 %	-0.8 %	49.3 %	-0.8 %
Revenue Tonne-Kilometres (millions)	738,132	5.9 %	305,970	7.0 %	1,044,102	6.2 %
Avialable Tonne-Kilometres (millions)	1,046,283	5.8 %	447,262	6.8 %	1,493,545	6.1 %
Weight Load Factor	70.5 %	0.1 %	68.4 %	0.1 %	69.9 %	0.1 %

The scope of transport by air was determined by accessing World Bank data. Figure 15.2 show the global number of passengers carried between 1970 and 2017. Figure 15.3 shows the freight carried in tonnes kilometers. In summary (Source: World Bank Group [US] 2019):

- 3 979 billion passengers carried globally in 2017
- 213 590.2 million tonne-km of freight was carried by air in 2017

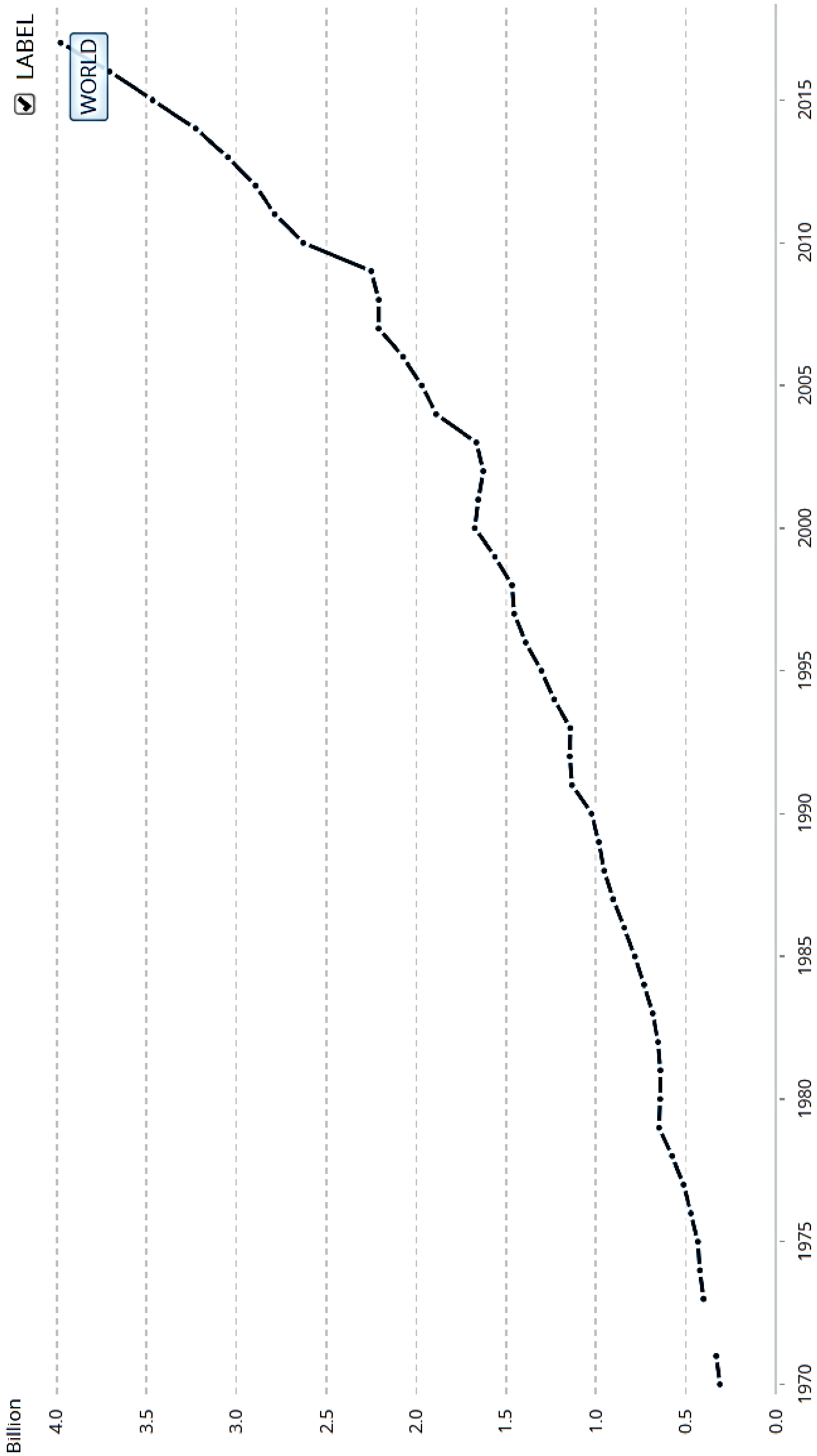


Figure 15.2. Air transport, passengers carried 1970 to 2017
(Source: World Bank Group [US], https://data.worldbank.org/indicator/IS.AIR.PSGR)
(Copyright License: https://www.worldbank.org/en/about/legal/terms-and-conditions)

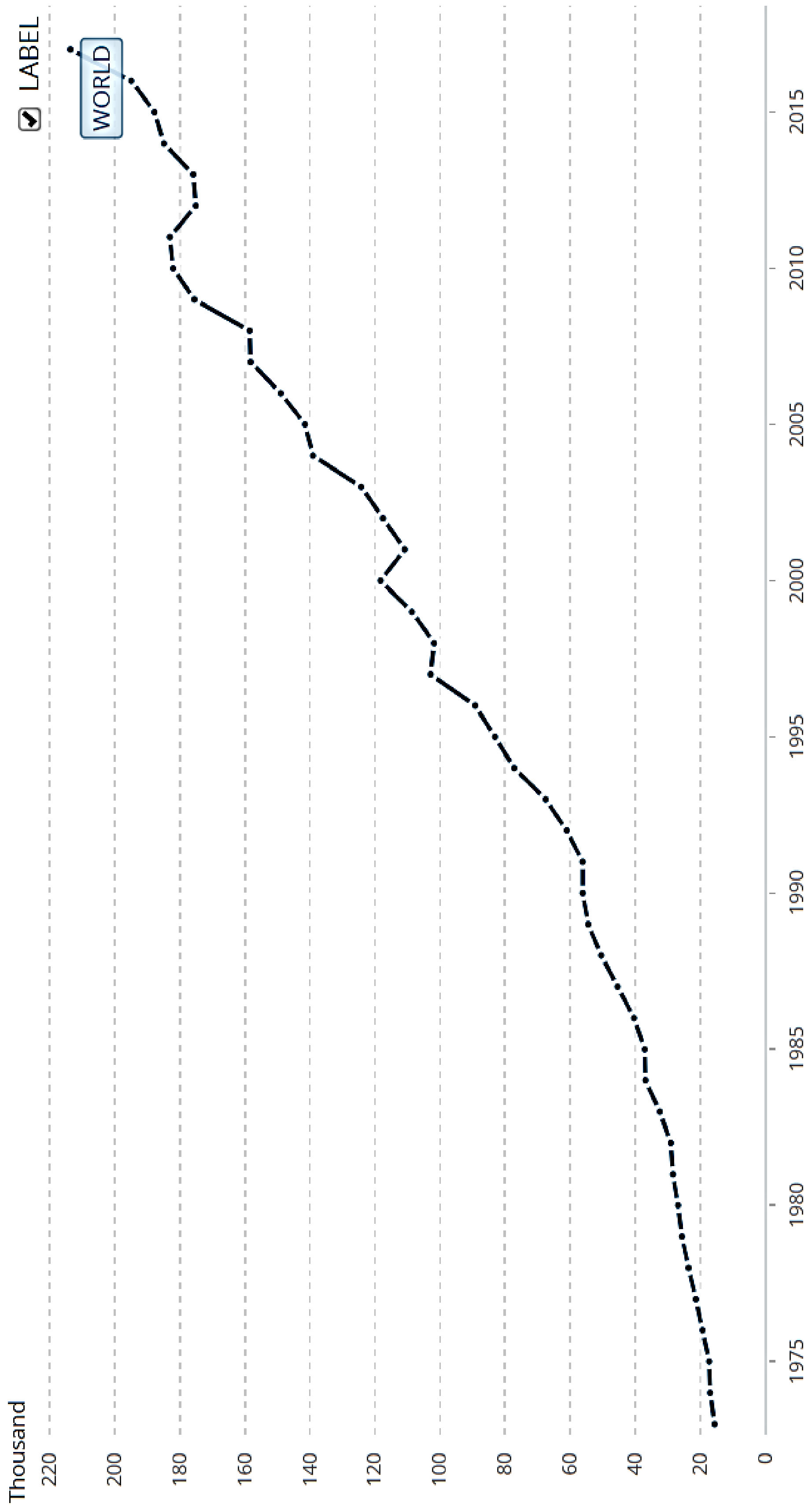
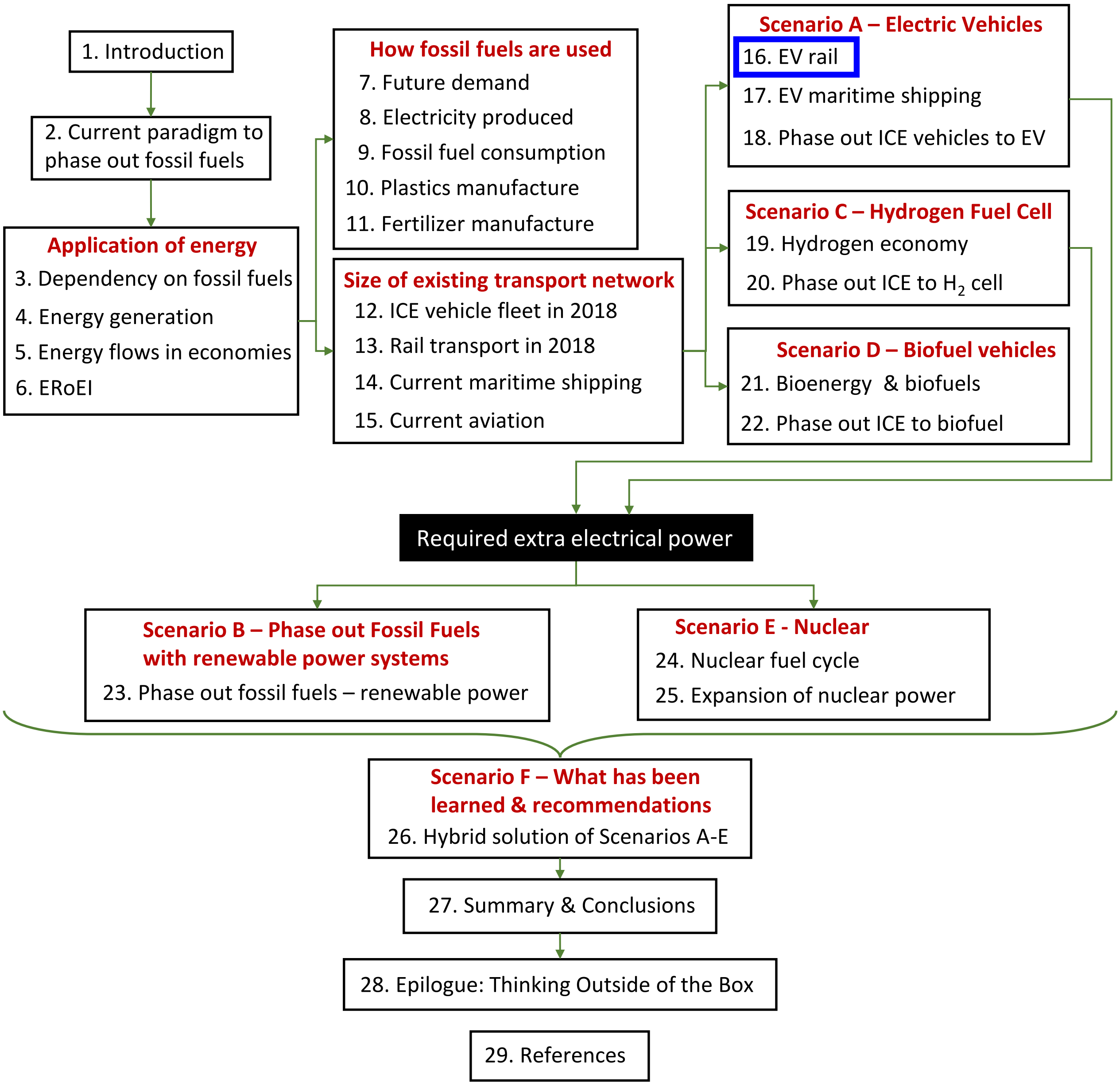


Figure 15.3. Air transport, freight (million tonne-km) 1970 to 2017
(Source: World Bank Group [US], https://data.worldbank.org/indicator/IS.AIR.GOOD.MT.K1)

16 ESTIMATED ENERGY CONSUMPTION OF A COMPLETE EV RAIL TRANSPORT SYSTEM IN 2018

Section 16 examines what would be required to phase out diesel fueled ICE rail transport and substitute with a completely EV rail network. Some of the existing rail network (both passenger and freight) is electric. This section examines what is involved with electrifying the remaining locomotives. The numbers collected in this section, will also be used later in Section 20 to examine what a hydrogen fueled freight rail system would entail.



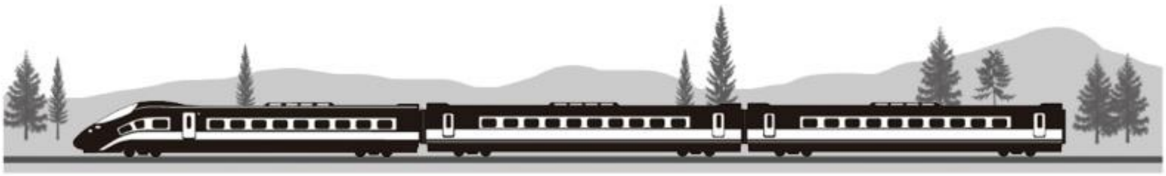
Assessment of the Extra Capacity Required of Alternative Energy Electrical Power Systems to Completely Replace Fossil Fuels

Taking the summary statistics from Section 13 (Rail transport scope size), an estimate was made to transition the whole system to a complete electric propulsion system by phasing out the use of diesel fuel.

- The energy intensity for passenger rail transport as an estimated global average is 112 kJ/passenger-km (IEA 2019).
- The energy intensity for passenger rail transport in Europe is 340 kJ/passenger-km (IEA 2019).
- The energy intensity for freight as an estimated global average is 108kJ/tonne-km (IEA 2019).
- The energy intensity for freight in Europe is 166kJ/tonne-km (IEA 2019).

To phase out diesel fuel, all rail activity would have to become EV based technology. As previously stated, 45% of passenger rail transport and 85% of rail freight is driven by diesel fuel locomotives. The scope of transport of freight and passengers by rail in a global context is shown in Appendix J. These numbers were assembled on a country by country basis then summed up.

- Global number of million passengers carried per year was 32 355 in 2018
- Global number of passenger-kilometers was 3 823 billion passenger-kilometers in 2018



- Global tonne-kilometers of rail freight transport per year was 11 067 billion tkm in 2018
- Global tonnes carried in rail freight transport per year was 12 545 tonnes in 2018

If the number of million passengers carried per year in diesel fueled trains, on a global scale was 45%, then 1 720 billion passenger-kilometers was in trains powered by diesel (45% of 3 823 billion passenger-kilometers = 1 720 billion passenger-kilometers). With an energy intensity for passenger rail transport as an estimated global average is 112 kJ/passenger-km, 1.92×10^{14} kJ of energy would need to be added to the electric grid in extra capacity to transport all rail passengers. Converting from kJ to kWh, this would require 5.35×10^{10} kWh of extra power draw capacity.

As diesel fuel Internal Combustion Engine (ICE) technology is 45% efficient, this means that 2.4×10^{10} kWh of useful work would be done (45% of 5.35×10^{10}kWh = 2.4×10^{10} kWh). If these systems were replaced with Electric Vehicle technology, which have an efficiency of 73%, then then the required extra power draw capacity to transition the remainder of the global rail passenger transport system would be 3.30×10^{10} kWh (2.4×10^{10} kWh/73% = 3.30×10^{10} kWh).

If the number of tonne-kilometers of rail freight transport per year in diesel fueled trains, on a global scale was 85%, then 9 407 billion tkm were transported by locomotives powered by diesel. With an energy intensity for freight as an estimated global average is 108 kJ/tonne-km, 1.02×10^{15} kJ of energy would need to be added to the electric grid in extra capacity to transport all rail freight. This would require 2.82×10^{11} kWh of extra power draw capacity.

As diesel fuel Internal Combustion Engine (ICE) technology is 45% efficient, this means that 1.27 x 10^{11} kWh of useful work would be done (45% of 2.82 x 10^{11} kWh = 1.27 x 10^{11} kWh). If these systems were replaced with Electric Vehicle technology, which have an efficiency of 73%, then then the required extra power draw capacity to transition the remainder of the global rail passenger transport system would be 1.73 x 10^{11} kWh (1.27 x 10^{10}kWh/73% = 1.73 x 10^{11} kWh).

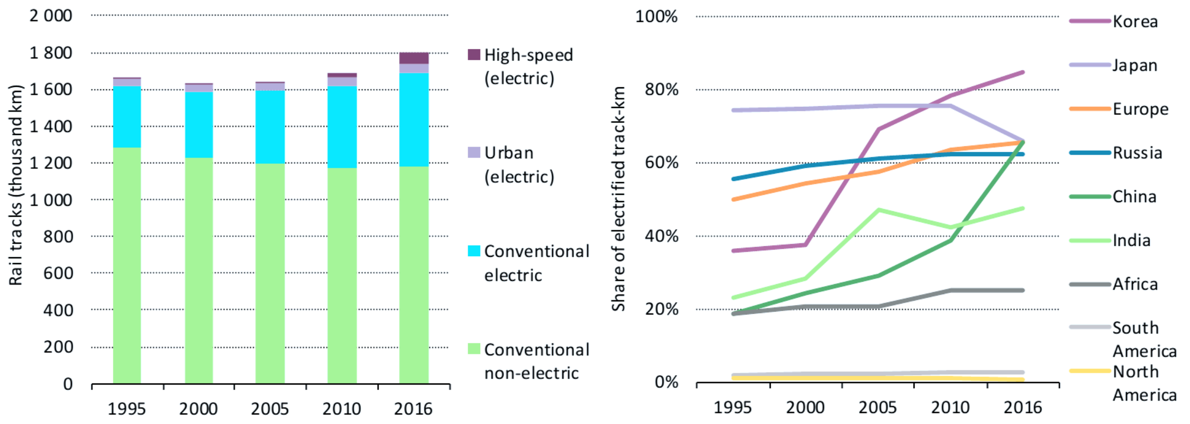
So, the work done by a complete EV rail network of the scope and size of the 2018 would be:

$$3.30 \times 10^{10}\text{ kWh} + 1.73 \times 10^{11}\text{kWh} = 2.06 \times 10^{11}\text{ kWh}$$

Assuming a 10 % loss in power between the power station and the point of application, of extra power will need to be supplied, would be:

2.27 x 10^{11} kWh or 226.6 TWh

To do this, however, requires more than just extra capacity to be added to the electric power grid. More infrastructure is required. The importance of electric rail activity for passenger services contrasts with the dominance of non-electrified lines in rail networks (Figure 16.1). While three-quarters of passenger-kilometers and around half of tonne-kilometers worldwide are carried by electric trains, only one-third of rail tracks are equipped with electrical infrastructure. This means that if all rail transport was electrified, then large portions of infrastructure need to be constructed.



Sources: IEA Mobility Model (IEA, 2018a) using assessments based on UIC (2018a); National Bureau of Statistics of China (2018); Eurostat (2018); Indian Railways (2018a); Japan Ministry of Land, Infrastructure and Tourism (2018); AAR (2017) and Russian Federation State Statistics Service (2018).

Figure 16.1. Share of electrified rail tracks by application, (LHS), Share of electrified rail tracks by country, (RHS) (Source: IEA 2019)
(Copyright License: https://www.iea.org/media/copyright/Termsandconditions_2019update_FINAL.docx.pdf)

16.1 Battery size of an EV Freight Train

According to the AAR (Association of American Railroads http://www.aar.org/), moving freight by rail is 4 times more fuel efficient than moving freight on the highway.

As an average example, a train might haul 3 000 tonnes of freight 804.6 km (500 miles) and consume approximately 11 541 liters (3,049 gallons) of diesel fuel. It is to be remembered that this example is an average of what was actually transported in the United States in 2017. This means there will be longer journeys with high haulage tonnes required. For the purpose of this report, this average will suffice to form a crude estimate.

The efficiency calculation of the average example above becomes (3000 tonnes x 804.6 km) / (11 541 liters) = 209.1 ton-km per gallon. This efficiency might be stated as "a train can move a tonne of freight 209.1 km (492 miles) on a liter of fuel. Alternatively, this train hauling 3000 tonnes of freight consumed 14.34 liters per km travelled.

So, for a train hauling 3 000 tonnes a distance of 804.6 km, 11 541 liters of diesel fuel was consumed. The density of petroleum diesel is about 0.852 kg/liter (Table 4), which means that 11 541 liters of diesel has a mass of 9 832.9 kg. Diesel fuel has an energy content of 12.67kWh/kg (Table 4), so 9 832.9 kg of diesel fuel has 124 583.2 kWh of energy content. As diesel internal combustion engines have an efficiency of approximately 38%, then this 124 583.2 kWh of energy did 47 341.6 kWh of useful work.

If this train was a fully electric EV system, it would have an approximately 73% energy efficiency (IEA 2019b). To do the same amount of useful physical work (47 341.6 kWh), an EV system would require from a battery bank 64 851.6 kWh.

So, for an EV freight train to replace a diesel locomotive, it would need to have a 65 000 kWh battery bank (estimated). Using an estimated energy density for a lithium ion battery technology of 230 kg per Wh of capacity (IEA 2019b), a 65 000 kWh battery would have a mass of 281 963 kg, or 281.9 tonnes.

The AC6000CW is a 6,000-horsepower (4 500 kW) road switcher diesel electric locomotive built by GE Transportation (American Rails 2020). Its power output is 4 500 kW. If an EV locomotive was manufactured to have the same power output with a 65 000 kWh battery bank, it would be able to haul freight for 14.4 hours (at the speed of the average example above).

Table 13.1 in Section 13 (and Table K5 in Appendix K) shows that there is an estimated 104 894 diesel freight locomotives in the major economies within the global fleet. This table shows the number of diesel locomotives in each of the top 15 ranked economies in context of freight carried (tonne-km). While this is only part of the world fleet of diesel freight trains, this number will probably represent a majority share of the true number of diesel locomotives in the global fleet.

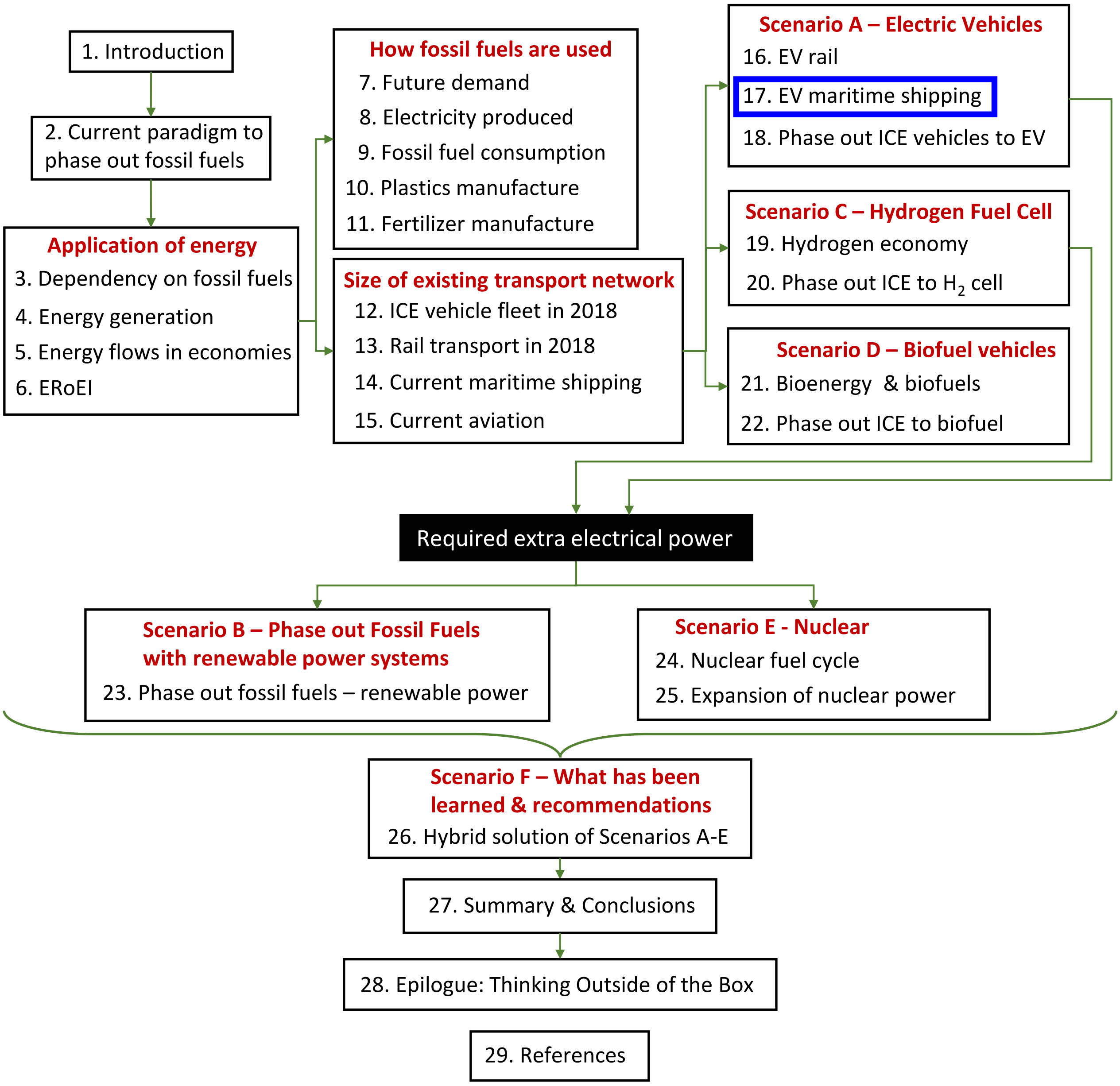
Using this number of 104 894 locomotives, and each needing a 65 000 kWh battery bank, to electrify the global rail transport fleet, a total of **6.81 TWh** of batteries will need to be manufactured.

Using this number of 104 894 locomotives, and each needing a 281.9 tonne battery bank, to electrify the global rail transport fleet, a total of **29 576 256,1 tonnes** of batteries will need to be manufactured.

It is assumed that rail transport within cities can be run off overhead electrical power cables and each train will have a relatively small EV battery. Also not included is what battery size would intercity passenger trains need to be. To address these details is beyond the scope of this report. The calculated number above is to be taken as a crude estimate only.

17 ESTIMATED ENERGY CONSUMPTION OF A COMPLETE EV MARITIME SHIPPING FLEET IN 2018

The purpose of Section 17 is to examine what is involved with phasing out diesel fueled ICE powered vessels in the global maritime shipping fleet, and substituting with a completely electric alternative, where each vessel has an electric propulsion system, powered with a battery bank. Some of the numbers collected in this section will be later used in Section 20 to examine the viability of a hydrogen fueled power cell system in each maritime shipping vessel.



Assessment of the Extra Capacity Required of Alternative Energy Electrical Power Systems to Completely Replace Fossil Fuels

The global industrial ecosystem is completely dependent on maritime shipping of commodities and cargo. Maritime/Ocean transport, fluvial transport, or more generally waterborne transport is the transport of people (passengers) or goods (cargo) via waterways. Global goods movement is a critical element in the global freight transportation system. This includes ocean and coastal routes, inland waterways, railways, roads, and air freight. In some cases, the freight transportation network connects locations by multiple modal routes, functioning as modal substitutes (Corbett & Winebrake 2008).

There has been a lot of good work done to improve the efficiency and effectiveness of the maritime industry and the vessels it manufactures (Sources: UNCTAD 2019, OECD International Transport Forum 2018, Decarbonizing Maritime Transport: Pathways to Zero Carbon Shipping by 2035, European Federation for Transport and Environment 2018, Road Map to Decarbonizing European Shipping, University Maritime Advisory Services 2019). Work done seems to fall into two broad groups:

1. Technological measures to improve ship design efficiency
    - Lighter construction materials
    - Slender design
    - Propulsion improvement devices
    - Bulbous bows
    - Air lubrication systems
    - Advanced hull coating
    - Ballast water system design
    - Energy efficiency measures
    - Engine and auxiliary systems improvements

2. Use of alternative zero-carbon fuels or energy sources
    - Batteries to power ships
    - Hydrogen fuel cells
    - Hydrogen as fuel for internal combustion engines
    - Ammonia fuel cells
    - Ammonia as fuel for internal combustion engines
    - Synthetic diesel
    - Synthetic methane
    - Advanced biofuels
    - Electricity to power ships
    - Wind assistance

It will be a challenge to phase out fossil fuels in the maritime industry. The volumes of cargo and commodities moved are truly vast and the distances travelled are longer than any other transport system currently in use (See Section 14). Multiple options to phase out fossil fuels have been proposed (EFTE 2018), ranging from fully EV, to sail assisted and nuclear propulsion (currently used in large military vessels like aircraft carriers). Several hybrid systems have also been proposed. Thinking outside the box, a solution could be engineered where large ships are propelled by sail, assisted by EV in port, where each sail could function like a solar panel, could be engineered. This conceptual idea is not available at this time, however. For the purpose of this report, the fully electric propulsion system is modelled.

Diesel propulsion system is the most commonly used marine propulsion system converting mechanical energy from thermal forces. Diesel propulsion systems are mainly used in almost all types of vessels along with small boats and recreational vessels. In conventional power system arrangements, the ship's propellers are driven by a diesel propulsion engine while the supply of electricity for the other shipboard loads is transmitted via the shipboard generators (Figure 17.1). As shown in Figure 17.1, 3 oil fueled generator-drive engines are referred to as the "ship's electric power station" supplying power for both propulsion and electrical requirements on board.

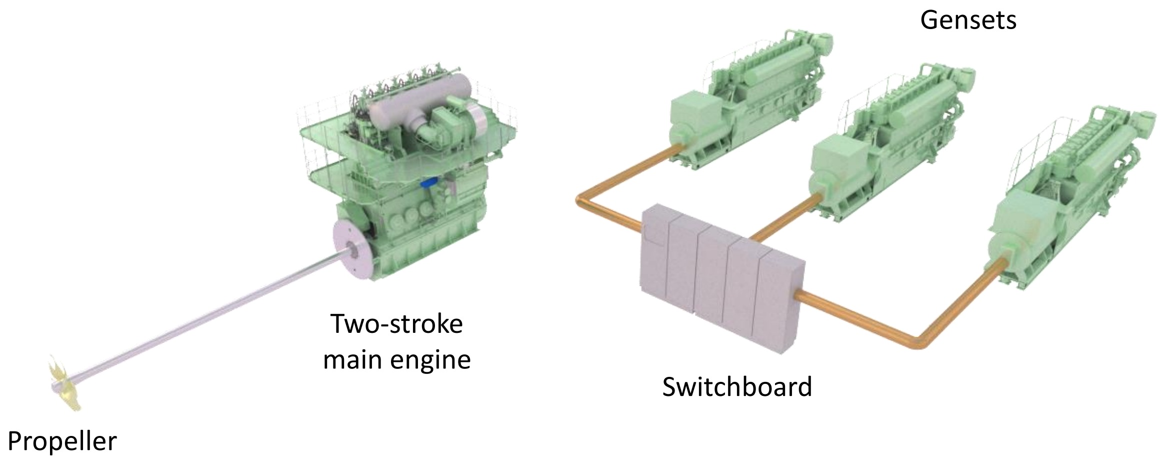


Figure 17.1. Traditional diesel-mechanic propulsion of a large merchant vessel
(Source: MAN Energy Solutions 2019, copyright granted)

In electric propulsion systems, the power used to drive the propellers becomes an electrical load meaning that the generators can take care of all shipboard loads. Electric propulsion systems utilize electrical power to drive propeller blades for propulsion. From commercial and research ships through to fishing vessels, over the last five years, electric propulsion has gained momentum in a wide range of marine applications across Europe and in Japan. The basic configuration of the electric propulsion system is shown in Figure 17.2.

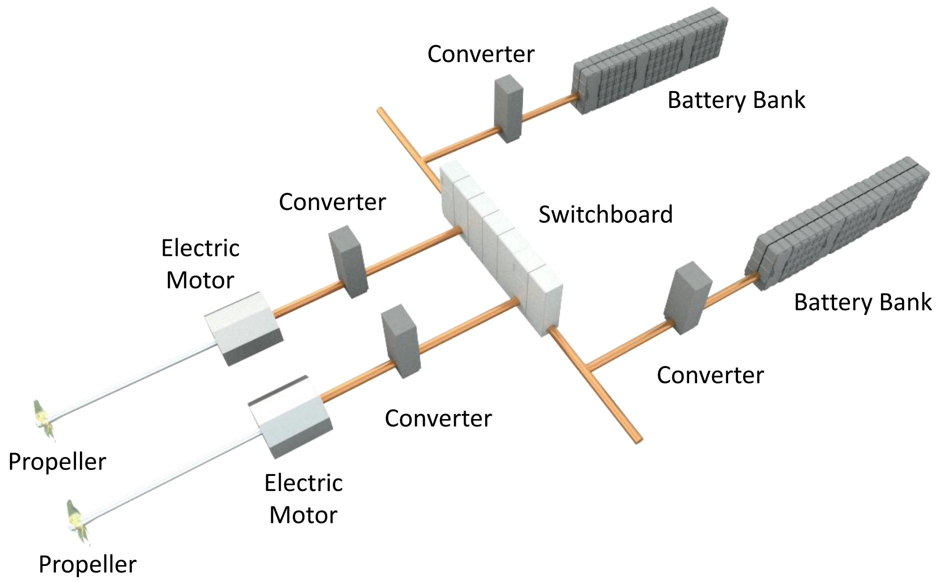


Figure 17.2. Pure battery electric propulsion system for a maritime shipping vessel
(Source: MAN Energy Solutions 2019, copyright granted)

This section seeks to examine what is involved with transitioning all actions taken by maritime shipping of cargo and commodities, from Internal Combustion Engine (ICE) technology systems to a full electric propulsion (EV) technology system. This will require a restructure of how the maritime industry operates. Very large and concentrated power generation capacity will be required to be readily available for large ships to charge their batteries in port, in greater numbers. This alone will be a logistically challenging proposition.

There will have to be more EV vessels than there are ICE vessels currently, due to the difference in cargo capacity. An ICE vessel can store its fuel in a comparatively small volume compared to the volume required for a battery bank to power an EV vessel of the same size (Figure 17.3).

This is due simply to the energy density of diesel marine fuel oil (or bunker oil) is 12 750 Wh/kg (Table 8.4 in Section 8), where current lithium ion batteries have an energy density of approximately 230 Wh/kg (IEA 2019b). This difference in density results in very different energy storage mass and volume. This means an EV system will take up more ship gross tonne capacity than an ICE system. Even if battery technology became 10 fold more efficient, it would still be only have 1/6th the energy density of diesel fuel oil. This is partially balance out by a difference in energy transfer efficiency, where diesel ICE is 38% and EV propulsion is approximately 73% (this is not clear for large ships at the time of writing this report).

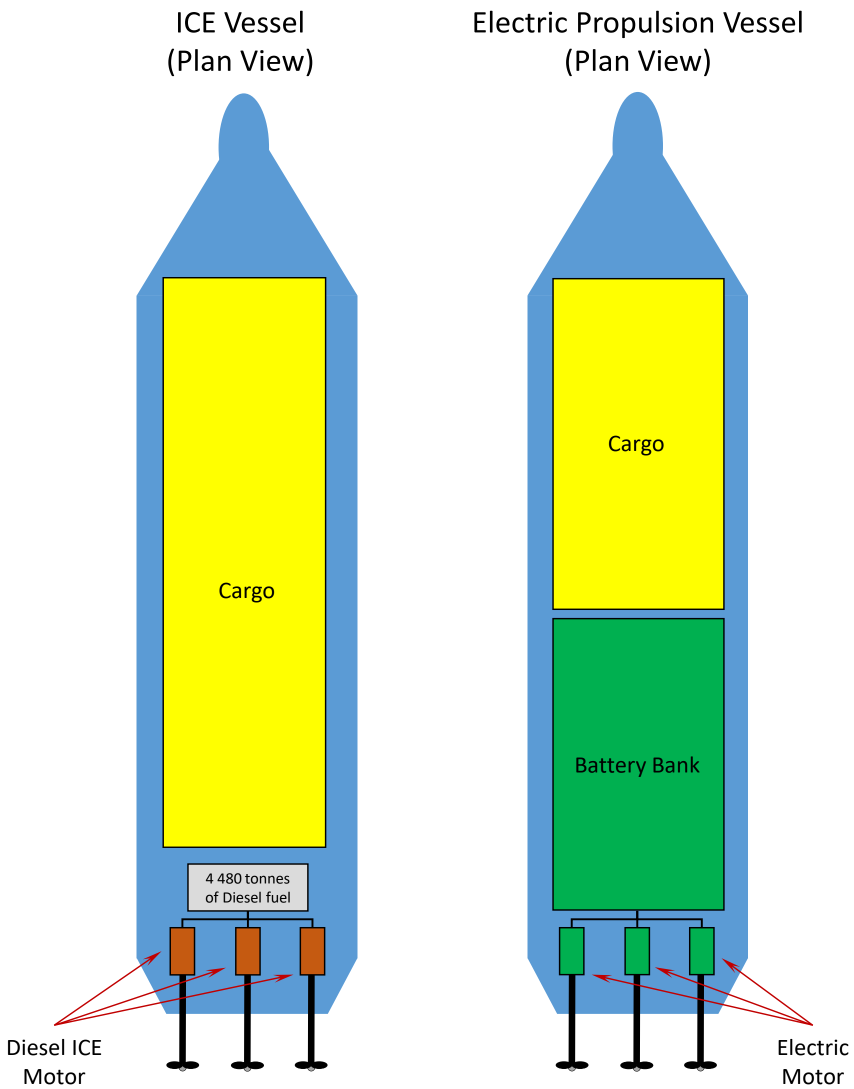


Figure 17.3. Conventional ICE diesel fuel system LHS, Fully electric propulsion system RHS
(Image: Simon Michaux)

EV Maritime Example – 2000 dwt coal carrier in China

An example of an industrial scale EV ship is the 2000 dwt vessel used for coal transport in China. In 2017, CSSC subsidiary Guangzhou Shipyard International (GSI) launched the world's first all-electric, battery-powered inland coal carrier. This 2 000 deadweight tonnes (dwt) vessel (classified as a Medium Class vessel in size) will carry bulk cargo for up to 40 nautical miles (74.08 km) per charge along a stretch of the Pearl River in China at speeds of up to seven knots (Maritime Executive 2017). This ship will travel exclusively along inland waterways in China and will not be operating in the open ocean. Chinese State media reports indicate that this vessel relies on two Voith-type cycloidial drives for propulsion. The manufacturer stated that there are few obstacles to larger vessels with bigger batteries and more deadweight tonnage (Maritime Executive 2017).

This ship carries lithium ion batteries rated at 2,400 kWh. This battery size is approximately 20 times the mass of a Tesla Model S Sedan EV. Lithium-ion batteries have one of the highest energy densities of any battery technology today (100-265 Wh/kg or 250-670 Wh/L) (Global EV Outlook IEA 2019b). So using a proposed energy density of a lithium ion battery of 230 Wh/kg, the battery on this ship has a mass of 10 435 tonnes. This 10 435 tonne battery recharges in two hours, according to GSI (Maritime Executive 2017).

The energy consumption for this Medium Class vessel is estimated at 32.4 kWh/km (2400 kWh travels 74.08 km on a one charge). This produces an energy consumption per dwt of 0.0162 kWh/km/dwt (2000 dwt travels 74.08 km consuming 32.4 kWh/km).

EV Maritime Example – passenger and vehicle ferry in Norway

In 2019, the world’s most powerful fully-electric ferry, the Ellen E-ferry was commissioned in Norway. This ferry will travel between the Danish islands of Ærø and Fynshav, which is a 22 nautical mile distance (40.74 km) (Liang 2019). This ferry is to do 5 return trips on this route every day of operation. This vessel has the specifications to travel seven times further than any other electric ferry currently in operation anywhere in the world at the time of commissioning.

The Ellen E-ferry will travel at speeds between 13-15.5 knots. The propulsion system is four electric engines and a 56 tonne lithium–ion battery bank with a capacity of 4.3 MWh (Fourneris & Copier 2020). This 750 tonne vessel is 59.5m in length and is classified as a Medium Vessel Class. As a ferry, this vessel is capable of carrying 198 passengers in summer months, with this capacity dropping to 147 during the winter. The ferry can also carry 31 cars or five trucks on its open deck. The vessel has the largest battery pack currently installed for maritime use and it is also the first electric ferry to have no emergency back-up generator on board.

This is a useful example as in Europe, about 80 % of the ferry transportation needs that can be covered in a 22 nautical miles (40km) range.

The purpose of this report section is to address the following questions:

- If an ICE ship was converted to EV, how big does the battery need to be?
- How much gross tonnes capacity is left for commodity transport in the above EV vessel?
- How many batteries are needed, and what size will they be?
- How much extra capacity in the electric power grid is needed to charge these batteries, if the same volume of commodities (in tonne-km) in 2018 was transported by fully EV vessels?

These questions were addressed in a series of calculations in Steps 1 through to Step 22, with supporting data in Appendix N- MARITIME SHIPPING STATISTICS & DATA.

17.1 Maritime terms definitions

- **Gross tonnage** (GT, G.T. or gt) is a nonlinear measure of a ship's overall internal volume. Gross tonnage is different from gross register tonnage. Neither gross tonnage nor gross register tonnage should be confused with measures of mass or weight such as deadweight tonnage or displacement. Gross tonnage (GT) is a function of the volume of all of a ship's enclosed spaces (from keel to funnel) measured to the outside of the hull framing. The numerical value for a ship's GT is always smaller than the numerical values of gross register tonnage (GRT).

- A **nautical mile** is a unit of measurement used in air, marine, and space navigation, and for the definition of territorial waters. Historically, it was defined as one minute (160 of a degree) of latitude along any line of longitude.

- In maritime tonnage, referred to as **deadweight tonnage,** is a measurement of total contents of a ship including cargo, fuel, crew, passengers, food, and water aside from boiler water. It is expressed in long tons of 2,240 lbs (1 016.04 kg).

- Shipping containers come in different sizes, but most are the standard **twenty-foot equivalent units** (**TEU**)—rectangular prisms 6.1 meters (20 feet) long and 2.4 meters wide. The first small container ships of the 1960s carried mere hundreds of TEUs; now Maersk’s Triple-E class ships load 18,000 TEUs, and OOCL Hong Kong holds the record, at 21,413 TEU’s.

- **Tonne-mile** is defined as the distance covered by a quantity of cargo. For example, 1,000 tonnes carried 500 miles equals 500,000 tonne miles. A measure of demand for capacity. Calculated as the amount of freight times the transport in nautical miles.

- **Tonne-km** is defined as the distance covered by a quantity of cargo. For example, 1,000 tonnes carried 500 kilometers equals 500,000 tonne km. A measure of demand for capacity. Calculated as the amount of freight times the transport in nautical miles.

17.2 Estimation of the required power draw to charge a total EV maritime shipping fleet

To estimate the required power draw that will have to come from the electric power grid, if the maritime shipping fleet phased out fossil fuel based Internal Combustion Engines (ICE) and became entirely electric powered (EV), the following calculations were conducted:

1. **Determine the number of ships in the global fleet in 2018 (Table 14.1, Section 14)**

2. **Determine the different types of shipping class by size in 2018 (Gross Tonnes GT)**

Table 17.1. Number of ships in global maritime fleet by size and their fuel consumption (Appendix N)

Size Classification	Number of ships in Global Fleet (Source: The World Merchant Fleet in 2018 Statistics from Equasis)	Ship Size (TEU)	Gross Tonnage (GT)	Fuel Consumption @ 20 knots (tonnes per day)	Source
Small (100 GT to 499 GT)	53,854		300	8.6	IHS Markit 2018
Medium (500 GT to 24 999 GT)	44,696	1000	12,300	27	Maloni et al 2013
Large (25 000 GT to 59 999 GT)	12,000	4000-5000	54,000	75	Transport Geography
Very Large (>60 000 GT)	6,307	10000+	196,000	175	Transport Geography

A large proportion of cargo in maritime shipping is transported in the Very Large shipping class. One of the most common examples is the Maersk Triple E-class container ship, which is used for the example in the calculation of energy consumption of an EV very large ship (Source: https://www.ship-technology.com/projects/triple-e-class-container-ship/). These specifications are shown in Appendix N.

Table 17.2. Shipping Class global proportion by number and Gross Tonnage

Ship Class by GT	Number Proportion in 2018	Gross Tonnage (GT) in 2018
Small (100 GT to 499 GT)	46 %	1 %
Medium (500 GT to 24 999 GT)	38 %	17 %
Large (25 000 GT to 59 999 GT)	10 %	33 %
Very Large (>60 000 GT)	6 %	49 %
Total	100 %	100 %

3. **Estimate the tonne-km of cargo for each commodity type moved by the global fleet in 2018 (tonne-km)**

4. **Estimate the proportion of each commodity carried by each shipping class in 2018 (tonne-km)**

Table 17.3. World seaborne trade in cargo tonne-miles -2018
(Source: UNCTAD 2018) (World Map Image by Clker-Free-Vector-Images from Pixabay)

Commodity	World seaborne trade in cargo tonne-miles in 2018 (billions of tonne-miles)	World seaborne trade in cargo tonne-miles in 2018 (billions of tonne-km)	Proportion in 2018 (%)
Chemicals	1,111	1788	1.8 %
Gas	1,766	2,841	2.9 %
Oil	13,809	22,219	22.9 %
Other dry cargo	4,497	7,236	7.4 %
Containers	9,535	15,342	15.8 %
Minor dry bulk	11,967	19,255	19.8 %
Main bulks	17,729	28,526	29.3 %
	60,414	97,206	100.0 %

Table 17.4. World seaborne trade of each commodity in cargo tonne-miles -2018
(Source: UNCTAD 2018, The World Merchant Fleet in 2018 Statistics from Equasis)
(World Map Image by Clker-Free-Vector-Images from Pixabay)

Commodity 	Small Vessel Proportion (100 GT to 499 GT) (billions of tonne-km)	Medium Vessel Proportion (500 GT to 24 999 GT) (billions of tonne-km)	Large Vessel Proportion (25 000 GT to 59 999 GT) (billions of tonne-km)	Very Large Vessel Proportion (>60 000 GT) (billions of tonne-km)	Total (billions of tonne-km)
Chemicals	17.9	303.9	589.9	875.9	1,787.6
Gas	28.4	483.1	937.7	1,392.3	2,841.5
Oil	222.2	3,777.2	7,332.2	10,887.2	22,218.7
Other dry cargo	72.4	1,230.1	2,387.8	3,545.5	7,235.7
Containers	153.4	2,608.1	5,062.8	7,517.5	15,341.8
Minor dry bulk	192.5	3,273.3	6,354.1	9,434.9	19,254.9
Main bulks	285.3	4,849.4	9,413.6	13,977.7	28,526.0
Sum	972.1	16,525.0	32,078.0	47,631.0	**97,206.1**

5. **Selection of appropriate economical speed for ship on a shipping route**

6. **Estimate the fuel consumption efficiency at a set speed (20 knots) of each shipping class per day at sea (tonnes per day)**

The speed selected is classified as Extra slow steaming (15-18 knots; 27.8 – 33.3 km/hr), as discussed in Section 14. This is so known as super slow steaming or economical speed. A substantial decline in speed for the purpose of achieving a minimal level of fuel consumption while still maintaining a commercial service. It can be applied on specific short-distance routes. Figure 17.4 shows how fuel consumption at 20 knots was estimated for several shipping class sizes, used Table 17.5.

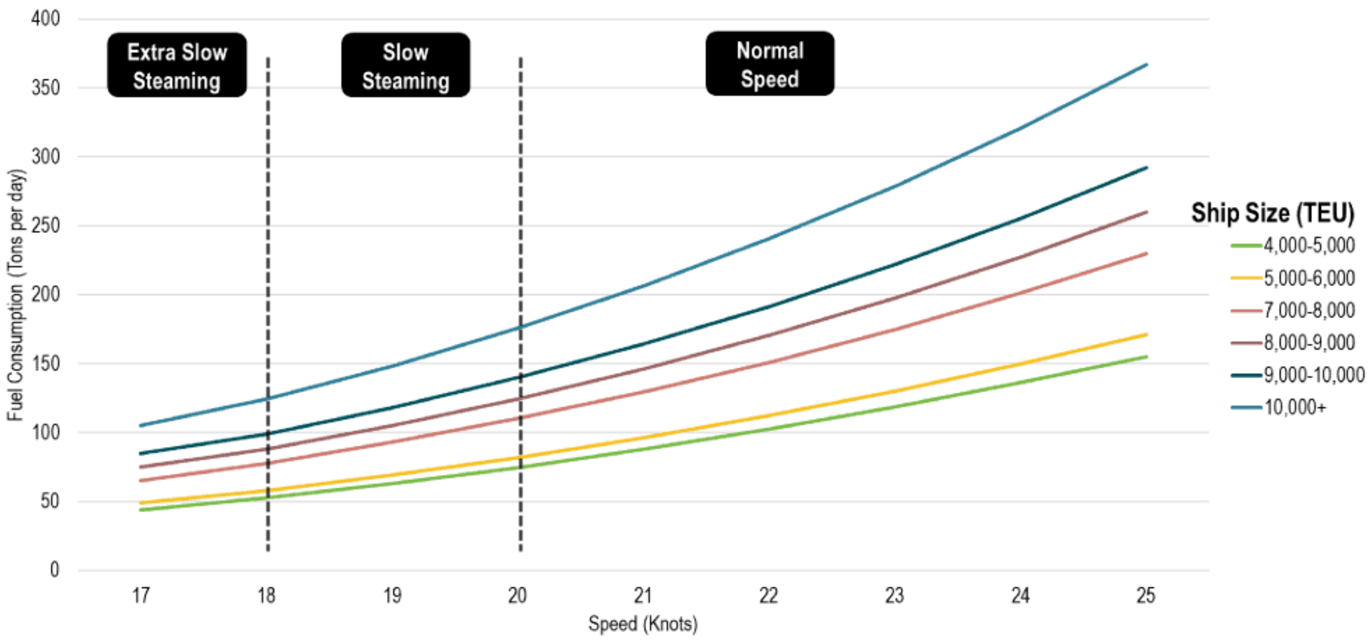


Figure 17.4. Fuel Consumption by Containership Size and Speed
(Source: adapted from Notteboom & Carriou 2009, copyright granted)

7. Estimate the distance travelled and time taken for several shipping routes (days travelled, and distance nautical miles & km)

Table 17.5 shows the distance of several examples of shipping routes, and days at sea at the selected speed of 20 knots.

Table 17.5. Shipping route distance and estimated time at sea
(Source: Ports.com, Shipping Trade Route Calculator)
(http://ports.com/sea-route/port-of-shanghai,china/port-of-hamburg,germany/)

Origin	Destination	Distance in Nautical Miles (nm)	Distance in kilometers (km)	Estimated time at sea (days)	Speed of Ship (knots)
Port of Shanghai (China)	Port of Hamburg (Germany)	12 277	22 737	25,6	20
Port of Hamburg (Germany)	Port of Melbourne (Australia)	13 372	24 765	27,8	20
Port of Hamburg (Germany)	Port of Osaka (Japan)	12 999	24 074	27,1	20
Port of Hamburg (Germany)	Port Hong Kong	11 416	21 142	23,8	20
Port of Amsterdam (Netherlands)	Port Los Angelas (United States)	10 279	19 037	21,4	20
Port of Amsterdam (Holland)	Port of Singapore	9 378	17 368	19,6	20
Port of Shanghai (China)	Port Los Angelas (United States)	19 270	35 688	40,1	20
Port of Shanghai (China)	Port of Cape Town (South Africa)	9 250	17 131	19,3	20

8. Estimate the fuel consumption for each shipping class of oil of diesel fuel for one of these shipping routes (tonnes) (Shanghai to Hamburg)

Table 17.6. Fuel consumption by ship class across route Shanghai to Hamburg
(Source: Ports.com, Shipping Trade Route Calculator. Notteboom & Carriou 2009)

Size Classification	Number of ships in Global Fleet (Source: The World Merchant Fleet in 2018 Statistics from Equasis)	Gross Tonnage (GT)	Fuel Consumption @ 20 knots (tonnes per day)	Diesel Oil consumption for whole route, Time at sea between Hamburg and Shanghai 25,6 days (tonnes)
Small (100 GT to 499 GT)	53 854	300	9	220
Medium (500 GT to 24 999 GT)	44 696	12 300	27	691
Large (25 000 GT to 59 999 GT)	12 000	54 000	75	1 920
Very Large (>60 000 GT)	6 307	196 000	175	4 480
Sum	116 857	262 600		7 311

As shown in Figure 17.4 and Table 17.5 in ICE, a Maersk's Triple-E class ship (capacity load of 18,340 TEUs) TEU diesel fuel oil consumption, while travelling at 20 knots (Slow Steaming speed), is estimated at 175 tons per day.

9. **Determine the energy density of diesel (marine gas oil) calorific content (kWh/kg) (Table 3.3, Section 3)**
   - Diesel (marine gas oil) calorific content (Table 3.3) 12.75 kWh/kg
   - Energy content in diesel (joules) 45.9 MJ/kg
45 900 000 J/kg

10. **Estimate the energy density of the diesel fuel consumed in this route (kWh)**

For the purpose of this report, just one route will be used for calculations. The most useful route would be Port of Shanghai to Port of Hamburg, which reflects the shipping route that would supply the majority of manufactured goods to Europe from China.

Table 17.7. Diesel fuel consumed in several shipping routes, by ship class – units of tonnes diesel

Origin	Destination	Distance in kilometers	Estimated time at sea	Speed of Ship	Diesel fuel consumed in each shipping route			
					Small Vessel (100 GT to 499 GT) Fuel consumption @20 knots = 8,6 t/day	Medium Vessel (500 GT to 24 999 GT) Fuel consumption @20 knots = 27 t/day	Large Vessel (25 000 GT to 59 999 GT) Fuel consumption @20 knots = 75 t/day	Very Large Vessel (>60 000 GT) Fuel consumption @20 knots = 175 t/day
		(km)	(days)	(knots)	(tonnes)	(tonnes)	(tonnes)	(tonnes)
Port of Shanghai (China)	**Port of Hamburg (Germany)**	**22,737**	**25.6**	**20**	**219.9**	**690.5**	**1,918.1**	**4,475.6**
Port of Hamburg (Germany)	Port of Melbourne (Australia)	24,765	27.8	20	239.3	751.3	2,086.9	4,869.4
Port of Hamburg (Germany)	Port of Osaka (Japan)	24,074	27.1	20	232.8	731.0	2,030.6	4,738.1
Port of Hamburg (Germany)	Port Hong Kong	21,142	23.8	20	204.5	641.9	1,783.1	4,160.6
Port of Amsterdam (Netherlands)	Port Los Angelas (United States)	19,037	21.4	20	183.8	577.1	1,603.1	3,740.6
Port of Amsterdam (Holland)	Port of Singapore	17,368	19.6	20	168.3	528.5	1,468.1	3,425.6
Port of Shanghai (China)	Port Los Angelas (United States)	35,688	40.1	20	345.1	1,083.4	3,009.4	7,021.9
Port of Shanghai (China)	Port of Cape Town (South Africa)	17,131	19.3	20	165.8	520.4	1,445.6	3,373.1

Using the diesel (marine gas oil) calorific content (Table 3.3) of 12,75 kWh/kg, Table 17.7 is updated to Table 17.8.

Table 17.8. Energy consumed in several shipping routes, by ship class – units of kWh

Origin	Destination	Distance in kilometers	Estimated time at sea	Energy consumed in this shipping route			
				Small Vessel (100 GT to 499 GT)	Medium Vessel (500 GT to 24 999 GT)	Large Vessel (25 000 GT to 59 999 GT)	Very Large Vessel (>60 000 GT)
				Fuel consumption @20 knots = 8,6 t/day of diesel, where energy density = 12.75 kW/kg	Fuel consumption @20 knots = 27 t/day of diesel, where energy density = 12.75 kW/kg	Fuel consumption @20 knots = 75 t/day of diesel, where energy density = 12.75 kW/kg	Fuel consumption @20 knots = 175 t/day of diesel, where energy density = 12.75 kW/kg
		(km)	(days)	(kW)	(kW)	(kW)	(kW)
Port of Shanghai (China)	**Port of Hamburg (Germany)**	**22,737**	**25.6**	**2,804,299**	**8,804,194**	**24,456,094**	**57,064,219**
Port of Hamburg (Germany)	Port of Melbourne (Australia)	24,765	27.8	3,051,011	9,578,756	26,607,656	62,084,531
Port of Hamburg (Germany)	Port of Osaka (Japan)	24,074	27.1	2,968,774	9,320,569	25,890,469	60,411,094
Port of Hamburg (Germany)	Port Hong Kong	21,142	23.8	2,606,929	8,184,544	22,734,844	53,047,969
Port of Amsterdam (Netherlands)	Port Los Angelas (United States)	19,037	21.4	2,343,769	7,358,344	20,439,844	47,692,969
Port of Amsterdam (Holland)	Port of Singapore	17,368	19.6	2,146,399	6,738,694	18,718,594	43,676,719
Port of Shanghai (China)	Port Los Angelas (United States)	35,688	40.1	4,399,706	13,813,031	38,369,531	89,528,906
Port of Shanghai (China)	Port of Cape Town (South Africa)	17,131	19.3	2,113,504	6,635,419	18,431,719	43,007,344

11. Determine the work done energy efficiency of a diesel ICE system

- Efficiency of an ICE diesel engine is 38% (Table 3.4, Section 3)

12. Estimate the useful work done by the ship diesel engine during this shipping route (kWh)

Using the efficiency of an ICE diesel engine of 38% Table 17.8 was updated to become Table 17.9 to show the useful work done by the propulsion system in each shipping route.

Table 17.9. Useful work done in each ship route, by shipping class

Origin	Destination	Distance in kilometers	Estimated time at sea	Useful work done in this route			
				Small Vessel (100 GT to 499 GT)	Medium Vessel (500 GT to 24 999 GT)	Large Vessel (25 000 GT to 59 999 GT)	Very Large Vessel (>60 000 GT)
		(km)	(days)	Diesel work efficiency @ 38% (kW)	Diesel work efficiency @ 38% (kW)	Diesel work efficiency @ 38% (kW)	Diesel work efficiency @ 38% (kW)
Port of Shanghai (China)	**Port of Hamburg (Germany)**	**22 737**	**25,6**	**1 065 633,5**	**3 345 593,6**	**9 293 315,6**	**21 684 403,1**
Port of Hamburg (Germany)	Port of Melbourne (Australia)	24 765	27,8	1 159 384,3	3 639 927,4	10 110 909,4	23 592 121,9
Port of Hamburg (Germany)	Port of Osaka (Japan)	24 074	27,1	1 128 134,0	3 541 816,1	9 838 378,1	22 956 215,6
Port of Hamburg (Germany)	Port Hong Kong	21 142	23,8	990 632,9	3 110 126,6	8 639 240,6	20 158 228,1
Port of Amsterdam (Netherlands)	Port Los Angelas (United States)	19 037	21,4	890 632,1	2 796 170,6	7 767 140,6	18 123 328,1
Port of Amsterdam (Holland)	Port of Singapore	17 368	19,6	815 631,5	2 560 703,6	7 113 065,6	16 597 153,1
Port of Shanghai (China)	Port Los Angelas (United States)	35 688	40,1	1 671 888,4	5 248 951,9	14 580 421,9	34 020 984,4
Port of Shanghai (China)	Port of Cape Town (South Africa)	17 131	19,3	803 131,4	2 521 459,1	7 004 053,1	16 342 790,6

13. Estimate the work done energy efficiency of an EV system

- The work done energy efficiency of an Electric Vehicle (EV) system is taken at 73% (Malins 2017).

14. Estimate the energy consumption, of an EV system to do the needed useful work to propel all cargo carrying ship classes across this shipping route at a speed of 20 knots for the number of days estimated (kWh)

Using the efficiency of an EV propulsion system of 73% Table 17.9 was updated to become Table 17.10 to show the useful work done if all of these maritime shipping the propulsion systems were EV, for each shipping route. It is to be remembered here that diesel fuel has an energy density of 12 750 Wh/kg, where current lithium-ion battery energy density is approximately 230 Wh/kg. This is a 55 fold difference, which shows why the EV batteries for long range shipping have to be so physically large. It is for this reason that EV technology will struggle to replace petroleum products in spite of the difference in efficiency (diesel ICE 38% vs Electric Vehicle 73%).

Table 17.10. Estimation of energy consumption for an EV system for each ship route, by shipping class

Origin	Destination	Distance in kilometers (km)	Estimated time at sea (days)	Useful work done in this route if propulsion was EV			
				Small Vessel (100 GT to 499 GT) EV work efficiency @ 73% (kW)	Medium Vessel (500 GT to 24 999 GT) EV work efficiency @ 73% (kW)	Large Vessel (25 000 GT to 59 999 GT) EV work efficiency @ 73% (kW)	Very Large Vessel (>60 000 GT) EV work efficiency @ 73% (kW)
Port of Shanghai (China)	**Port of Hamburg (Germany)**	**22 737**	**25,6**	**1 459 772,0**	**4 583 005,0**	**12 730 569,3**	**29 704 661,8**
Port of Hamburg (Germany)	Port of Melbourne (Australia)	24 765	27,8	1 588 197,6	4 986 201,9	13 850 560,8	32 317 975,2
Port of Hamburg (Germany)	Port of Osaka (Japan)	24 074	27,1	1 545 389,1	4 851 802,9	13 477 230,3	31 446 870,7
Port of Hamburg (Germany)	Port Hong Kong	21 142	23,8	1 357 031,4	4 260 447,4	11 834 576,2	27 614 011,1
Port of Amsterdam (Netherlands)	Port Los Angelas (United States)	19 037	21,4	1 220 044,0	3 830 370,7	10 639 918,7	24 826 476,9
Port of Amsterdam (Holland)	Port of Singapore	17 368	19,6	1 117 303,5	3 507 813,2	9 743 925,5	22 735 826,2
Port of Shanghai (China)	Port Los Angelas (United States)	35 688	40,1	2 290 258,0	7 190 345,0	19 973 180,7	46 604 088,2
Port of Shanghai (China)	Port of Cape Town (South Africa)	17 131	19,3	1 100 180,0	3 454 053,6	9 594 593,3	22 387 384,4

15. Estimate the size and mass of the needed battery, for each shipping class, assuming an energy density of 230 kWh/kg (NMC 811 battery chemistry) (in kg and tonne)

16. Estimate the number and size of EV batteries (size by class times the number of ships in each class)

Tables 17.11 to 17.14 below shows an estimation of the required physical mass of the battery to power a ship (each table shows a different ship class size) to travel each of the example shipping routes. Currently, the energy density of a lithium ion battery is approximately 230 Wh/kg (IEA 2019b). Also shown in these tables is an estimation of battery size if an efficiency breakthrough happens and the energy density increases to 500 Wh/kg (a 217% increase in energy density).

Table 17.11. Estimation of the battery mass for an EV system for each ship route, Small Vessel Class (100 GT to 499 GT)

Origin	Destination	Distance in kilometers (km)	Energy Required for Distance Traveled Small Vessel (kW)	Mass of battery @ 230 Wh/kg (kg)	Mass of battery @ 230 Wh/kg (tonne)	Mass of battery @ 500 Wh/kg (tonne)
Port of Shanghai (China)	Port of Hamburg (Germany)	22,737	1,459,772	6,346,835	6,347	2,920
Port of Hamburg (Germany)	Port of Melbourne (Australia)	24,765	1,588,198	6,905,207	6,905	3,176
Port of Hamburg (Germany)	Port of Osaka (Japan)	24,074	1,545,389	6,719,083	6,719	3,091
Port of Hamburg (Germany)	Port Hong Kong	21,142	1,357,031	5,900,137	5,900	2,714
Port of Amsterdam (Netherlands)	Port Los Angelas (United States)	19,037	1,220,044	5,304,539	5,305	2,440
Port of Amsterdam (Netherlands)	Port of Singapore	17,368	1,117,303	4,857,841	4,858	2,235
Port of Shanghai (China)	Port Los Angelas (United States)	35,688	2,290,258	9,957,644	9,958	4,581
Port of Shanghai (China)	Port of Cape Town (South Africa)	17,131	1,100,180	4,783,391	4,783	2,200

Table 17.12. Estimation of the battery mass for an EV system for ship route, Medium Vessel Class (500 GT to 24 999 GT)

Origin	Destination	Distance in kilometers (km)	Energy Required for Distance Traveled Medium Vessel (kW)	Mass of battery @ 230 Wh/kg (kg)	Mass of battery @ 230 Wh/kg (tonne)	Mass of battery @ 500 Wh/kg (tonne)
Port of Shanghai (China)	Port of Hamburg (Germany)	22 737	4 583 005	19 926 109	19 926	9 166
Port of Hamburg (Germany)	Port of Melbourne (Australia)	24 765	4 986 202	21 679 139	21 679	9 972
Port of Hamburg (Germany)	Port of Osaka (Japan)	24 074	4 851 803	21 094 795	21 095	9 704
Port of Hamburg (Germany)	Port Hong Kong	21 142	4 260 447	18 523 684	18 524	8 521
Port of Amsterdam (Netherlands)	Port Los Angelas (United States)	19 037	3 830 371	16 653 786	16 654	7 661
Port of Amsterdam (Holland)	Port of Singapore	17 368	3 507 813	15 251 362	15 251	7 016
Port of Shanghai (China)	Port Los Angelas (United States)	35 688	7 190 345	31 262 370	31 262	14 381
Port of Shanghai (China)	Port of Cape Town (South Africa)	17 131	3 454 054	15 017 624	15 018	6 908

Table 17.13. Estimation of the battery mass for an EV system for each ship route, Large Vessel Class (500 GT to 24 999 GT)

Origin	Destination	Distance in kilometers (km)	Energy Required for Distance Traveled Small Vessel (kW)	Mass of battery @ 230 Wh/kg (kg)	Mass of battery @ 230 Wh/kg (tonne)	Mass of battery @ 500 Wh/kg (tonne)
Port of Shanghai (China)	Port of Hamburg (Germany)	22 737	12 730 569	55 350 302	55 350	25 461
Port of Hamburg (Germany)	Port of Melbourne (Australia)	24 765	13 850 561	60 219 830	60 220	27 701
Port of Hamburg (Germany)	Port of Osaka (Japan)	24 074	13 477 230	58 596 654	58 597	26 954
Port of Hamburg (Germany)	Port Hong Kong	21 142	11 834 576	51 454 679	51 455	23 669
Port of Amsterdam (Netherlands)	Port Los Angelas (United States)	19 037	10 639 919	46 260 516	46 261	21 280
Port of Amsterdam (Holland)	Port of Singapore	17 368	9 743 926	42 364 894	42 365	19 488
Port of Shanghai (China)	Port Los Angelas (United States)	35 688	19 973 181	86 839 916	86 840	39 946
Port of Shanghai (China)	Port of Cape Town (South Africa)	17 131	9 594 593	41 715 623	41 716	19 189

Table 17.14. Estimation of the battery mass for an EV system for each ship route, Very Large Vessel Class (>60 000 GT)

Origin	Destination	Distance in kilometers (km)	Energy Required for Distance Traveled Small Vessel (kW)	Mass of battery @ 230 Wh/kg (kg)	Mass of battery @ 230 Wh/kg (tonne)	Mass of battery @ 500 Wh/kg (tonne)
Port of Shanghai (China)	Port of Hamburg (Germany)	22 737	29 704 662	129 150 704	129 151	59 409
Port of Hamburg (Germany)	Port of Melbourne (Australia)	24 765	32 317 975	140 512 936	140 513	64 636
Port of Hamburg (Germany)	Port of Osaka (Japan)	24 074	31 446 871	136 725 525	136 726	62 894
Port of Hamburg (Germany)	Port Hong Kong	21 142	27 614 011	120 060 918	120 061	55 228
Port of Amsterdam (Netherlands)	Port Los Angelas (United States)	19 037	24 826 477	107 941 204	107 941	49 653
Port of Amsterdam (Holland)	Port of Singapore	17 368	22 735 826	98 851 418	98 851	45 472
Port of Shanghai (China)	Port Los Angelas (United States)	35 688	46 604 088	202 626 470	202 626	93 208
Port of Shanghai (China)	Port of Cape Town (South Africa)	17 131	22 387 384	97 336 454	97 336	44 775

17. Estimate the Gross tonnes left for ship operation and cargo after installation of this EV battery system for each class of ship

Given the large size of batteries needed to make EV in long maritime journeys, it becomes clear that many existing maritime ICE based shipping vessels will not be able to travel in the same manner, once they transition to EV. Table 17.15 shows an estimate of what Gross Tonnes capacity is left in each shipping class after a proposed EV battery large enough to propel the vessel for the shown distances has been installed. This is a very crude estimate and could be refined with a more detailed study.

As it is clear that most of the long distance routes would become impractical due to the sheer size of the needed battery, Table 17.15 also estimates the needed battery size if the travelled routes were shorter. The shipping route between Shanghai in China and Hamburg in Germany has a distance of 22 737 km and requires 25.6 days at sea at an average speed of 20 knots. Shorter routes were calculated as examples:

- 10 days at sea (8 890km), example Port of Singapore to Port of Sydney
- 2 days at sea (1 778km), example Port of Stockholm to Port of Hamburg
- 0.25 days at sea (222km), example Port of Helsinki to Port of St Petersburg

The mass of the needed EV battery for each shipping class for each of these distances was estimated.

Table 17.15 below shows an estimation of the required battery size for an EV system to propel a vessel (by size class) for the distances shown. Once the battery size was estimated (in tonnes), a very crude estimation of what mass cargo capacity is left on the vessel (by shipping class). This calculation is achieved by subtracting the mass of the battery from the Gross Tonnage of the vessel. In this fashion the Gross Tonnes left in each ship traveling that distance can be estimated. The assumption is all of this is used to carry cargo. This is a crude calculation. It is recommended that a more sophisticated study to be done on what an EV system in maritime shipping would be.

Of course, this is a gross oversimplification, which does not account for all the engineering requirements for the ship to run. It is well beyond the scope of this report to have a more complex and appropriate estimate of the Gross Tons left in these scenarios. These calculations are understood to be very crude ballpark estimates.

Table 17.15. Estimation of the Gross tonnes left for ship operation and cargo after installation of this EV battery system for each class of ship

Ship Vessel Size Class	Distance (km)	Estimated time at sea (days)	Energy Required for Distance Traveled for Vessel (Battery Size) (kW)	Mass of battery @ 230 Wh/kg (tonne)	GT left after battery installation for mininum vessel size in given class (tonne)	GT left after battery installation for maximum vessel size in given class (tonne)
Small Vessel	22 737	25,6	1 459 772	6 347	-	-
(100 GT to 499 GT)	8 890	10	570 781	2 482	-	-
	4 445	5	285 390	1 241	-	-
	1 778	2	114 156	496	-	-
	889	1	57 078	248	-	251
	222	0,25	14 270	62	38	437
Medium Vessel	22 737	25,6	4 583 005	19 926	-	5 073
(500 GT to 24 999 GT)	8 890	10	1 791 986	7 791	-	17 208
	4 445	5	895 993	3 896	-	21 103
	1 778	2	358 397	1 558	-	23 441
	889	1	179 199	779	-	24 220
	222	0,25	44 800	195	305	24 804
Large Vessel	22 737	25,6	12 730 569	55 350	-	4 649
(25 000 GT to 59 999 GT)	8 890	10	4 977 740	21 642	3 358	38 357
	4 445	5	2 488 870	10 821	14 179	49 178
	1 778	2	995 548	4 328	20 672	55 671
	889	1	497 774	2 164	22 836	57 835
	222	0,25	124 443	541	24 459	59 458
Very Large Vessel	22 737	25,6	29 704 662	129 151	-	66 849
(>60 000 GT)	8 890	10	11 614 726	50 499	9 501	145 501
(Maerks Triple E	4 445	5	5 807 363	25 249	34 751	170 751
196 000 GT)	1 778	2	2 322 945	10 100	49 900	185 900
	889	1	1 161 473	5 050	54 950	190 950
	222	0,25	290 368	1 262	58 738	194 738

18. For this net cargo capacity (assuming all remaining mass is for cargo), estimate the tonne-km rate for each shipping class to travel this example route (Shanghai to Hamburg)

The results shown in Table 17.15 were developed further to estimate the energy consumption per tonne for each vessel class, traveling the distances selected (shown in Table 17.16). It quickly becomes clear that the smaller vessels (Size Class) are only suitable for shorter distances. For example, a small EV ship vessel (100 to 499 Gross Tons) has an operational range of approximately 200 km. There is an economy of scale in action, where the larger ships are capable of going longer distances without recharging. The calculations in Table 17.17 were taken from the **red** colored numbers in Table 17.16.

Table 17.16. Estimation of the Gross tonnes left for ship operation and cargo after installation of this EV battery system for each class of ship

Ship Vessel Size Class	Distance (km)	Energy Required for Distance Traveled Small Vessel(Battery Size) (kW)	Energy Consumed per km (kW/km)	GT left after battery installation for mininum vessel size in given class (tonne)	Energy Consumption per tonne for given distance for Min size in class (kW/tonne)	GT left after battery installation for maximum vessel size in given class (tonne)	Energy Consumption per tonne for given distance for Max size in class (kW/tonne)
Small Vessel	22 737	1 459 772	-	-	-	-	-
(100 GT to 499 GT)	8 890	570 781	-	-	-	-	-
	4 445	285 390	-	-	-	-	-
	1 778	114 156	-	-	-	-	-
	889	57 078	64	-	-	251	228
	222	14 270	**64**	38	376	**437**	**32,7**
Medium Vessel	22 737	4 583 005	202	-	-	5 073	903
(500 GT to 24 999 GT)	8 890	1 791 986	202	-	-	17 208	104
	4 445	895 993	202	-	-	21 103	42,5
	1 778	358 397	**202**	-	-	**23 441**	**15,3**
	889	179 199	202	-	-	24 220	7,4
	222	44 800	202	305	147	24 804	1,8
Large Vessel	22 737	12 730 569	560	-	-	4 649	2739
(25 000 GT to 59 999 GT)	**8 890**	4 977 740	**560**	3 358	1 483	**38 357**	**130**
	4 445	2 488 870	560	14 179	176	49 178	50,6
	1 778	995 548	560	20 672	48,2	55 671	17,9
	889	497 774	560	22 836	21,8	57 835	8,6
	222	124 443	560	24 459	5,1	59 458	2,1
Very Large Vessel	22 737	29 704 662	1 306	-	-	66 849	444
(>60 000 GT)	**8 890**	11 614 726	**1 306**	9 501	1 222	**145 501**	**79,8**
(Maerks Triple E	4 445	5 807 363	1 306	34 751	167	170 751	34,0
196 000 GT)	1 778	2 322 945	1 306	49 900	46,6	185 900	12,5
	889	1 161 473	1 306	54 950	21,1	190 950	6,1
	222	290 368	1 306	58 738	4,9	194 738	1,5

For the Very Large vessel class travelling the route Shanghai to Hamburg (22 737 km), just 66 849 GT was left from the original 196 000 GT (Maerks Triple E container ship example) after the installation of a 129 151 tonne battery to power the electric propulsion system (remember this is a desk top thought experiment). This means that only 34% is left for engineering and cargo in a Maerks Triple E container ship (with 196 000 Gross Tonnes available). This was considered not reasonable in a logistical context (let alone an economic context). A more practical approach would be to have the Very Large vessel travel a shorter distance and recharge along the way. To illustrate this, the data from Table 17.16 above is the 8 890 km (Shipping route from Singapore to Sydney), which needs a 21 642 tonne battery, leaving 145 501 Gross Tonnes (Maerks Triple E container ship example). This allows for 89% of the Gross Tonnes available.

19. Estimate for each shipping class the power consumption per tonne-km for this route (kWh/tonne-km)

Table 17.17. Estimate for each shipping class the power consumption per tonne-km for this route (kWh/tonne-km)

Ship Vessel Size Class	Distance Traveled Shipping Route (km)	Estimated Size of Battery in Vessel (kWh)	Mass of Battery to travel Target Shipping Route Distance (tonne)	Gross Tonnes left after battery installation for maximum vessel size in given class (tonne)	Tonne-km per run on example shipping route (tonne-km)	Energy Consumption per tonne for given distance for Max size in class (kW/tonne)	Energy Consumed by EV system per tonne-km (kW/tonne-km)
Small Vessel (100 GT to 499 GT)	222 Port of Helsinki to Port of St Petersburg	14 270	62	437	97 118	32,7	2,97E+03
Medium Vessel (500 GT to 24 999 GT)	1 778 Port of Stockholm to Port of Hamburg	358 397	1 558	23 441	41 679 156	15,3	2,73E+06
Large Vessel (25 000 GT to 59 999 GT)	8 890 Port of Singapore to Port of Sydney	4 977 740	21 642	38 357	341 002 923	129,8	2,63E+06
Very Large Vessel (>60 000 GT) (Maerks Triple E 196 000 GT)	8 890 Port of Singapore to Port of Sydney	11 614 726	50 499	145 501	1 293 552 150	79,8	1,62E+07

For a Very Large vessel to travel between the Port of Shanghai and the Port of Hamburg (22 737 km), with a proposed range of 8 890 km, it would have to stop and recharge from the electric power grid 3 times during the journey (2.6 times precisely). This would mean a complete reworking and restructuring of the infrastructure supporting the maritime shipping system. If for example an industrial scale electric charging for ships was installed in the Port Singapore, ships could recharge. To handle the sheer number of large ships to do this would be logistically complex. Also, how long would it take to recharge an 8 890 tonne lithium ion battery (the equivalent of 16 463 Telsa Roadsters with a battery mass 540 kg) is unclear.

20. Estimate the energy consumption for each shipping class (which are now all assumed to be EV) for the tonne-km needed for each commodity (kWh)

At this point, it should be clear that the maritime industry and shipping of cargo in general will have to be completely restructured. EV ships are generally suited to short distances only. Currently, a large proportion of raw materials are shipped to China and manufactured goods are shipped from China to Europe and the United States.

Tables 17.18 and 17.19 show the tonne-km for each of the major commodities in 2018. Table 17.20 shows the number and size of shipping vessels by class. These two tables were combined to estimate the tonne-km for each commodity transported by each shipping class. Oil and gas tankers are excluded in this calculation.

Table 17.18. Global tonne-km of commodities transported in 2018
(Source: UNCTAD 2019 - Review of maritime transport 2019, United Nations Conference on Trade and Development)
(World Map Image by Clker-Free-Vector-Images from Pixabay)

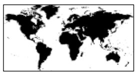
Commodity 	World seaborne trade in cargo tonne-miles in 2018 (billions of tonne-miles)	World seaborne trade in cargo tonne-miles in 2018 (billions of tonne-km)	Proportion in 2018 (%)
Chemicals	1,111	1788	1.8 %
Gas	1,766	2,841	2.9 %
Oil	13,809	22,219	22.9 %
Other dry cargo	4,497	7,236	7.4 %
Containers	9,535	15,342	15.8 %
Minor dry bulk	11,967	19,255	19.8 %
Main bulks	17,729	28,526	29.3 %
	60,414	97,206	100.0 %

Table 17.19. Number of ship vessels by size class and Gross Tonnage – Global fleet
(Source: The World Merchant Fleet in 2018 Statistics from Equasis) (World Map Image by Clker-Free-Vector-Images from Pixabay)

Ship Class by GT	Number Proportion in 2018	Gross Tonnage (GT) in 2018
Small (100 GT to 499 GT)	46 %	1 %
Medium (500 GT to 24 999 GT)	38 %	17 %
Large (25 000 GT to 59 999 GT)	10 %	33 %
Very Large (>60 000 GT)	6 %	49 %
Total	100 %	100 %

Table 17.20. Estimated 2018 global tonne-km of commodities transported in 2018 by Shipping Class
(World Map Image by Clker-Free-Vector-Images from Pixabay)

Commodity 	Small Vessel Proportion (100 GT to 499 GT) (billions of tonne-km)	Medium Vessel Proportion (500 GT to 24 999 GT) (billions of tonne-km)	Large Vessel Proportion (25 000 GT to 59 999 GT) (billions of tonne-km)	Very Large Vessel Proportion (>60 000 GT) (billions of tonne-km)	Total (billions of tonne-km)
Chemicals	17.9	303.9	589.9	875.9	1,787.6
Gas	28.4	483.1	937.7	1,392.3	2,841.5
Oil	222.2	3,777.2	7,332.2	10,887.2	22,218.7
Other dry cargo	72.4	1,230.1	2,387.8	3,545.5	7,235.7
Containers	153.4	2,608.1	5,062.8	7,517.5	15,341.8
Minor dry bulk	192.5	3,273.3	6,354.1	9,434.9	19,254.9
Main bulks	285.3	4,849.4	9,413.6	13,977.7	28,526.0
Sum	972.1	16,525.0	32,078.0	47,631.0	**97,206.1**

To convert the maritime cargo fleet to EV, it is practical to have all shipping transport conducted by Large and Very Large vessels, where Very Large is estimated using the Maersk Triple E-class container ship. Smaller ships (Medium and Small) would be tasked to transport of people and cars over short distances. To make this adjustment, the Very Large vessel proportion of 49% gross tonnage from Table 17.20 becomes 59.8% of global cargo commodity transport. The Large vessel proportion of 33% from Table 17.20 becomes 40.2% of global cargo commodity transport.

Table 17.21. Estimated global tonne-km for commodities in 2018, if all commodities was transported by Large and Very Large vessels only (World Map Image by Clker-Free-Vector-Images from Pixabay)

Commodity 	Large Vessel Proportion (25 000 GT to 59 999 GT) (billions of tonne-km)	Very Large Vessel Proportion (>60 000 GT) (billions of tonne-km)	Total (billions of tonne-km)
Chemicals	719.4	1,068.2	1,787.6
Gas			
Oil			
Other dry cargo	2,911.9	4,323.8	7,235.7
Containers	6,174.2	9,167.7	15,341.8
Minor dry bulk	7,748.9	11,506.0	19,254.9
Main bulks	11,480.0	17,046.0	28,526.0
Sum	29,034.4	43,111.6	72,146.0

Table 17.22. Estimated energy consumption of maritime shipping of cargo, if all commodities tonne-km for commodities in 2018 was transported by Large and Very Large Electric Vehicle propulsion vessels only (World Map Image by Clker-Free-Vector-Images from Pixabay)

Commodity 	Large Vessel Proportion of Cargo Transport in 2018 (25 000 GT to 59 999 GT) (billions of tonne-km)	Energy Consumed by EV system per tonne-km for Large Vessel rate 2.63 x 10^6 kW/tonne-km (kW)	Very Large Vessel Proportion of Cargo Transport in 2018 (>60 000 GT) (billions of tonne-km)	Energy Consumed by EV system per tonne-km for Large Vessel rate 3.42 x 10^6 kW/tonne-km (kW)
Chemicals	719.4	1.89E+09	1,068.2	1.73E+10
Gas	N/A		N/A	
Oil	N/A		N/A	
Other dry cargo	2,911.9	7.65E+09	4,323.8	7.01E+10
Containers	6,174.1	1.62E+10	9,167.7	1.49E+11
Minor dry bulk	7,748.9	2.04E+10	11,506.0	1.86E+11
Main bulks	11,480.0	3.02E+10	17,046.0	2.76E+11
	29,034.3		43,111.6	
Sum		7.63E+10		6.99E+11
			Total (kWh)	7.75E+11
				774.9 TWh

21. Sum all shipping class energy consumption for all commodities moved in 2018

In 2018, there was 16 250 Small Vessels (100 to 499 GT), making up passenger ferries, car ferries and small fishing boats. As a crude estimation of power draw consumption for the Small Vessel fleet was taken as each vessel taking one trip per day for all 2018 (consuming 14 270 kWh for each 222 km trip). The calculation becomes:

Small Vessel Energy consumption = 16 250 (number of ships) x 365 (trips in 2018) x 14 270 (kWh per trip)

= 8.46×10^{10} kWh

Total transport of commodities in the same volumes of what was transported in 2018 was calculated as:

EV Maritime Energy Consumption for 2018 = $7.63 \times 10^{10} + 4.31 \times 10^{4} + 6.99 \times 10^{11} + 8.46 \times 10^{10}$

= 8.60×10^{11} kWh

Where:

2018 volume Very Large Vessel Cargo transport	= 6.99×10^{11} kWh
2018 volume Large Vessel Cargo transport	= 7.63×10^{10} kWh
2018 volume Medium Vessel various transport	= 4.31×10^{4} kWh
2018 volume Small Vessel various transport	= 8.46×10^{10} kWh

Assuming a 10 % loss in power between the power station and the point of application, of extra power will need to be supplied, would be:

9.459×10^{11} kWh or 945.9 TWh

22. Estimate the number and size of batteries needed to power an EV maritime fleet

The number and size of batteries needed to transform the maritime shipping fleet to fully electric EV and phase out Internal Combustion Engine systems is estimated. How many batteries and how large in mass are they? Shown in Tables 17.23 to 17.27. Oil and gas tankers are included in this calculation as both commodities will be needed for petrochemical manufacture of plastics and fertilizers (which has no viable substitution). So, oil and gas tankers will still be needed but in smaller numbers.

Table 17.23. Global number and size of EV batteries for Small Vessels (100-499 GT)

Ship Type	**Small Vessel (100 GT to 499 GT)**				
	Number of Vessels **(number)**	**Estimated Size of Battery in Vessel** **(kWh)**	**Estimated Summed for Vessel Class Battery Capacity to be Manufactured** **(kWh)**	**Mass of Battery to travel 222km** **(tonne)**	**Total mass of Batteries to Manufacture** **(tonne)**
General Cargo Ships	4 346	14 270	62 015 336	62	269 452
Specialized Cargo Ships	8	14 270	114 156	62	496
Container Ships	19	14 270	271 121	62	1 178
Ro-Ro Cargo Ships	30	14 270	428 086	62	1 860
Bulk Carriers	316	14 270	4 509 168	62	19 592
Oil and Chemcial Tankers	N/A				
Gas Tankers	N/A				
Other Tankers	396	14 270	5 650 730	62	24 552
Passenger Ships	4 094	14 270	58 419 417	62	253 828
Offshore Vessels	2 727	14 270	38 912 983	62	169 074
Service Ships	2 744	14 270	39 155 564	62	170 128
Tugs	17 848	14 270	254 682 403	62	1 106 576
Fishing Vessels	19 359	14 270	276 243 648	62	1 200 258
Total	**51 887**		**740 402 613**		**3,22E+06**

51 887 Vessels 740.4 GWh of Batteries 3.2 million tonnes of Li-Ion batteries

Table 17.24. Global number and size of EV batteries for Medium Vessels (500-24 999 GT)

Ship Type	**Medium Vessel (500 GT to 24 999 GT)**				
	Number of Vessels **(number)**	**Estimated Size of Battery in Vessel** **(kWh)**	**Estimated Summed for Vessel Class Battery Capacity to be Manufactured** **(kWh)**	**Mass of Battery to travel 1 778 km** **(tonne)**	**Total mass of Batteries to Manufacture** **(tonne)**
General Cargo Ships	11 659	358 397	4 178 553 658	1 558	18 164 722
Specialized Cargo Ships	227	358 397	81 356 178	1 558	353 666
Container Ships	2 213	358 397	793 133 137	1 558	3 447 854
Ro-Ro Cargo Ships	629	358 397	225 431 877	1 558	979 982
Bulk Carriers	3 788	358 397	1 357 608 822	1 558	5 901 704
Oil and Chemcial Tankers	N/A				
Gas Tankers	N/A				
Other Tankers	698	358 397	250 161 288	1 558	1 087 484
Passenger Ships	2 793	358 397	1 001 003 548	1 558	4 351 494
Offshore Vessels	5 297	358 397	1 898 430 288	1 558	8 252 726
Service Ships	2 750	358 397	985 592 466	1 558	4 284 500
Tugs	1 041	358 397	373 091 548	1 558	1 621 878
Fishing Vessels	5 244	358 397	1 879 435 233	1 558	8 170 152
Total	**36 339**		**13 023 798 041**		**5,66E+07**

36 339 Vessels 13.0 TWh of Batteries 56.6 million tonnes of Li-Ion batteries

Table 17.25. Global number and size of EV batteries for Large Vessels (25 000 – 59 999 GT)
(World Map Image by Clker-Free-Vector-Images from Pixabay)

Ship Type	Large Vessel (25 000 GT to 59 999 GT)				
	Number of Vessels (number)	Estimated Size of Battery in Vessel (kWh)	Estimated Summed for Vessel Class Battery Capacity to be Manufactured (kWh)	Mass of Battery to travel 8 890 km (tonne)	Total mass of Batteries to Manufacture (tonne)
General Cargo Ships	245	4,977,740	1,219,546,233	21,642	5,302,290
Specialized Cargo Ships	61	4,977,740	303,642,123	21,642	1,320,162
Container Ships	1,538	4,977,740	7,655,763,699	21,642	33,285,396
Ro-Ro Cargo Ships	565	4,977,740	2,812,422,945	21,642	12,227,730
Bulk Carriers	6,119	4,977,740	30,458,789,384	21,642	132,427,398
Oil and Chemcial Tankers	N/A				
Gas Tankers	N/A				
Other Tankers	12	4,977,740	59,732,877	21,642	259,704
Passenger Ships	277	4,977,740	1,378,833,904	21,642	5,994,834
Offshore Vessels	149	4,977,740	741,683,219	21,642	3,224,658
Service Ships	27	4,977,740	134,398,973	21,642	584,334
Tugs					
Fishing Vessels	3	4,977,740	14,933,219	21,642	64,926
Total	**8,996**		**44,779,746,575**		**1.95E+08**

8 996 Vessels 44.7 TWh of Batteries 194.7 million tonnes of Li-Ion batteries

Table 17.26. Global number and size of EV batteries for Very Large Vessels (>60 000 GT)
(World Map Image by Clker-Free-Vector-Images from Pixabay)

Ship Type	Very Large Vessel (>60 000 GT)				
	Number of Vessels (number)	Estimated Size of Battery in Vessel (kWh)	Estimated Summed for Vessel Class Battery Capacity to be Manufactured (kWh)	Mass of Battery to travel 8 890 km (tonne)	Total mass of Batteries to Manufacture (tonne)
General Cargo Ships					
Specialized Cargo Ships	5	11,614,726	58,073,630	50,499	252,495
Container Ships	1,441	11,614,726	16,736,820,205	50,499	72,769,059
Ro-Ro Cargo Ships	247	11,614,726	2,868,837,329	50,499	12,473,253
Bulk Carriers	1,706	11,614,726	19,814,722,603	50,499	86,151,294
Oil and Chemcial Tankers	N/A				
Gas Tankers	N/A				
Other Tankers					
Passenger Ships	184	11,614,726	2,137,109,589	50,499	9,291,816
Offshore Vessels	294	11,614,726	3,414,729,452	50,499	14,846,706
Service Ships	6	11,614,726	69,688,356	50,499	302,994
Tugs					
Fishing Vessels					
Total	**3,883**		**45,099,981,164**		**1.96E+08**

3 883 Vessels 45.1 TWh of Batteries 196.1 million tonnes of Li-Ion batteries

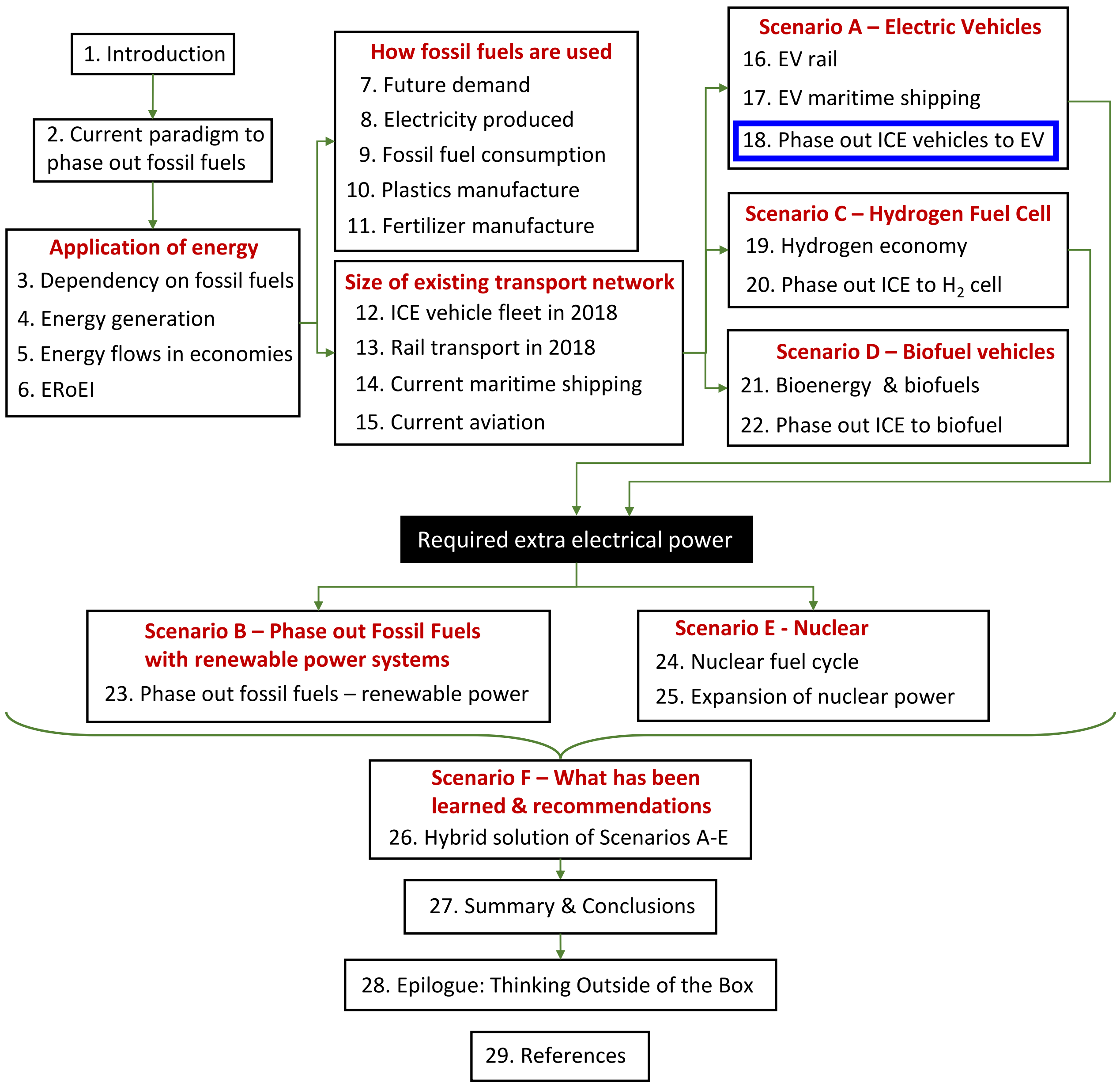
Table 17.27. Total mass of batteries to be manufactured for all ship classes – Global Fleet
(World Map Image by Clker-Free-Vector-Images from Pixabay)

Ship Type 	**Sum Total Number of Vessels** **(number)**	**Estimated Summed for Vessel Class Battery Capacity to be Manufactured** **(kWh)**	**Sum Total Mass of Batteries to Manufacture** **(tonne)**
General Cargo Ships	16,250	5,460,115,227	2.37E+07
Specialized Cargo Ships	301	443,186,088	1.93E+06
Container Ships	5,211	25,185,988,162	1.10E+08
Ro-Ro Cargo Ships	1,471	5,907,120,236	2.57E+07
Bulk Carriers	11,929	51,635,629,977	2.24E+08
Oil and Chemcial Tankers			
Gas Tankers			
Other Tankers	1,106	315,544,895	1.37E+06
Passenger Ships	7,348	4,575,366,458	1.99E+07
Offshore Vessels	8,467	6,093,755,941	2.65E+07
Service Ships	5,527	1,228,835,359	5.34E+06
Tugs	18,889	627,773,951	2.73E+06
Fishing Vessels	24,606	2,170,612,100	9.44E+06
Total	**101,105**	**103,643,928,393**	**4.51E+08**

101 105 Vessels | 103.6 TWh of Batteries | 450.5 million tonnes of Li-Ion batteries

18 SCENARIO A – PHASE OUT ICE TECHNOLOGY SYSTEMS AND COMPLETE SUBSTITUTION WITH EV TECHNOLOGY SYSTEMS

Currently thinking for a sustainable future often proposes a solution to phase out fossil fuel powered ICE vehicles and phase in Electric Vehicles (EV). The purpose of Section 18 was to assemble the data for Scenario A, where the size and scope of the proposed EV global transport fleet (cars, trucks, trains, maritime shipping) was mapped out and the extra power generation requirement for the electricity grid is estimated. The number of new power stations was also estimated.



Assessment of the Extra Capacity Required of Alternative Energy Electrical Power Systems to Completely Replace Fossil Fuels

To phase out the use of Internal Combustion Engine (ICE) technology systems, the following applications need a substitute technology system. This is how petroleum and oil derived products are used in the transport system.

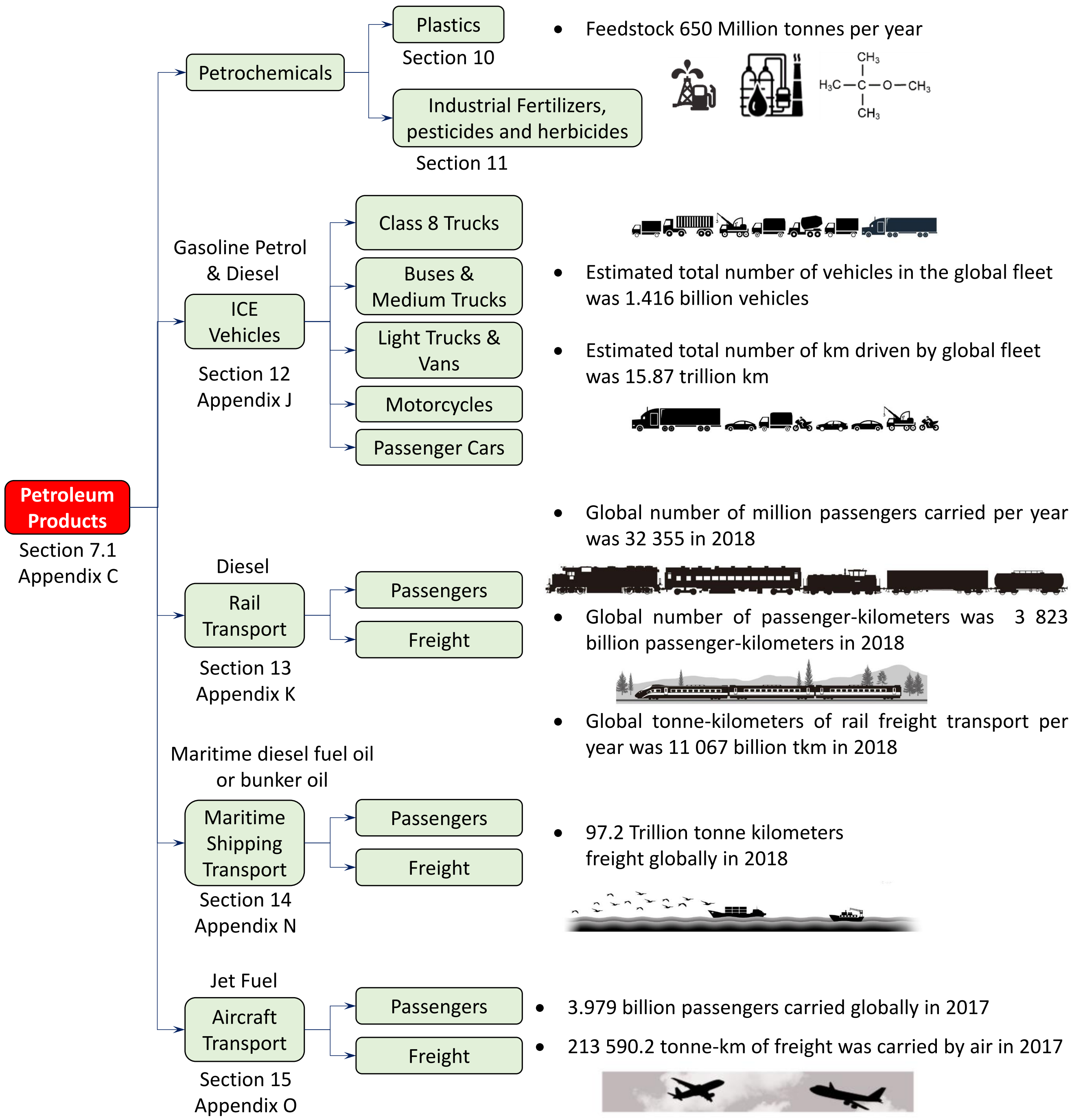


Figure 18.1. The different kinds of transport that use petroleum products
(Image: Simon Michaux) (World Map Image by Clker-Free-Vector-Images from Pixabay, royalty free clipart)

Table 18.1 (complied from Table 12.8) shows the annual distance travelled by each vehicle class, in each of the four regions used in Scenario A. This is what any system to replace ICE technology will be required to do if society is to engage in the same activities it did in the year 2018. The concept of a reduction in energy consumption is beyond the scope of this report.

Table 18.1. Estimated total annual distance travelled for each vehicle class in Europe, China, and Rest of World (Source: compiled from Table 12.8) (World Map Image by Clker-Free-Vector-Images from Pixabay)

Vehicle Class	Total km driven by class in 2018 U.S. Fleet (Ratio 1:1)  (km)	Total km driven by class in 2018 EU-28 Fleet (Ratio 1 : 0.21)  (km)	Total km driven by class in 2018 Chinese Fleet (Ratio 1 : 0.25)  (km)	Total km driven by class in 2018 Rest of World (RoW) Fleet (Ratio 1 : 0.62) (km)	Total km driven by class in 2018 GLOBAL Fleet  (km)
Class 8 Truck	4.79E+11	1.23E+11	2.93E+11	7.25E+11	1.62E+12
Transit Bus	1.38E+11	7.56E+09	1.50E+10	2.08E+11	8.03E+11
Refuse Truck	7.45E+10			1.13E+11	
Paratransit Shuttle	6.13E+10			9.27E+10	
Delivery Truck	2.00E+10			3.03E+10	
School Bus	1.72E+10			2.59E+10	
Light Truck/Van	1.59E+12	1.11E+11	8.82E+10	2.41E+12	7.89E+12
Light-Duty Vehicle	1.47E+12			2.22E+12	
Passenger Car	1.43E+12	8.56E+11	9.44E+11	2.17E+12	5.40E+12
Motorcycle	6.15E+10	3.62E+09	1.79E+09	9.30E+10	1.60E+11
Sum Total Nation (km)	5.34E+12	1.10E+12	1.34E+12	8.08E+12	1.59E+13
	5.34 trillion km	1.1 trillion km	1.34 trillion km	8.1 trillion km	15.87 trillion km

Section 18.1 to 18.3 will examine what is required for the complete substitution of the ICE vehicle fleet with EV vehicles, in context of required extra power supply capacity from the electrical power grid, to charge all the required batteries. This is estimated for the numbers and work done by the 2018 ICE vehicle fleet on a global scale, for the United States, for Europe (EU-28) and China. Sections 18.4 to 18.6 will examine what is required to phase out petroleum products used for the entire transport network. Scenario A only considers phasing out petroleum products, not gas and coal. The major task in phasing out oil and petroleum is the substation of the Internal Combustion Engine (ICE) technology with Electric Vehicle (EV) technology. Figure 18.2 shows the steps in calculation to achieve this outcome, as shown in Figure 18.20.

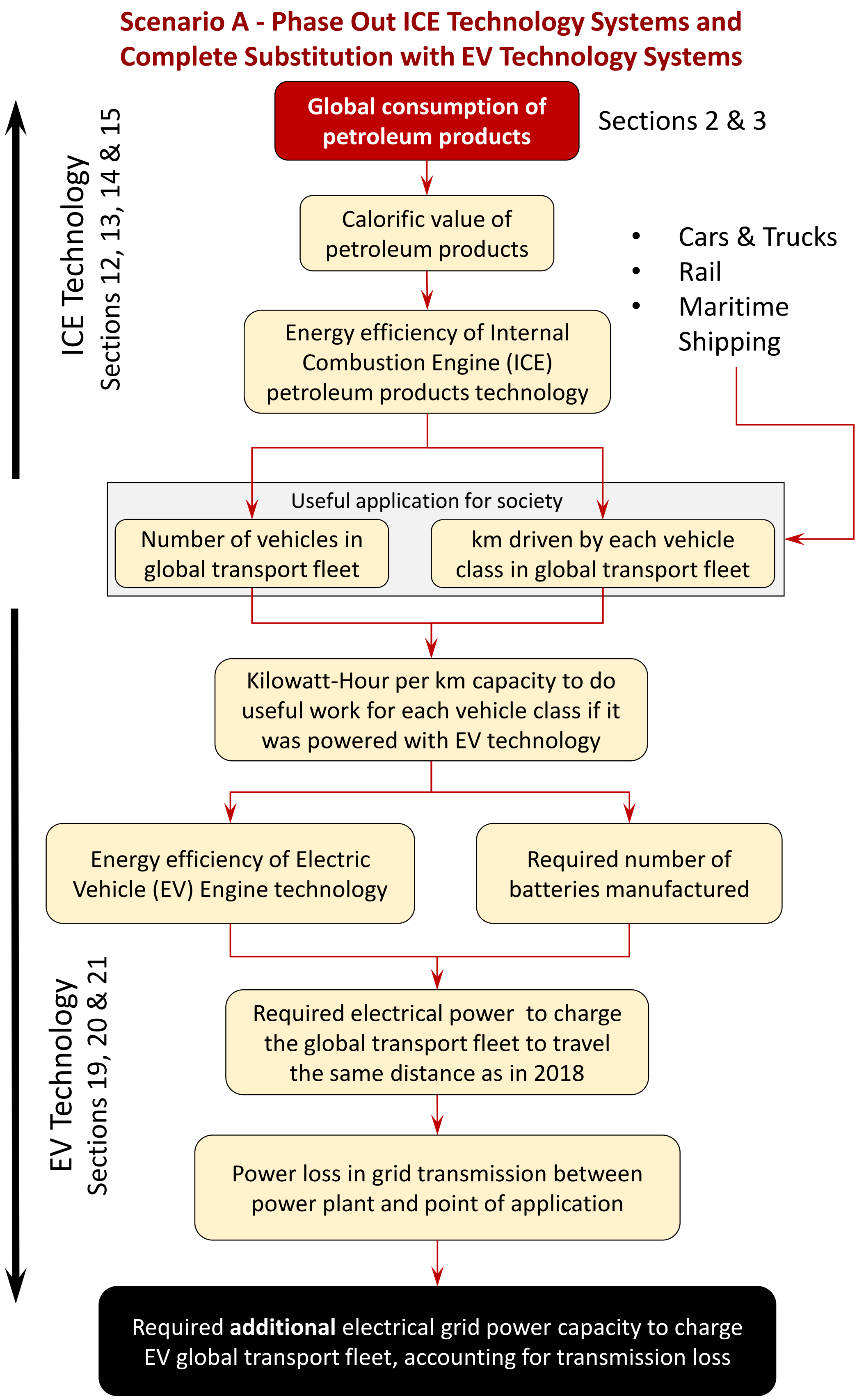


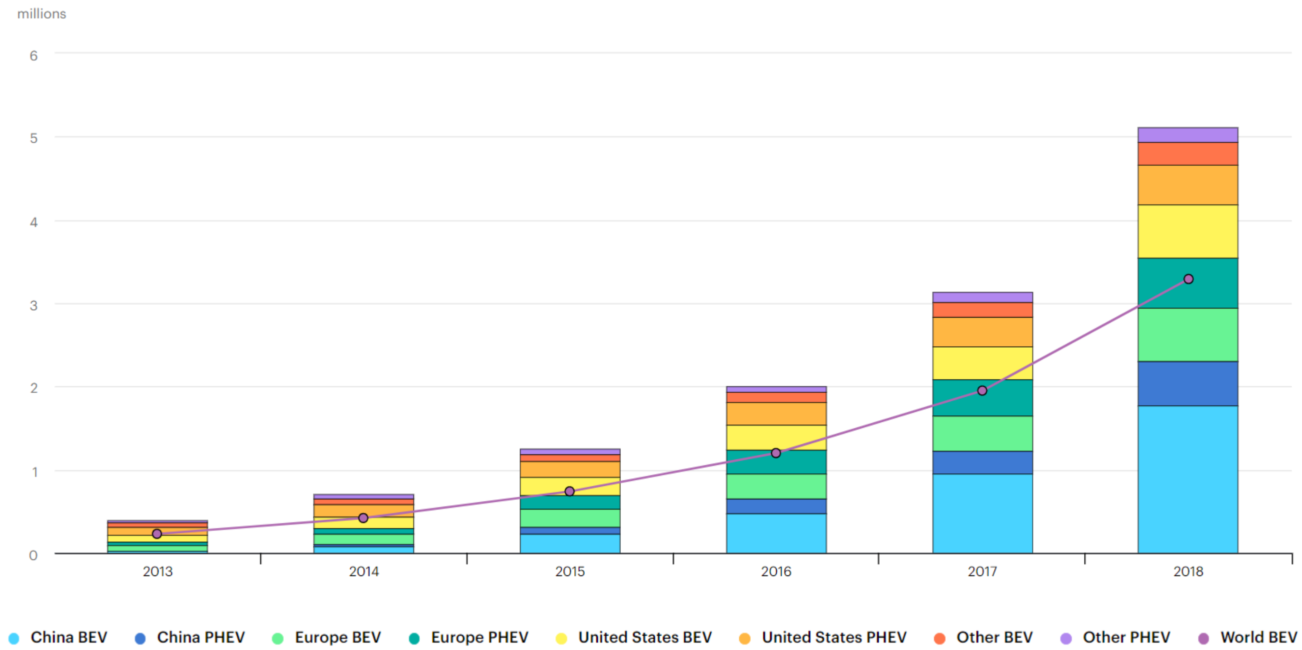
Figure 18.2. Required calculations for the steps to phase out petroleum products – Scenario A (Image: Simon Michaux)

18.1 Electric Vehicle specifications of vehicles for the transport fleet

There are three main types of electric vehicles (EVs), classed by the degree to which electricity is used as their energy source (Figure 18.4). BEVs, or battery electric vehicles, PHEVs, or plug-in hybrid electric vehicles, and HEVs, or hybrid electric vehicles. Only BEVs are capable of charging on a level 3, DC fast charge. All of these EV's will need to be charged from the electric power grid.

In EVs the power consumption at any given point is in kilowatts (kWs), but the consumption over a period of time is in kilowatt/hours, (kWhs). The reality is an EV will draw very variable amounts of power, and all the power peaks and troughs averaged out over a period of time gives the kWhs.

The concept of the electric vehicle was developed decades ago. Over the last decade, market vehicle share has increased with each passing year (Figure 18.3). This technology is perceived to be the substitution system to phase out the Internal Combustion Engine (ICE) technology system. Figure 18.3 shows the market share of electric vehicles between 2013 and 2018. The global EV car fleet in 2018 was 5.2 million vehicles (Global EV Outlook 2019, IEA 2019b). This represents 1.25% of the global fleet of passenger cars and 0.36% of the global fleet of all vehicle classes.



Notes: BEV = battery electric vehicle; PHEV = plug-in electric vehicle. Other includes Australia, Brazil, Chile, India, Japan, Korea, Malaysia, Mexico, New Zealand, South Africa and Thailand.

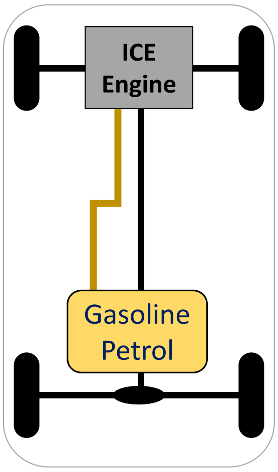
Electric vehicle (EV) stocks by country are calculated as the sum of EV sales starting from the earliest data available in our time series (in most cases after 2011), i.e. without considering scrappage rates at this early market stage and excluding second-hand imports, unless access to sources with direct EV stock numbers was possible.

Stock shares are calculated based on EV stock by country and, for total rolling passenger light-duty vehicle stocks per country, on estimates developed with the IEA Mobility Model. The latter are estimated based on new vehicle registration data and the use of scrappage functions that account for a lifetime range of 13-18 years. Lifetimes at the low end of the range are used for countries with higher income levels (and vice versa).

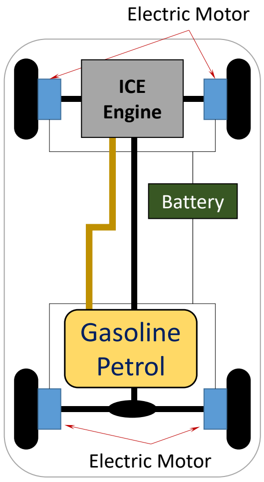
Europe includes Austria, Belgium, Bulgaria, Croatia, Cyprus[8], Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Liechtenstein, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey and United Kingdom. Other includes Australia, Brazil, Chile, India, Japan, Korea, Malaysia, Mexico, New Zealand, South Africa and Thailand.

Sources: IEA analysis based on country submissions, complemented by ACEA (2019); EAFO (2019); EV Volumes (2019); Marklines (2019); OICA (2019); CAAM (2019).

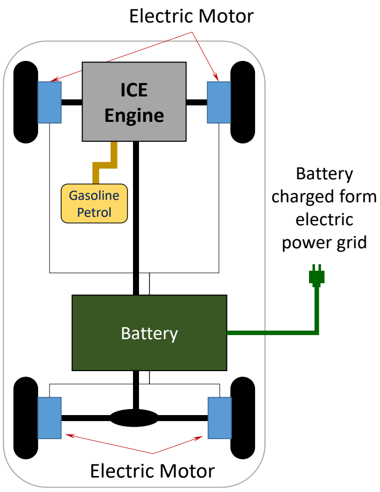
Figure 18.3. Passenger electric car stock in main markets and the top-ten EVI countries
(Source: Global EV Outlook 2019, IEA 2019b)



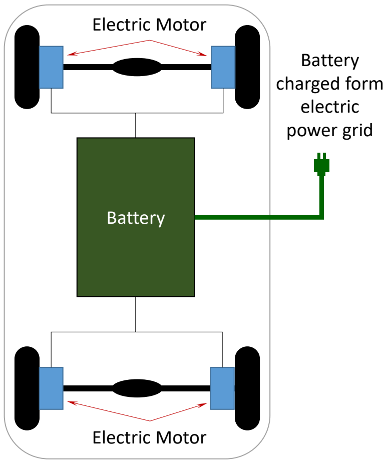
ICE Internal Combustion Vehicle
Powered by a gasoline or diesel internal combustion engine. Uses fuel derived from oil.



HEV Hybrid Electric Vehicle
Powered by both gasoline/diesel and an electric motor. The battery is recharged by the ICE engine when it is running. The vehicle alternates between ICE and electric motor to optimize efficiency and performance.



PHEV Plug-in Hybrid Electric Vehicle
Versatile hybrids in which the electric battery can be charged both by the electric grid and/or the ICE engine. Like HEV's, PHEV have greater range than BEV.



BEV Battery Electric Vehicle
Also known as 'plug in' electric vehicles. They are propelled by an electric motor that is powered from a battery, which is charged of the electric grid. BEV are a short range vehicle that requires infrastructure to be practical.

Figure 18.4. The different kinds of Electric Vehicles
(Image: Simon Michaux)

The following tables provides a list of current electric vehicles (EV), with battery size, efficiency, average range, and a range of ranges in the city, and out on the open freeway. The range is between driving in sub-zero temperatures with heating on and driving in the warm with no air conditioning. All of the vehicles listed can achieve longer ranges on road trips, if driven in the right way. Table 18.2 shows that on average, a passenger car (car) consumes 0.19 kWh/km, or for every kilometer traveled, the vehicle needs 0.19 kWh, where current lithium ion batteries have an energy density of approximately 230 Wh/kg (IEA 2019b).

Table 18.2. Electric Vehicle Passenger car range and distance per kWh capacity (Source: data taken from United States Environmental Protection Agency, Electric Vehicle Database https://ev-database.org/car/1125/Kia-e-Niro-64-kWh, and Cleantechnica https://cleantechnica.com updated October 17th, 2018)

Manufacturer	Model	Battery Capacity (kWh)	Distance per kWh (km/kWh)	Range Average (km)	Range in City (km)		Range in Freeway (km)	
					Min Distance (km)	Max Distance (km)	Min Distance (km)	Max Distance (km)
Smart	EQ for-four	16.7	0.13	88.5	96.5	144.8	64.4	80.5
Mitsubishi	i-MiEV	15	0.12	88.5	88.5	136.8	56.3	88.5
Volkswagen	e-up!	18.7	0.13	104.6	104.6	160.9	72.4	88.5
BMW	i3	27.2	0.17	168.9	168.9	257.4	120.7	152.9
KIA	Soul EV	30	0.13	177.0	177.0	265.5	120.7	152.9
Hyundai	Ioniq	28	0.10	201.1	185.0	289.6	136.8	177.0
Volkswagen	e-Golf	32	0.14	201.1	193.1	297.7	136.8	185.0
Renault	Zoe	37	0.16	233.3	225.3	345.9	160.9	209.2
KIA	Niro EV Mid-Range	39.2	0.17	233.3	241.4	362.0	168.9	217.2
Nissan	Leaf 2018	38	0.17	241.4	233.3	362.0	168.9	217.2
Hyundai	Kona Electric	40	0.17	249.4	241.4	378.1	168.9	225.3
Tesla	Model 3 (Standard)	52	0.15	329.8	345.9	571.2	257.4	345.9
Tesla	Model X 75D	72.5	0.18	329.8	337.9	490.7	241.4	289.6
Mercedes	EQC (2019)	70	0.21	345.9	370.1	539.0	265.5	337.9
Chevrolet	Bolt *	60	0.47	378.1	-	410.3	-	345.9
Opel	Ampera*	60	0.47	378.1	-	410.3	-	345.9
Hyundai	Kona Electric (64 kWh)	64	0.19	386.2	386.2	595.3	281.6	362.0
Tesla	Model S 75D	72.5	0.22	386.2	378.1	555.1	281.6	362.0
Jaguar	i-Pace	85	0.25	402.3	402.3	579.2	281.6	362.0
Tesla	Model 3 (Long Range)	78	0.17	490.7	466.6	708.0	345.9	458.6
Average		46.79	0.19	270.71				

* Opel Ampera is the EU version of the Chevy Bolt, and figures are taken from the EPA site, where a range of ranges is not available, just city and highway ranges.

The Mitsubishi i-MiEV is not currently available, but is sold as Citroen C-Zero and Peugeot Ion.

All figures for range are rounded to 0 or 5.

Table 18.3 shows the specifications of electric commercial vans. These vehicles are in production and specifications are readily available. An average energy consumption for a Light Truck/Van vehicle to be used is 0.23 km/kWh, where current lithium ion batteries have an energy density of approximately 230 Wh/kg (IEA 2019b).

Table 18.3. Electric Vehicle commercial van (Light Truck/Van) range and distance per kWh capacity (Source: https://evcompare.io/search/)

Manufacturer	Model	Range in km (NEDC) (km)	Battery Size (kWh)	Efficiency Distance per kWh (km/kWh)	Engine Torque (Nm)	Engine Horsepower (hp)
Citroen	Berlingo Electric	170	22,5			
Iveco	Daily Electric	280	91	0,33	300	107
Nissan	e-NV200	200	40	0,2	254	107
Peugeot	Partner electric	170	22,5			
Renault	Kangoo Z.E.	270	33	0,28	225	59
Renault	Master Z.E.	120	33	0,12	225	76
SAIC Maxus	EV-80	230	53	0,23	320	136
		Average (Light Truck/Van)	42,14	0,23		

Table 18.4 shows the estimated specifications of EV pick-up trucks like the Tesla Cybertruck. None of these vehicles have been released yet and specifications have had to be estimated from manufacture press releases. An average energy consumption for a Light-Duty vehicle to be used is 0.31 km/kWh.

Table 18.4. Electric Vehicle Light-Duty Vehicle (Pick-up truck) range and distance per kWh capacity

Manufacturer	Model	Date of Release	Possible Battery Capacity (kWh)	Estimated Range (miles)	Estimated Range (km)	Power Horsepower (hp)	Estimated Distance per kWh (km/kWh)	Source (Manufacturer website)
Chevrolet Silverado / GMC Hummer Electrics	Hummer EV SUT	2021	200	400	643,6	1000	0,31	https://www.gmc.com/electric-truck/hummer-ev
Ford	Electric Ford F-150	2022		300	482,7			https://insideevs.com/reviews/377328/ford-f150-electric-truck-details/
Tesla	Cybertruck			500	804,5			https://www.tesla.com/en_gb/cybertruck
Rivian	R1T	2021	105	230	370,07		0,28	https://rivian.com/r1t
			135	300	482,7		0,28	
			180	400	643,6		0,28	
Lordstown	Endurance	2021				600	0,25	https://lordstownmotors.com/pages/endurance
Bollinger	B2	2020	142	200	321,8	614	0,44	https://bollingermotors.com/bollinger-b2/
Nikola	Badger	2022	160	300	482,7	455	0,33	https://nikolamotor.com/badger
Average (Light-Duty Vehicle	- Pick up truck)		153,67				0,31	

Table 18.5 shows the specifications of EV buses to transport lots of people. Only two examples are shown here (7900 Volvo and BYD K9), but these two models represent a large proportion of the current EV bus fleet. Specifications are from manufacturer's press releases. An average energy consumption for a Transit Bus, Paratransit Shuttle, or School Bus EV vehicle to be used is 1.32 km/kWh, where current lithium ion batteries have an energy density of approximately 230 Wh/kg (IEA 2019b).

Table 18.5. Electric Vehicle Bus (Transit Bus, Paratransit Shuttle, School Bus) range and distance per kWh capacity (Source: Volvo 7900 Electric specifications, www.volvobuses.co.uk and BYD 2020, www.byd.com)

Manufacturer	Model	Range in km (NEDC) (km)	Battery Size (kWh)	Efficiency Distance per kWh (km/kWh)	Engine Torque (Nm)	Engine Horsepower (hp)
Volvo	7900 Electric	200	150 200 250	1,25	400	160
BYD Auto	BYD K9	250	310	0.9-1.8	700 1100 3000	245 410 490
Average (Transit Bus, Paratransit Shuttle, School Bus)			227,5	1,32		

Long haul trucks (HCV) have a capacity of 1.44 kWh/km, (noting that this from the less aerodynamic heavy duty truck travelling at 90 km/h) (Earl *et al* 2018). Tesla manufacturers are releasing the Tesla Semi HCV class 8 long haul truck, which is quoted at having a capacity of 1.24 kWh/km (2.0kWh/mile) (Source: Tesla Semi PR release: https://www.tesla.com/semi), and Sripad & Viswanathan 2017). A more recent study reports an average energy consumption for a Long Haul Class 8 Truck EV vehicle to be used is 1.46 km/kWh (Liimatainen *et al* 2019).

Table 18.6 shows the estimated specifications of electric trucks of various classes. An average energy consumption for a Refuse Truck EV vehicle to be used is 1.01 km/kWh. An average energy consumption for a Delivery Truck EV vehicle to be used is 0.82 km/kWh, where current lithium ion batteries have an energy density of approximately 230 Wh/kg (IEA 2019b).

Table 18.6. Electric Vehicle HCV Trucks (Refuse Truck, Medium Duty Delivery Truck, Large Duty Rigid Delivery Truck, Laong Haul Semi-Trailer Class 8) range and distance per kWh capacity (Source: Liimatainen et al 2019)

Manufacturer	Commercial Name	Type	Maximum Weight (tonnes)	Battery Capacity (kWh)	Range (km)	Energy Consumption (kWh/km)
Mitsubishi	eCanter	medium duty	7,5	82,8	120	0,69
BYD	T7	medium duty	11	175	200	0,88
Freightliner	eM2 106	medium duty	12	325	370	0,88
Volvo	FL Electric	rigid	16	100-300	100-300	1
Renault	D Z.E.	rigid	16	200-300	300	1
eMoss	EMS18	rigid	18	100-250	100-250	1
Mercedes-Benz		rigid	26	212	200	1,06
Renault	D WIDE Z.E.	rigid	26	200	200	1
Tesla	Semi	semitrailer	36		480-800	1,25
BYD	T9	semitrailer	36	350	200	1,75
Freightliner	eCascadia	semitrailer	40	550	400	1,38
		Average Medium Duty (Delivery Truck)		194,3		0,82
	Average Rigid (Refuse Truck, Large Rigid Delivery Truck)			206,0		1,01
		Average Semi Trailer (Class 8 Truck)		450,0		1,46

18.2 Power capacity required accounting for EV efficiency drivetrain loss

Tables 18.2-18.6 could be merged with Table 12.8 to estimate the total electrical power required to charge a global EV fleet. This does not account for the efficiency loss in power due between the battery (once fully charged) and the EV physically moving.

To determine the needed power draw for an EV to travel a given distance, the efficiency of the electric system to translate power stored in the battery to physically moving the vehicle (Ehsani *et al* 2018). The overall energy **efficiency of an electric vehicle is estimated as 73%**, comparing energy stored in the battery and the wheels turning (Malins 2017). This is far more efficient than any of the ICE technologies. The sources of lost energy in the system is listed below:

- Energy storage and distribution in battery: Approximately 5% energy losses
- Inversion AC/DC: Approximately 5% energy losses
- Battery Charge efficiency: Approximately 5% energy losses
- Inversion DC/AC: Approximately 5% energy losses
- Engine efficiency: Approximately 10% energy losses

This depends on a number of situational based contributing factors. The battery technology is evolving quickly, and the following is often dependent on age. The unadjusted (for transmission loss) direct electrical power for global vehicle transport fleet to travel the same distance as in 2018, 6 280 TWh is then adjusted for an EV 73% system efficiency to become 8 602.7 TWh (8.6 x 10^{12} kWh) (shown in Tables 18.7 to 18.16).

18.3 Power capacity required accounting for transmission loss between power station and application

So, 8 602.7 terawatt hours is required to be delivered to the point of charging in many places in the electric power grid. Electricity has to be transmitted from large power plants to the consumers via extensive networks. The transmission over long distances creates power losses. The major part of the energy losses comes from Joule effect in transformers and power lines. The energy is lost as heat in the conductors, which is included in the energy efficiency of the power generation source (Table 3.4, Section 3). Once the power has been generated, it has to be transmitted through the distribution network.

Considering the main parts of a typical Transmission & Distribution network, here are the average values of power losses at the different steps:

- 1 - 2% – Step-up transformer from generator to Transmission line
- 2 - 4% – Loss in energy due to resistance of transmission wires and electrical equipment
- 1 - 2% – Step-down transformer from Transmission line to Distribution network
- 4 - 6% – Distribution network transformers and cables

In addition, a further 7-10% electrical power can be lost, which could be caused by congestion, which occurs when the normal flow of electricity is disrupted by device constraints or safety regulations (Singh 2014 and Schneider Electric 2016). The true impact of this would vary considerable between different electrical grids around the world, where collecting this information was beyond the scope of this study. As such this was not included in calculations.

The overall losses between the power plant and consumers is then in the range between 8 and 15% (IEC 2007). For the purposes of this report, an **average value of 10% in power loss** during transmission will be used. This conservative value could account for future efficiency gains in some instances.

So, 8 602.7 TWh is adjusted to become 9 46.6 TWh of power needed to be supply at the point of electricity generated (power plant) to charge the needed number of self-propelled vehicles EV batteries. To add the required expansion in rail and in maritime shipping to self-propelled vehicles, a total of 10 801.8TWh of electrical power needs to be generated in the global electrical power grid.

18.4 Estimated energy consumption of a complete EV transport fleet in 2018

To estimate the electric power that would be consumed if the transport fleet was electric, the following information was assembled together (for each target economy):

- The number of vehicles in system in the year 2018 (Tables 12.2 to 12.7, Section12)
- Different vehicle classes (cars, trucks, etc.) and their proportions in the whole fleet (Table 12.7)
- The distance each vehicle class traveled in the year 2018 - km (Table 12.7, Section 12)
- The electrical power consumption per unit distance for each vehicle class – kWh/km (Tables 18.2 - 18.7)

Table 18.7 & 18.8 shows a compilation of these data structures for the **United States** transport fleet.

Table 18.9 & 18.10 shows a compilation of these data structures for the **European** transport fleet.

Table 18.11 & 18.12 shows a compilation of these data structures for the **Chinese** transport fleet.

Table 18.13 & 18.14 shows a compilation of these data structures for the **Rest of World (RoW)** transport fleet.

Table 18.15 & 18.16 shows a compilation of these data structures for the **Global** transport fleet.

Table 18.7. Estimated kilowatt hours needed to charge entire United States transport fleet if they were EV in 2018. This is the merging of Table 12.2 and Tables 18.2 to 18.6

Vehicle Class	Proportion of Total Fleet Power Conumption by Class (%)	Number of Self Propelled Vehicles in 2018 U.S. Fleet (number)	Total km driven by class in 2018 U.S. Fleet (km)	KiloWatt-Hour distance if all vehicles were EV (kWh/km)	KiloWatt-hours needed to power U.S. transport fleet if all vehicles were EV (assuming no efficiency loss) (kWh)	KiloWatt-hours needed in EV Battery capacity, assuming a 73% efficiency for EV systems (kWh)	Electrical power to be generated, assuming a 10% loss in transmission between power station and charging point (kWh)
Class 8 Truck	32,4 %	4 694 851	4,79E+11	1,46	7,00E+11	9,58E+11	1,05E+12
Transit Bus	8,4 %	2 517 520	1,38E+11	1,32	1,82E+11	2,49E+11	2,74E+11
Refuse Truck	3,5 %	1 850 465	7,45E+10	1,01	7,52E+10	1,03E+11	1,13E+11
Paratransit Shuttle	2,9 %	1 678 668	6,13E+10	1,01	6,19E+10	8,48E+10	9,32E+10
Delivery Truck	0,8 %	959 133	2,00E+10	0,82	1,64E+10	2,25E+10	2,47E+10
School Bus	1,0 %	888 223	1,72E+10	1,32	2,26E+10	3,10E+10	3,41E+10
Light Truck/Van	17,0 %	82 569 993	1,59E+12	0,23	3,66E+11	5,02E+11	5,52E+11
Light-Duty Vehicle	21,1 %	79 237 170	1,47E+12	0,31	4,55E+11	6,23E+11	6,85E+11
Passenger Car	12,6 %	78 293 789	1,43E+12	0,19	2,72E+11	3,73E+11	4,10E+11
Motorcycle	0,3 %	16 223 409	6,15E+10	0,11	6,77E+09	9,27E+09	1,02E+10
Total	100,0 %	268 913 221	5,34,E+12				3,25,E+12
		269 million vehicles	5.3 trillion km travelled in 2018			Extra power required to be generated by power stations	**3 254 TWh**

Table 18.8 Estimated number and mass of Li-Ion batteries for all self-propelled vehicles in the United States fleet

Vehicle Class	Number of Self Propelled Vehicles in 2018 U.S. Fleet (number)	Battery Capacity (kWh)	Estimated Range (km)	Estimated Summed for Vehicle Class Battery Capacity to be Manufactured (kWh)	Energy Consumption of EV System (kWh/km)	Average Li-Ion Battery Mass @230Wh/kg in vehicle (kg)	Total Mass of Li-Ion batteries (tonne)
Class 8 Truck	4 694 851	450,0	367	2,11E+09	1,46	1 956,5	9 185 578
Transit Bus	2 517 520	227,5	226	5,73E+08	1,32	989,1	2 490 156
Refuse Truck	1 850 465	206,1	233	3,81E+08	1,01	896,1	1 658 177
Paratransit Shuttle	1 678 668	227,5	225	3,82E+08	1,01	989,1	1 660 421
Delivery Truck	959 133	206,1	233	1,98E+08	0,82	896,1	859 466
School Bus	888 223	227,5	225	2,02E+08	1,32	989,1	878 569
Light Truck/Van	82 569 993	42,1	205,8	3,48E+09	0,23	183,2	15 129 284
Light-Duty Vehicle	79 237 170	153,7	328,8	1,22E+10	0,31	668,1	52 939 617
Passenger Car	78 293 789	46,8	270,1	3,66E+09	0,19	203,5	15 931 084
Motorcycle	16 223 409	21,5	322	3,49E+08	0,08	80,0	1 297 873
Total	268 913 221			2,35E+10			1,02,E+08
	269 million vehicles			25.52 TWh of Batteries	Total Li-Ion battery mass 102 million tonnes		

Table 18.9. Estimated kilowatt hours needed to charge entire European Union transport fleet if they were EV in 2018. This is the merging of Table 12.3 and Tables 18.2 to 18.6

Vehicle Class	Proportion of Total Fleet Power Conumption by Class (%)	Number of Self Propelled Vehicles in 2018 EU-28 Fleet (number)	Total km driven by class in 2018 EU-28 Fleet (km)	KiloWatt-Hour distance if all vehicles were EV (kWh/km)	KiloWatt-hours needed to power EU-28 transport fleet if all vehicles were EV (assuming no efficiency loss) (kWh)	KiloWatt-hours needed in EV Battery capacity, assuming a 73% efficiency for EV systems (kWh)	Electrical power to be generated, assuming a 10% loss in transmission between power station and charging point (kWh)
Class 8 Truck	47.2 %	5,716,322	1.2E+11	1.46	1.8E+11	2.45E+11	2.70E+11
Bus	2.6 %	657,714	7.6E+09	1.32	1.0E+10	1.37E+10	1.50E+10
Light Truck/Van	6.7 %	27,413,946	1.1E+11	0.23	2.6E+10	3.50E+10	3.85E+10
Passenger Car	43.3 %	222,683,327	8.6E+11	0.19	1.6E+11	2.23E+11	2.48E+11
Motorcycle	0.1 %	4,548,655	3.6E+09	0.11	4.0E+08	5.46E+08	6.00E+08
Total	100.0 %	2.61E+08	1.10E+12				5.7141E+11
		261 million vehicles	Travelled 1.1 trillion km in 2018			Extra power required to be generated by power stations	**571.4 TWh**

Table 18.10. Estimated number and mass of Li-Ion batteries for all self-propelled vehicles in the European fleet

Vehicle Class	Number of Self Propelled Vehicles in 2018 EU-28 Fleet (number)	Battery Capacity (kWh)	Estimated Range (km)	Estimated Summed for Vehicle Class Battery Capacity to be Manufactured (kWh)	Energy Consumption of EV System (kWh/km)	Average Li-Ion Battery Mass @230Wh/kg in vehicle (kg)	Total Mass of Li-Ion batteries (tonne)
Class 8 Truck	5 716 322	450,0	367	2,57E+09	1,46	1 956,5	11 184 108
Bus	657 714	227,5	226	1,50E+08	1,32	989,1	650 565
Light Truck/Van	27 413 946	42,1	205,8	1,16E+09	0,23	183,2	5 023 052
Passenger Car	222 683 327	46,8	270,1	1,04E+10	0,19	203,5	45 311 216
Motorcycle	4 548 655	21,5	322	9,78E+07	0,08	80	363 892
Total	2,61E+08			1,44E+10			6,25,E+07
	261 million vehicles			14.4 TWh of Batteries		Total Li-Ion battery mass 62.5 million tonnes	

Table 18.11. Estimated kilowatt hours needed to charge entire Chinese transport fleet if they were EV in 2018. This is the merging of Table 12.4 and Tables 18.2 to 18.6

Vehicle Class	Proportion of Total Chinese Fleet Power Conumption by Class (%)	Number of Self Propelled Vehicles in 2018 Chinese Fleet (number)	Total km driven by class in 2018 Chinese Fleet (km)	KiloWatt-Hour distance if all vehicles were EV (kWh/km)	KiloWatt-hours needed to power Chinese transport fleet if all vehicles were EV (assuming no efficiency loss) (kWh)	KiloWatt-hours needed in EV Battery capacity, assuming a 73% efficiency for EV systems (kWh)	Electrical power to be generated, assuming a 10% loss in transmission between power station and charging point (kWh)
Class 8 Truck	66.1 %	7,095,300	2.9E+11	1.46	4.3E+11	5.87E+11	6.46E+11
Transit Bus + School Bus + Refuse Truck + Paratransit Shuttle + Delivery Truck	3.0 %	1,243,900	1.5E+10	1.32	2.0E+10	2.71E+10	2.98E+10
Light Truck/Van + Light-Duty Vehicle + Other Vehicle Type	3.1 %	18,419,000	8.8E+10	0.23	2.0E+10	2.78E+10	3.06E+10
Passenger Car	27.7 %	203,689,500	9.4E+11	0.19	1.8E+11	2.46E+11	2.70E+11
Motorcycle	0.03%	1,864,600	1.79E+09	0.11	2.0E+08	2.70E+08	2.97E+08
Total	100.0 %	232,312,300	1.34E+12				9.7656E+11
		232 million vehicles	Travelled 1.34 trillion km in 2018		Extra power required to be generated by power stations		**976.6 TWh**

Table 18.12. Estimated number and mass of Li-Ion batteries for all self-propelled vehicles in the Chinese fleet

Vehicle Class	Number of Self Propelled Vehicles in 2018 Chinese Fleet (number)	Battery Capacity (kWh)	Estimated Range (km)	Estimated Summed for Vehicle Class Battery Capacity to be Manufactured (kWh)	Energy Consumption of EV System (kWh/km)	Average Li-Ion Battery Mass @230Wh/kg in vehicle (kg)	Total Mass of Li-Ion batteries (tonne)
Class 8 Truck	7 095 300	450,0	367	3,19E+09	1,46	1 956,5	13 882 109
Transit Bus + School Bus + Refuse Truck + Paratransit Shuttle + Delivery Truck	1 243 900	206,1	226	2,56E+08	1,16	896,1	1 114 643
Light Truck/Van + Light-Duty Vehicle + Other Vehicle Type	18 419 000	42,1	205,8	7,76E+08	0,23	183,2	3 374 910
Passenger Car	203 689 500	46,8	270,1	9,53E+09	0,19	203,5	41 446 385
Motorcycle	1 864 600	21,5	322	4,01E+07	0,08	80,0	149 168
Total	232 312 300			1,38E+10			5,9967E+07
	232 million vehicles			13.8 TWh of Batteries	Total Li-Ion battery mass 60.0 million tonnes		

Table 18.13. Estimated kilowatt hours needed to charge the Rest of World (RoW) transport fleet if they were EV in 2018. This is the merging of Table 12.7 and Tables 18.2 to 18.6

Vehicle Class	Proportion of Total Fleet Power Conumption by Class (%)	Number of Self Propelled Vehicles in 2018 Rest of World (RoW) (number)	Total km driven by class in 2018 RoW Fleet (km)	KiloWatt-Hour distance if all vehicles were EV (kWh/km)	KiloWatt-hours needed to power RoW transport fleet if all vehicles were EV (assuming no efficiency loss) (kWh)	KiloWatt-hours needed in EV Battery capacity, assuming a 73% efficiency for EV systems (kWh)	Electrical power to be generated, assuming a 10% loss in transmission between power station and charging point (kWh)
Class 8 Truck	49.0 %	11,422,874	7.25E+11	1.46	1.06E+12	1.45E+12	1.59E+12
Transit Bus	12.7 %	6,125,289	2.08E+11	1.32	2.75E+11	3.77E+11	4.15E+11
Refuse Truck	5.3 %	4,502,300	1.13E+11	1.01	1.14E+11	1.56E+11	1.71E+11
Paratransit Shuttle	4.3 %	4,084,306	9.27E+10	1.01	9.36E+10	1.28E+11	1.41E+11
Delivery Truck	1.1 %	2,333,632	3.03E+10	0.82	2.48E+10	3.40E+10	3.74E+10
School Bus	1.6 %	2,161,104	2.59E+10	1.32	3.42E+10	4.69E+10	5.16E+10
Light Truck/Van	25.7 %	200,898,093	2.41E+12	0.23	5.54E+11	7.59E+11	8.35E+11
Light-Duty Vehicle	31.9 %	192,789,122	2.22E+12	0.31	6.88E+11	9.43E+11	1.04E+12
Passenger Car	19.1 %	190,493,814	2.17E+12	0.19	4.12E+11	5.64E+11	6.20E+11
Motorcycle	0.5 %	39,472,597	9.30E+10	0.11	1.02E+10	1.40E+10	1.54E+10
Total	151.3 %	654,283,130	8.08.E+12				4.92.E+12
		654 million vehicles	8.1 trillion km travelled in 2018		Extra power required to be generated by power stations		**4 918.7 TWh**

Table 18.14. Estimated number and mass of Li-Ion batteries for all self-propelled vehicles in the Rest of World (RoW) fleet

Vehicle Class	Number of Self Propelled Vehicles in 2018 Rest of World (RoW) (number)	Battery Capacity (kWh)	Estimated Range (km)	Estimated Summed for Vehicle Class Battery Capacity to be Manufactured (kWh)	Energy Consumption of EV System (kWh/km)	Average Li-Ion Battery Mass @230Wh/kg in vehicle (kg)	Total Mass of Li-Ion batteries (tonne)
Class 8 Truck	11,422,874	450.0	367	5.14E+09	1.46	1,956.5	22,349,102
Transit Bus	6,125,289	227.5	226	1.39E+09	1.32	989.1	6,058,709
Refuse Truck	4,502,300	206.1	233	9.28E+08	1.01	896.1	4,034,452
Paratransit Shuttle	4,084,306	227.5	225	9.29E+08	1.01	989.1	4,039,911
Delivery Truck	2,333,632	206.1	233	4.81E+08	0.82	896.1	2,091,137
School Bus	2,161,104	227.5	225	4.92E+08	1.32	989.1	2,137,614
Light Truck/Van	200,898,093	42.1	205.8	8.47E+09	0.23	183.2	36,810,520
Light-Duty Vehicle	192,789,122	153.7	328.8	2.96E+10	0.31	668.1	128,805,486
Passenger Car	190,493,814	46.8	270.1	8.92E+09	0.19	203.5	38,761,350
Motorcycle	39,472,597	21.5	322	8.49E+08	0.08	93.5	3,689,830
Total	654,283,130			5.72E+10			2.49E+08
	654 million vehicles			57.3 TWh of Batteries		Total Li-Ion battery mass 248.8 million tonnes	

Table 18.15. Estimated kilowatt hours needed to charge entire Global transport fleet if they were EV in 2018. This is the merging of Table 12.7 and Tables 18.1 to 18.5 (World Map Image by Clker-Free-Vector-Images from Pixabay)

Vehicle Class 	Proportion of Total Fleet Power Conumption by Class (%)	Number of Self Propelled Vehicles in 2018 Global Fleet (number)	Total km driven by class in 2018 Global Fleet (km)	KiloWatt-Hour distance if all vehicles were EV (kWh/km)	KiloWatt-hours needed to power global transport fleet if all vehicles were EV (assuming no efficiency loss) (kWh)	KiloWatt-hours needed in EV Battery capacity, assuming a 73% efficiency for EV systems (kWh)	Electrical power to be generated, assuming a 10% loss in transmission between power station and charging point (kWh)
Class 8 Truck	36.7 %	28,929,348	1.62E+12	1.46	2.37E+12	3.24E+12	3.56E+12
Transit Bus + Refuse Truck + Paratransit Shuttle + Delivery Truck + School Bus	16.4 %	29,002,253	8.03E+11	1.32	1.06E+12	1.45E+12	1.60E+12
Light Truck/Van + Light-Duty Vehicle	30.7 %	601,327,324	7.89E+12	0.25	1.98E+12	2.72E+12	2.99E+12
Passenger Car	15.9 %	695,160,429	5.40E+12	0.19	1.03E+12	1.41E+12	1.55E+12
Motorcycle	0.3 %	62,109,261	1.60E+11	0.11	1.76E+10	2.41E+10	2.65E+10
Total	100.0 %	1,416,528,615	1.59.E+13		6.45E+12		9.72E+12

1.416 billion vehicles 15.87 trillion km travelled in 2018

Extra power required to be generated by power stations **9 722.7 TWh**

Table 18.16. Estimated number and mass of Li-Ion batteries for all self-propelled vehicles in the global fleet (World Map Image by Clker-Free-Vector-Images from Pixabay)

Vehicle Class 	Number of Self Propelled Vehicles in 2018 Global Fleet (number)	Battery Capacity (kWh)	Estimated Range (km)	Estimated Summed for Vehicle Class Battery Capacity to be Manufactured (kWh)	Energy Consumption of EV System (kWh/km)	Average Li-Ion Battery Mass @230Wh/kg in vehicle (kg)	Total Mass of Li-Ion batteries (tonne)
Class 8 Truck	28 929 348	450,0	367	1,30E+10	1,46	1 956,5	56 600 898
Transit Bus + Refuse Truck + Paratransit Shuttle + Delivery Truck + School Bus	29 002 253	206,1	226	5,98E+09	1,16	896,1	25 988 541
Light Truck/Van + Light-Duty Vehicle	601 327 324	42,1	205,8	2,53E+10	0,23	183,2	110 181 094
Passenger Car	695 160 429	46,8	270,1	3,25E+10	0,19	203,5	141 450 035
Motorcycle	62 109 261	21,5	322	1,34E+09	0,08	80,0	4 968 741
Total	1 416 528 615			7,82E+10			3,39,E+08

1.416 billion vehicles 78.2 TWh of Batteries Total Li-Ion battery mass 339 million tonnes

18.5 Estimated volume of power required to phase out the ICE vehicle transport fleet and substitute with an entirely EV global transport system

The following is a summation of the energy consumption required to be delivered over the power grid for the various sub-sections of the global transport system.

18.5.1 Self-propelled vehicles (cars & trucks) EV energy consumption - global

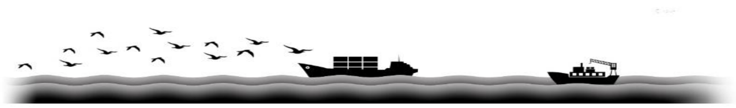
9 722.7 terawatt hours (**9.72×10^{12} kWh**) is required to be generated at the power station source, accounting for a 10% power loss in transmission.

18.5.2 Rail transport EV energy consumption - global

From Section 19, the estimated extra electrical power generation required to transition the whole global rail transport system to complete EV rail network was 2.06×10^{11} kWh (see Section 19). This was assumed to be direct charge from overhead power lines, not from batteries to power the trains. To account for a 10% power loss in transmission, **2.27×10^{11} kWh** would have to be generated at the power station source.

18.5.3 Maritime shipping EV energy consumption - global

From Section 20, the estimated extra electrical power required to charge the needed batteries for a fully EV global maritime shipping fleet was 8.60×10^{11} kWh (see Section 20). To account for a 10% power loss in transmission, **9.459×10^{11} kWh** would have to be generated at the power station source.



18.5.4 Aviation aircraft EV energy consumption - global

The EV solution for aviation was considered not viable due to the mass requirements of the batteries, which would be far too heavy to be practical.

18.5.5 Total petroleum System substitution EV energy consumption

Total extra electrical power that must be generated for the global power grid

$= 9.72 \times 10^{12}$ kWh + 2.27×10^{11} kWh + 9.46×10^{11} kWh

$= 1.09 \times 10^{13}$ kWh, or **10 895.7 TWh**

18.5.6 Energy storage to allow for intermittent power supply

The intermittent nature of renewable energy can be mitigated with measures like connecting lots of renewable power stations together and optimizing their power delivery through one system (Droste-Franke 2015). Power storage systems are mostly required to ensure consistent supply to the grid during the long periods of reduced sunlight hours and reduced wind where it is needed, for solar and

What is most flexible in application is a large battery storage power station. This is a type of energy storage power station that uses a group of batteries to store electrical energy. Yes, there are many other options. For simplicity, this report will just use Lithium Ion battery power storage stations. As of 2020, the maximum power of battery storage power plants is an order of magnitude less than pumped storage power plants, the most common form of grid energy storage.

Steinke *et al* 2012 put forward the recommendation for a fully renewable powered Europe to have 2 days of power storage, plus 10%. This study was to examine all power requirements for Europe to be 100% renewable. A practical approach for Scenario A could be an optimized and networked storage capacity of the scale of the kWh delivered to the power grid by **all wind and solar power sources only, over a 48 hour cycle**.

As of 2020, the largest battery storage power station in the world was the Australian Hornsdale Power Reserve, adjacent to the Hornsdale wind farm, built by Tesla (Parkinson 2017a). The plant is operated by Tesla and provides a total of 129 megawatt-hours (460 GJ) of storage capable of discharge at 100 MW into the power grid. Its 100 MW output capacity is contractually divided into two sections: 70 MW running for 10 minutes and 30 MW with a 3-hour capacity (Weatherill 2017). In construction of the EV batteries themselves, Samsung 21–70-size cells were used (Parkinson 2017b).

The system helps to prevent load-shedding blackouts (ElectraNet 2018) and provides stability to the grid (grid services) while other slower generators can be started in the event of sudden drops in wind or other network issues.

So, the problem issue to resolve is related to the variable nature of renewable energy. The solution is to have a series battery storage power station, much like the Australian Hornsdale storage power station (that can discharge 100 MWh into the grid). To address the question precisely of how many of these stations is needed is beyond the scope of this report. A crude estimate can be made though.

18.6 Estimation of New Power Generation Capacity and New Power Stations Required to Phase out Petroleum Fuels

The task at hand can now be quantified. To phase out petroleum products and substitute the use of oil in the transport sector with an completely Electric Vehicle fleet, an extra capacity of 1.09 x 10^{13} kWh (10 895.7 TWh) of electricity generation is required from the global power grid to charge the batteries of the 1.416 billion vehicles in the global fleet (Figure 18.12). As total global electricity generation in 2018 was 2.66 x 10^{13} kWh (Appendix B), this means that to make viable the EV revolution, an extra capacity of 66.7% the existing entire global capacity to generate electricity is required to be added.

The purpose of this report is to quantify the size of this important task. The task of making the EV battery revolution is much larger in scope than previously thought. To phase out just petroleum, all of the energy generations systems could be used.

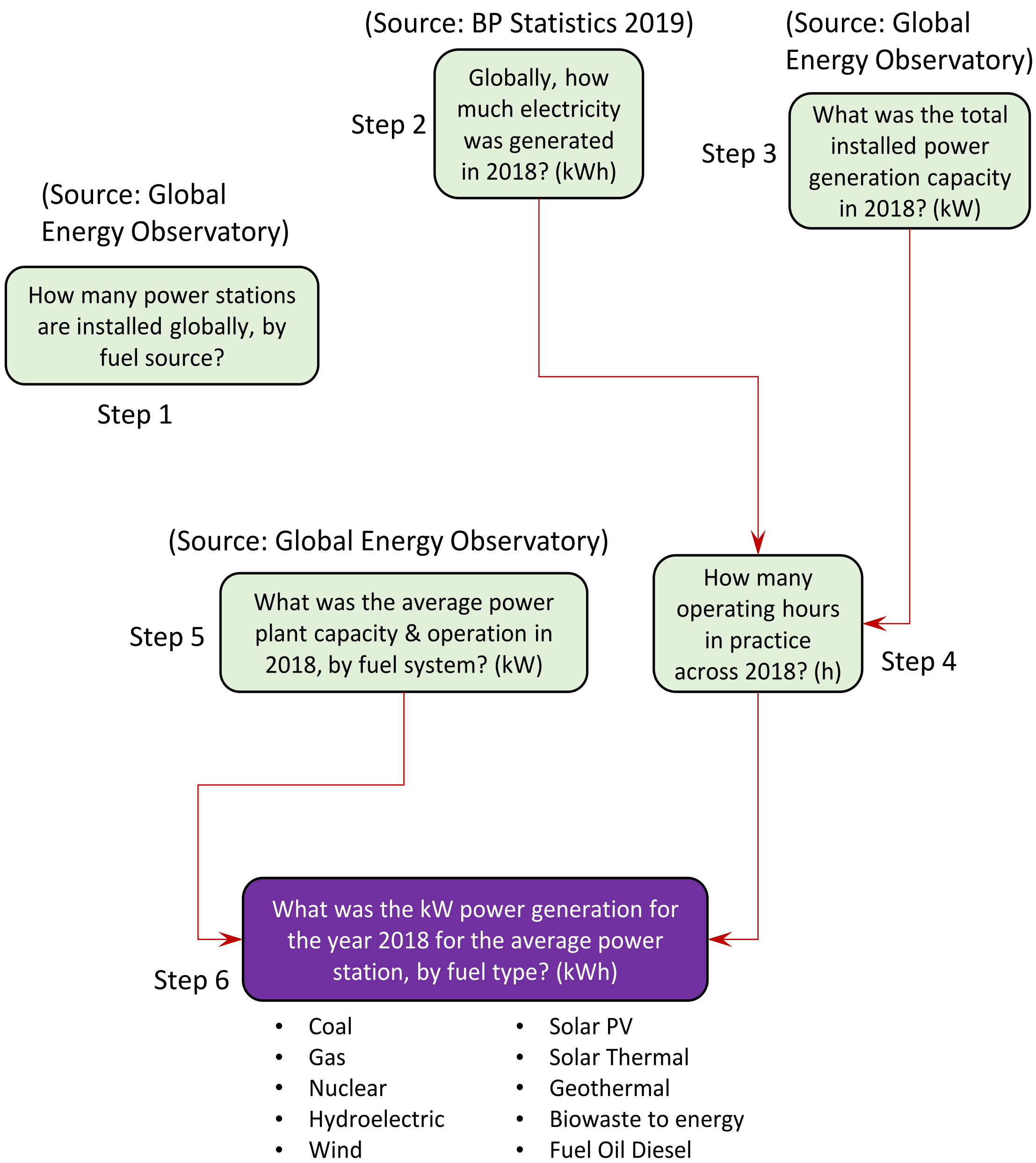


Figure 18.6. Calculation steps to determine the average power generation for each power station type in the year 2018

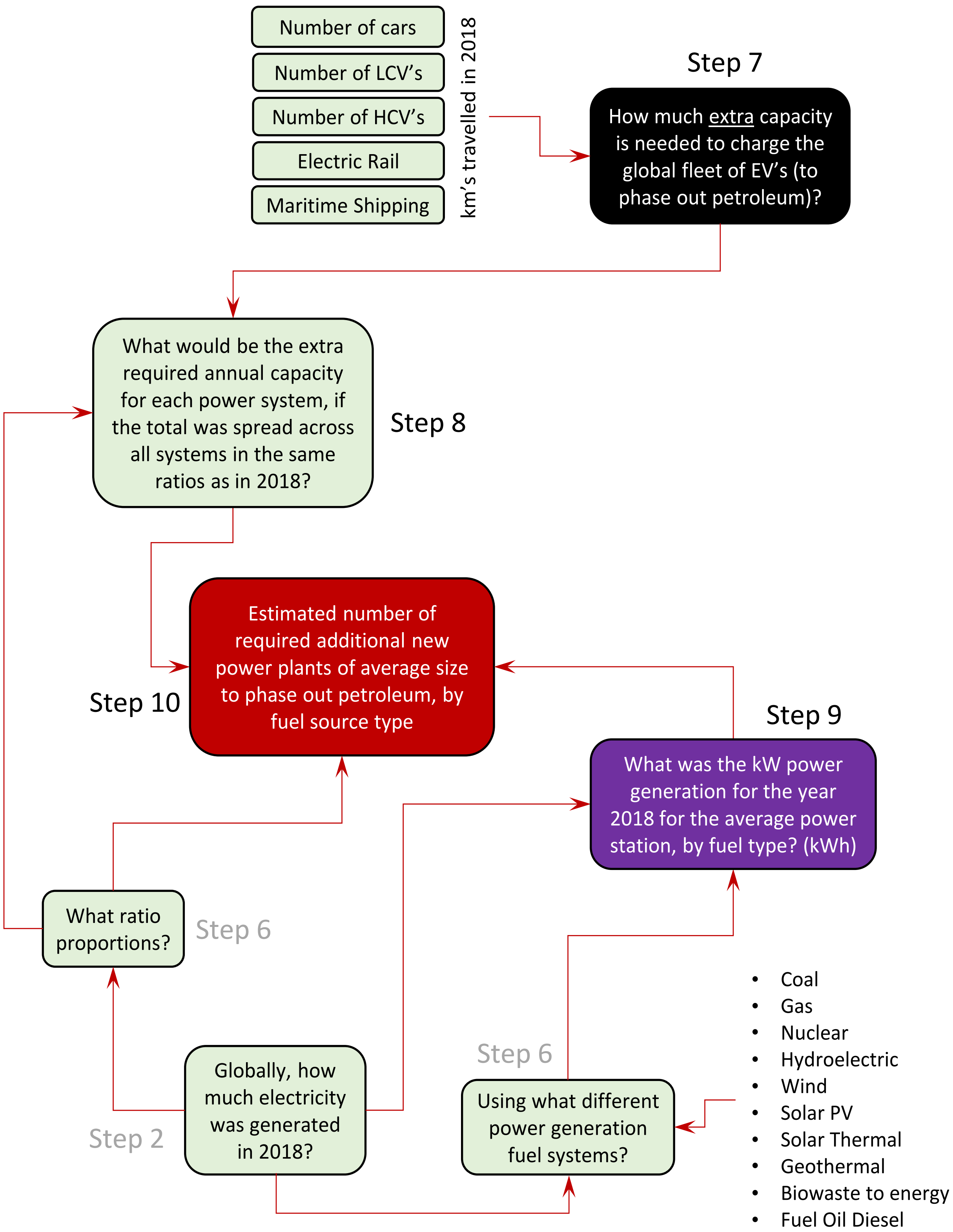


Figure 18.7. Calculation steps to determine the average power generation for each power station type, and the estimated number of new power stations needed to meet extra electric power generation

To phase out petroleum based ICE technology vehicles entirely and substitute with EV technology vehicles, extra capacity in the electric power grid would be required to charge the batteries of all the new EV vehicles. This is a separate problem to examine from installing the needed infrastructure, or the manufacture of 1.416 billion EV vehicles (and their batteries). This extra capacity would be 1.09 x 10^{13} kWh (10 895.7 TWh) to charge the EV fleet. This extra capacity would have to come from the following electric power generation sources:

- Coal
- Gas
- Nuclear
- Hydroelectric
- Wind
- Solar PV
- Solar Thermal
- Geothermal
- Bio-waste to energy

These are the systems that can be deployed at an industrial scale with current logistical technological capability. It is recognized that each of the non-fuel systems have their difficulties. For example, hydroelectricity, and geothermal can only be developed in some places, not all. Solar power can be more efficient in some parts of the world compared to others, due to the quantity of viable sun hours, and their intermittent availability. Wind power also has difficulties related to where it can be sited, and the intermittent nature of when it can generate electricity. Nuclear power can be deployed anywhere in the world in any weather conditions. The difficulties with nuclear is the management of waste fuel. If the nuclear grid was expanded to 1.5 times the existing global fleet, the proportionate volume of waste nuclear fuel would need to be managed.

For the purpose of this report, a more practical approach is taken on, where a crude estimated to show what would be necessary if the existing proportions of power generation were projected into the required new quantity.

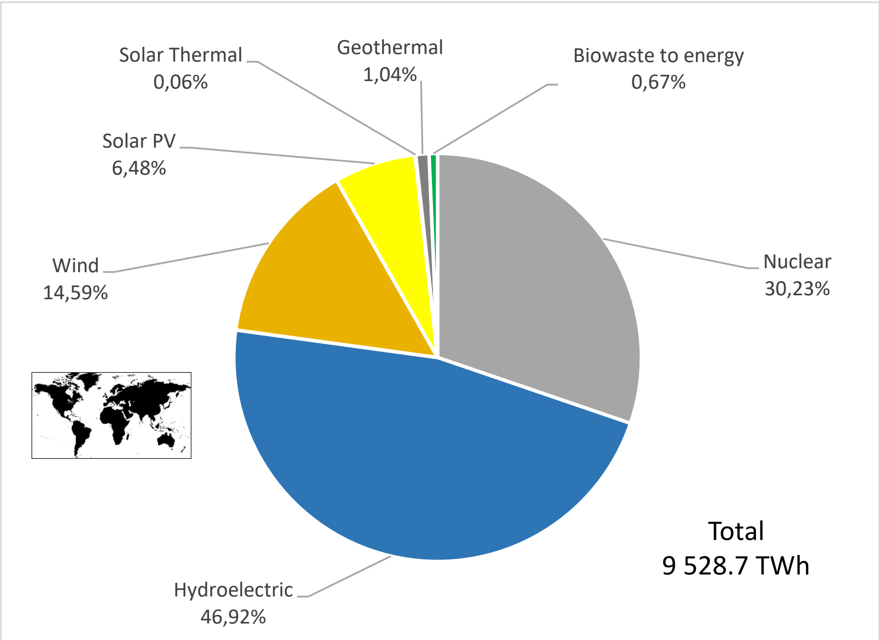
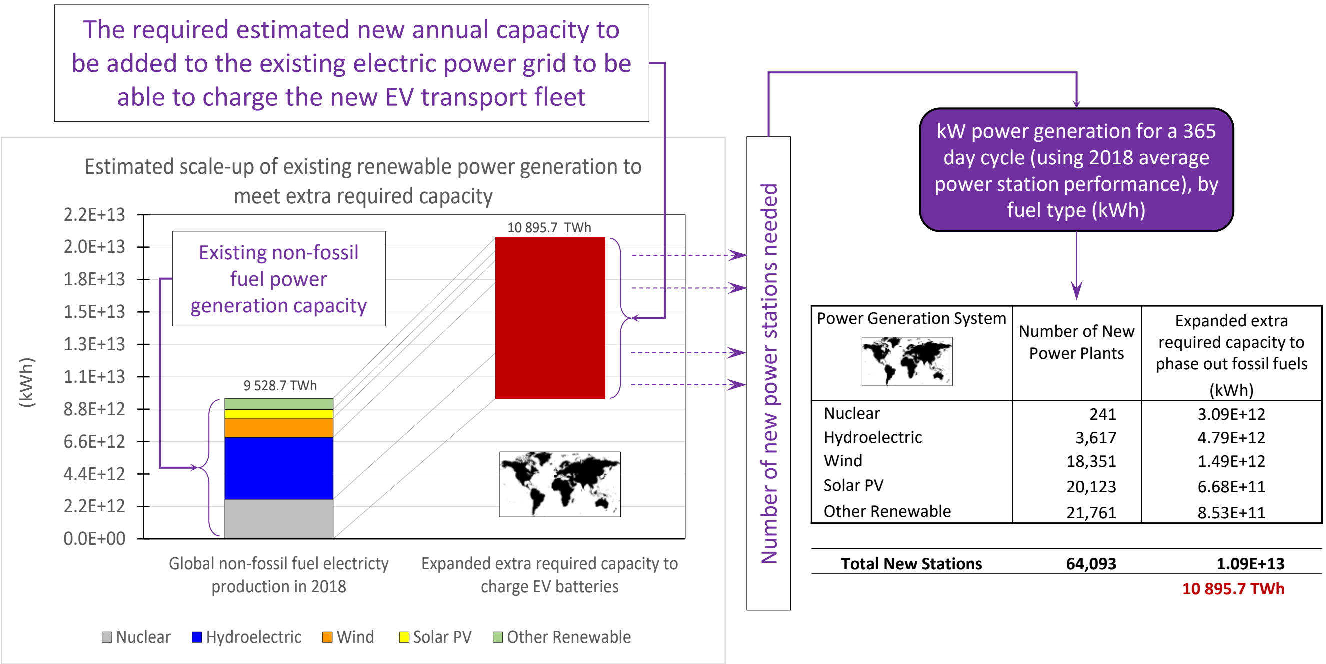


Figure 18.8. Global proportions of alternative and renewable power generation systems (non-fossil fuel) (Source: Table 8.4, Section 8, and BP Statistical Review of the World Energy 2019)

The proportional fraction of each non-fossil fuel generation system (for example nuclear was 30.2% of the 2018 non-fossil fuel electricity production in Figure 18.8) is then projected onto the total expansion of capacity. For example, to phase out only petroleum (oil) and charge an electric EV transport fleet, a total extra 1.09 x 10^{13} kWh is required. The nuclear proportion electric power generation of 30.2% was 2.70 x 10^{12} kWh in 2018. This was then scaled up to 30.2% of 1.09 x 10^{13} kWh, which would be 5.29 x 10^{12} kWh.

So if an extra 10 895.7 TWh of non-fossil fuel power generation was added to the global electrical power grid, in the same proportions as non-fossil fuel power generation systems in 2018, then 30.2% of that extra power capacity would come from 3.94 x 10^{12} kWh of nuclear power. This was done for each of the non-fossil fuel power generation systems, shown in Figure 18.9.



Power Generation System	Number of New Power Plants	Expanded extra required capacity to phase out fossil fuels (kWh)
Nuclear	241	3.09E+12
Hydroelectric	3,617	4.79E+12
Wind	18,351	1.49E+12
Solar PV	20,123	6.68E+11
Other Renewable	21,761	8.53E+11
Total New Stations	**64,093**	**1.09E+13**
		10 895.7 TWh

Figure 18.9. Scale up from existing capacity to estimate the proportions of non-fossil fuel power generation systems could contribute to the required new extra power generation capacity to charge an entirely EV transport fleet of the size of the GLOBAL 2018 transport fleet (World Map Image by Clker-Free-Vector-Images from Pixabay)

Tables 18.17 to 18.28 and Figures 18.10 to 18.18 show the 2018 production of electricity by non-fossil fuel sources, their current relative proportions, and a projection of the required expanded capacity at the same proportions. This extra capacity is what would be required to supply from the electricity power grid, if all self-propelled vehicle fleet (cars & trucks) were EV, the rail transport system was entirely EV, and the maritime shipping fleet was entirely EV. This is done for the global transport system, the United States transport system, the European transport system, and the Chinese transport system.

18.6.1 U.S. scope phase out of petroleum based ICE vehicles and substitution with EV vehicles

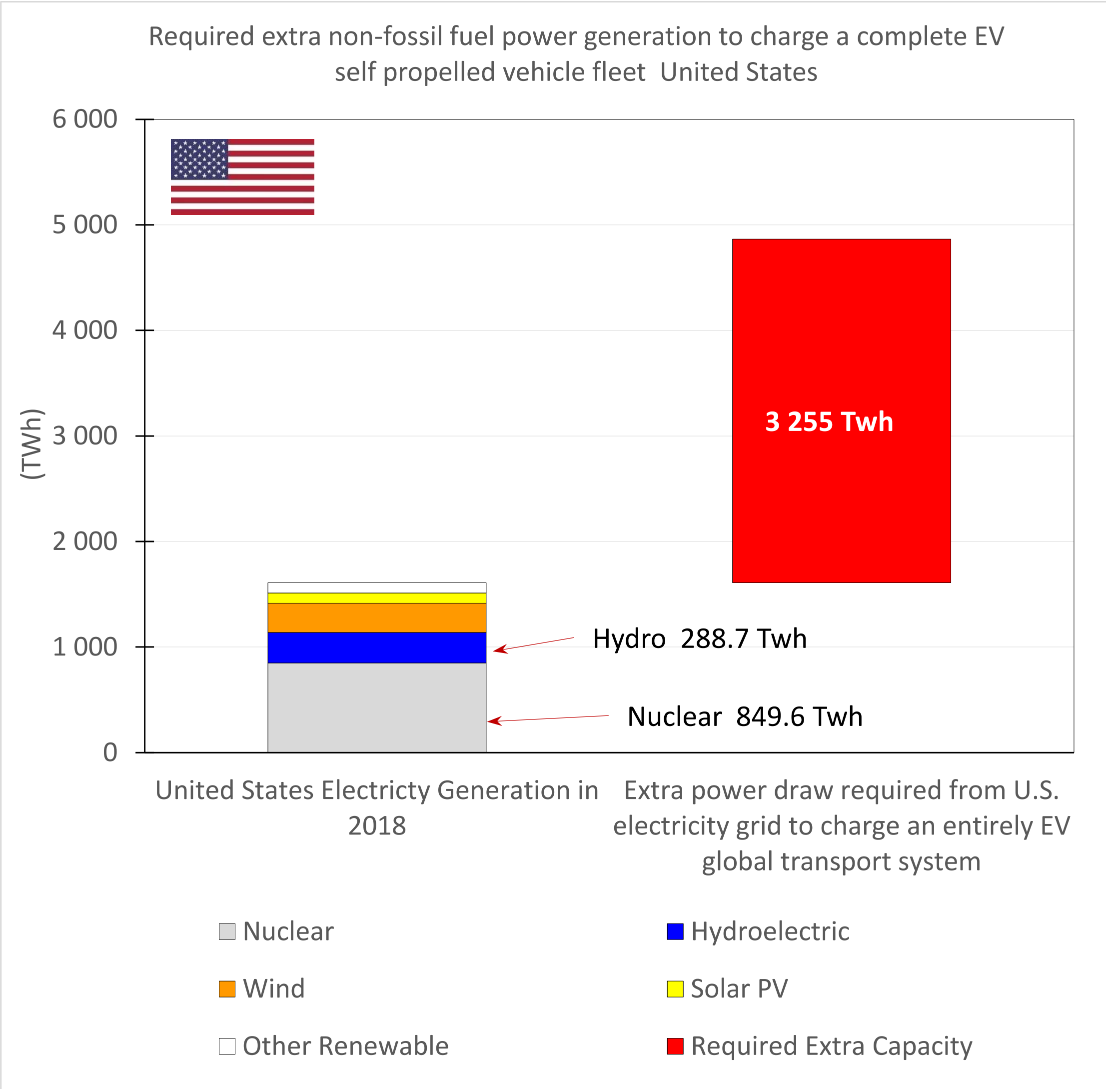


Figure 18.10. Required extra power generation to charge a completely EV United States vehicle fleet (Image: Simon Michaux)

Table 18.17. Estimated number of new power stations required to phase out petroleum fueled ICE vehicles – U.S. (Source: Appendix B, BP Statistical Review of World Energy, Global Energy Observatory)

Power Generation System	U.S. electricity production in 2018 (BP Statistical Review of World Energy 2019) (kWh)	2018 ratio percent of all U.S. electrical non-fossil fuel power systems (%)	Expanded extra required capacity to phase out petroleum (kWh)	Average Installed Plant Capacity in 2018 (Global Energy Observatory) (MW)	Power Produced by a Single Average Plant in 2018 (kWh)	Estimated required additional new power plants of average size to phase out petroleum (number)
Nuclear	8,50E+11	52,77 %	1,72E+12	2 046.5 MW	1,28E+10	134
Hydroelectric	2,89E+11	17,93 %	5,84E+11	225.4 MW	1,33E+09	440
Wind	2,78E+11	17,25 %	5,61E+11	37. 2 MW	8,12E+07	6 910
Solar PV	9,71E+10	6,03 %	1,96E+11	33.1 MW	3,30E+07	5 941
Other Renewable	9,70E+10	6,02 %	1,96E+11	76.97 MW	7,70E+07	2 548
Total (kWh)	1,61E+12		3,25E+12			15 972
Total (TWh)	1 610					

Table 18.18. Estimated number of 100 MW power storage stations to be built in the United States to address renewable source intermittency of supply

Power Generation System	Expanded extra required annual U.S. capacity to phase out petroleum (kWh)	Expanded extra required capacity in a 48 hour cycle to phase out petroleum (kWh)	Number of 100 MWh capacity power storage stations to meet power generation in a 48 hour cycle in U.S. (number)	Mass of Li-Ion batteries @230 Wh/kg (tonnes)
Wind	5,61E+11	3,08E+09	30 760	1,34E+07
Solar PV	1,96E+11	1,08E+09	10 755	4,68E+06
Total Storage Capacity	7,58E+11 757.7 TWh	4.2 TWh Summed Battery Capacity	41 515 number of storage stations	18 050 100 tonnes of batteries

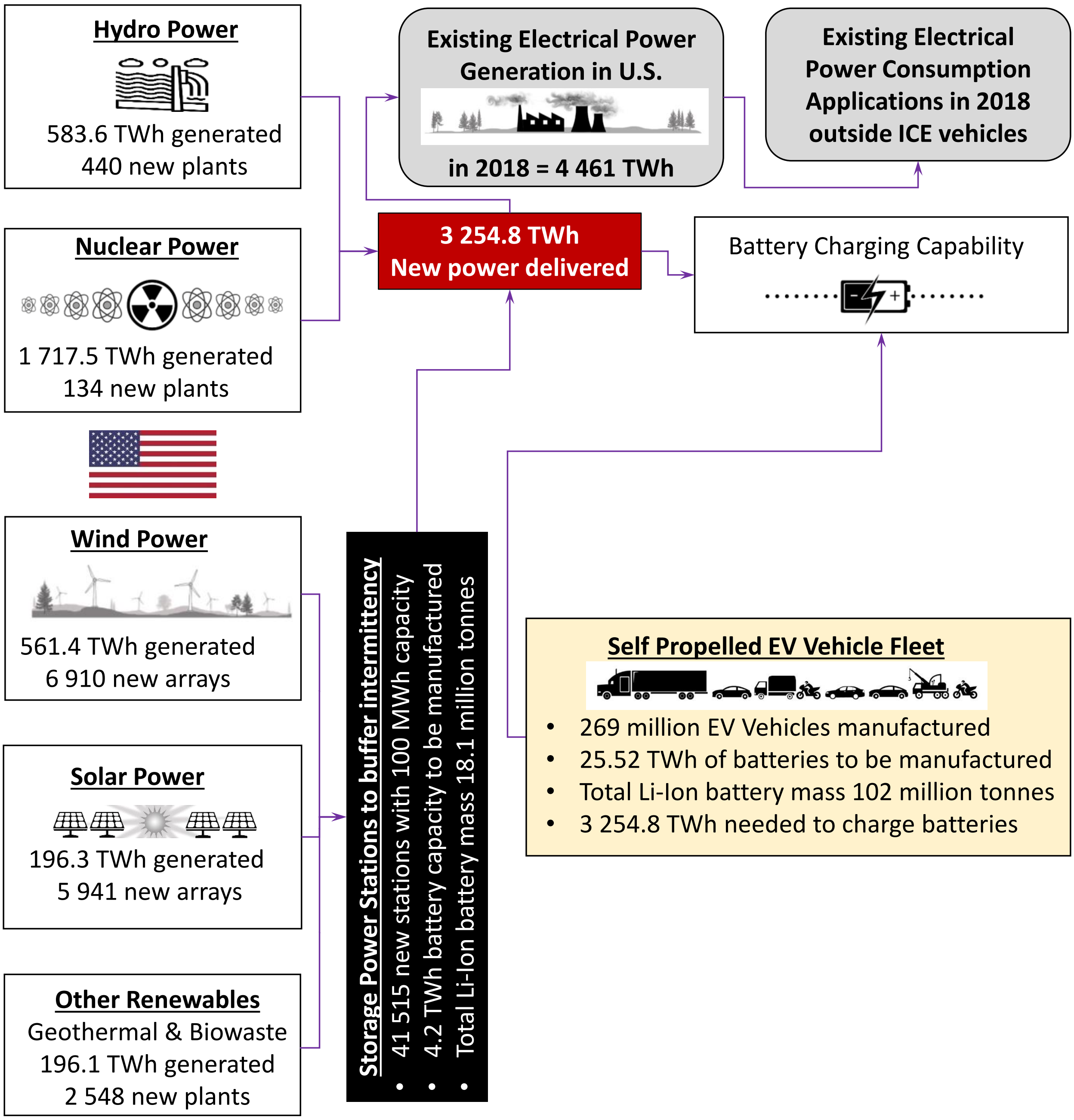


Figure 18.11. Estimated requirements for Global Scenario A – Phase out petroleum ICE technology and substitute with EV technology for a United States self-propelled vehicle fleet of the size and scope of 2018 (Images: Tania Michaux)

Figures 18.11 and 18.12 shows how the extra power grid capacity of 3 254.8 TWh is proportionally split between the different parts of the United Stated self-propelled vehicle fleet (assuming the size and scope of the fleet in 2018).

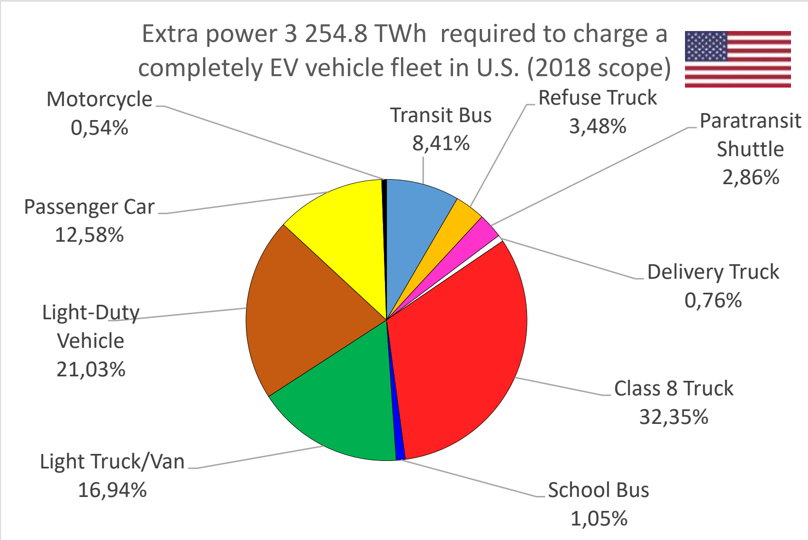


Figure 18.12. How the different parts of the United States self-propelled EV vehicles fleet make up the extra required 3 254.8 TWh power generation to charge batteries in Scenario A

Table 18.19. How the different parts of the United States self-propelled EV vehicles fleet make up the extra required 3 254.8 TWh power generation to charge batteries in Scenario A

Vehicle Class	TeraWatt-hours needed to power U.S. transport fleet if all vehicles were EV (assuming grid efficiency loss) (TWh)
Transit Bus	274,1
Refuse Truck	113,3
Paratransit Shuttle	93,2
Delivery Truck	24,7
Class 8 Truck	1 054,3
School Bus	34,1
Light Truck/Van	552,2
Light-Duty Vehicle	685,4
Passenger Car	410,2
Motorcycle	17,6
Total	3 254,8

Table 18.20. Mass of batteries required to be manufactured to install in vehicles for the entire U.S. self-propelled vehicle fleet to be completely EV (2018 number of vehicles)

Task for Battery Banks to Support	Needed Capacity of Batteries (TWh)	Mass of batteries @ 230Wh/kg (million tonnes)	Proportion (%)
Complete EV Self Propelled Vehicle fleet	25,52	102	89,9 %
Storage Power Station to manage intermittency of supply	2,60	11,40	10,1 %
Sum Total	28,12	113,40	100,0 %

18.6.2 EU-28 scope phase out of petroleum based ICE vehicles and substitution with EV vehicles

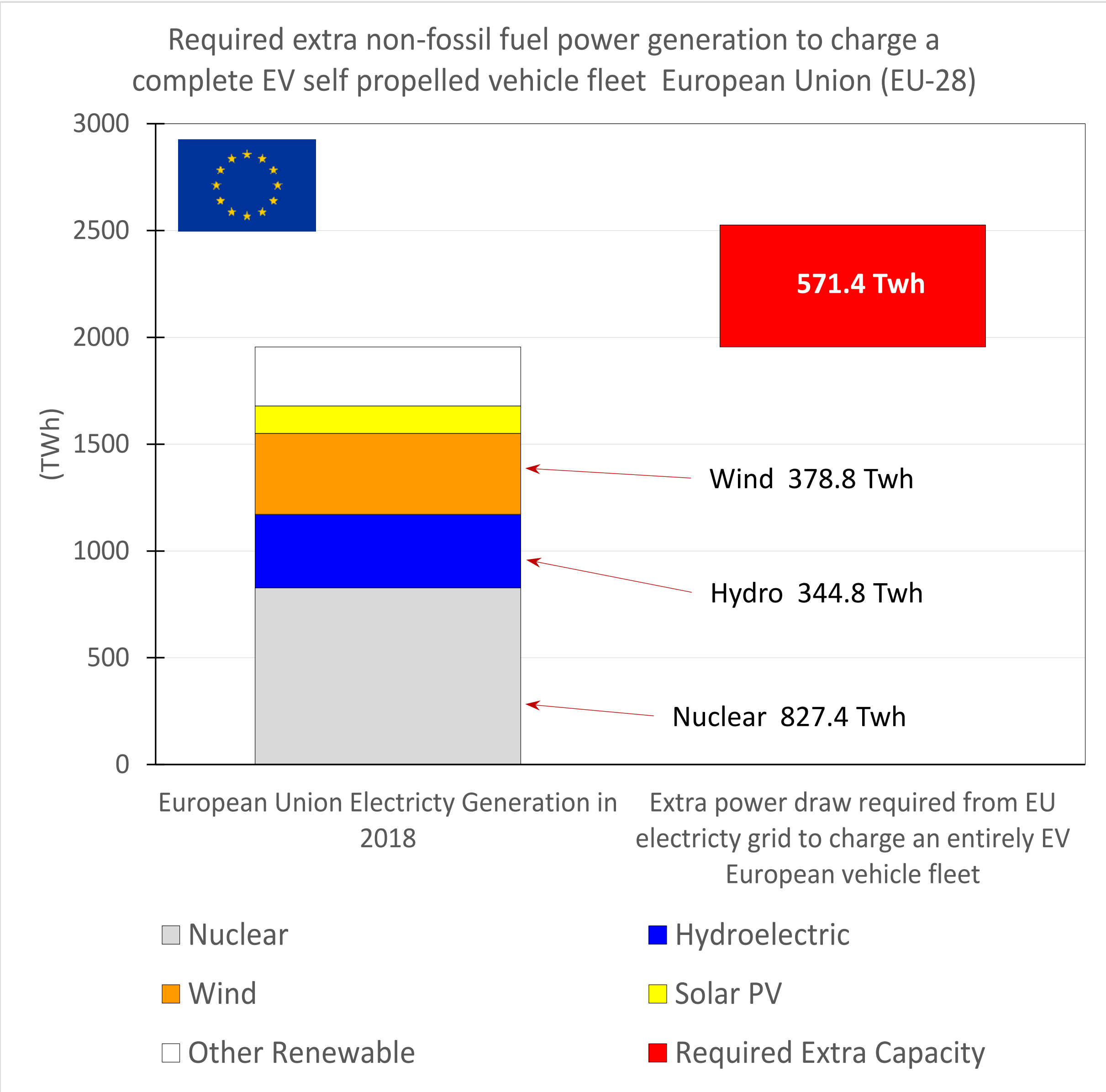


Figure 18.13. Required extra power generation to charge a completely EV European (EU-28) vehicle fleet

Table 18.21. Estimated number of new power stations required to phase out petroleum fueled ICE vehicles – EU-28 (Source: Appendix B, BP Statistical Review of World Energy, Global Energy Observatory)

Power Generation System	EU-28 electricity production in 2018 (BP Statistical Review of World Energy 2019) (kWh)	2018 ratio percent of all EU-28 electrical non-fossil fuel power systems (%)	Expanded extra required capacity to phase out petroleum (kWh)	Average Installed Plant Capacity in 2018 (Global Energy Observatory) (MW)	Power Produced by a Single Average Plant in 2018 (kWh)	Estimated required additional new power plants of average size to phase out petroleum (number)
Nuclear	8.27E+11	42.33%	2.42E+11	2 046.5 MW	1.28E+10	19
Hydroelectric	3.45E+11	17.64%	1.01E+11	225.4 MW	1.33E+09	76
Wind	3.79E+11	19.38%	1.11E+11	37. 2 MW	8.12E+07	1,363
Solar PV	1.28E+11	6.54%	3.74E+10	33.1 MW	3.30E+07	1,131
Other Renewable	2.76E+11	14.12%	8.07E+10	76.97 MW	7.70E+07	1,048
Total (kWh)	1.95E+12		5.71E+11			3,637
Total (TWh)	1,955					

Table 18.22. Estimated number of 100 MW power storage stations to be built in Europe (EU-28) to address renewable source intermittency of supply

Power Generation System	Expanded extra required annual EU-28 capacity to phase out petroleum (kWh)	Expanded extra required capacity in a 24 hour cycle to phase out petroleum (kWh)	Number of 100 MWh capacity power storage stations to meet power generation in a 24 hour cycle in Europe (number)	Mass of Li-Ion batteries @230 Wh/kg (tonnes)
Wind	1.11E+11	6.07E+08	6,067	2.64E+06
Solar PV	3.74E+10	2.05E+08	2,047	8.90E+05
Total Storage Capacity	1.48E+11 148.1 TWh	811.4 GWh Summed Battery Capacity	8,114 number of storage stations	3,527,908 tonnes of batteries

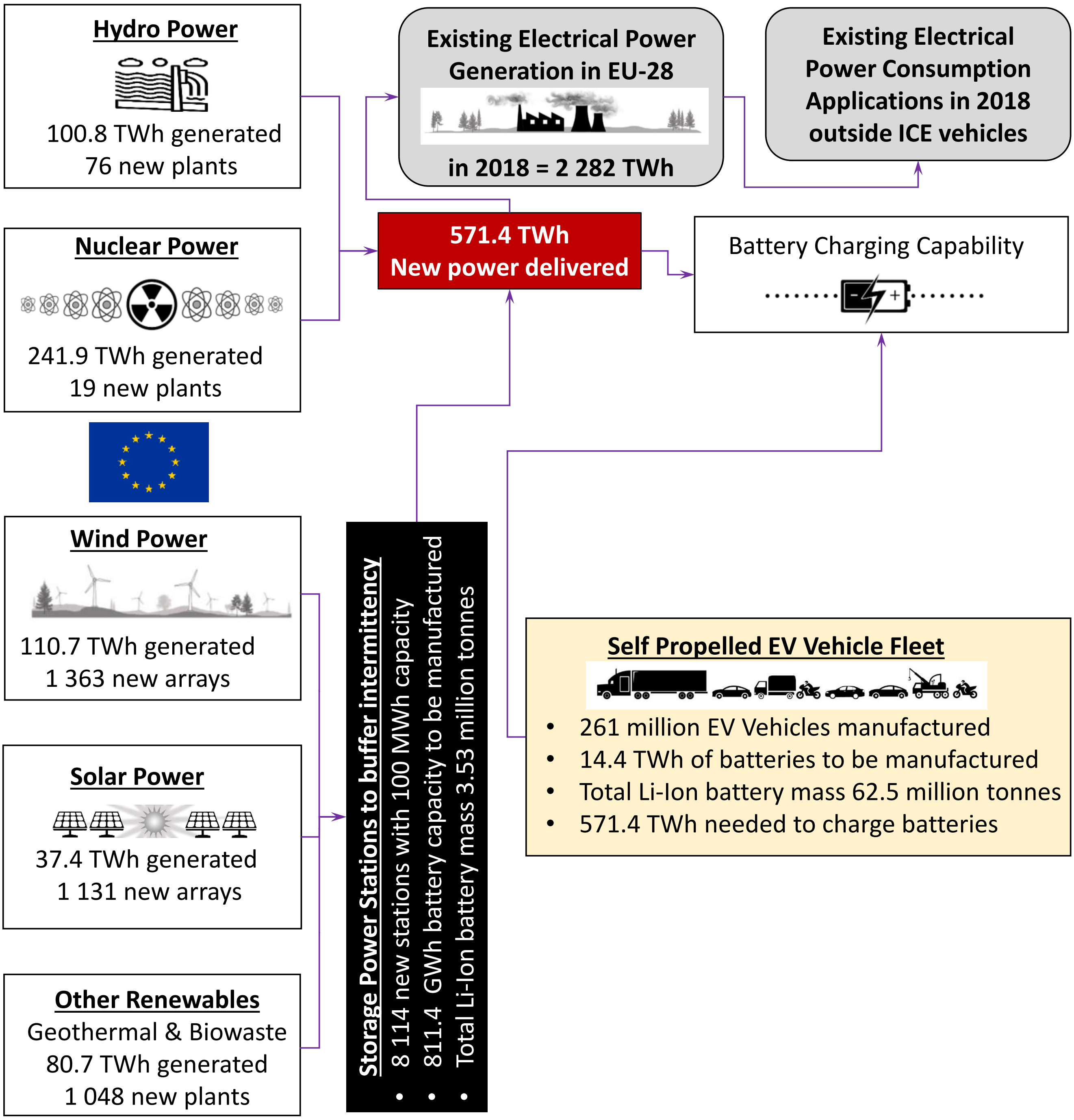


Figure 18.14. Estimated requirements for Global Scenario A – Phase out petroleum ICE technology and substitute with EV technology for a United States self-propelled vehicle fleet of the size and scope of 2018 (Images: Tania Michaux,)

Figures 18.14 and 18.15 shows how the extra power grid capacity of 2 710.8 TWh is proportionally split between the different parts of the European self-propelled vehicle fleet (assuming the size and scope of the fleet in 2018).

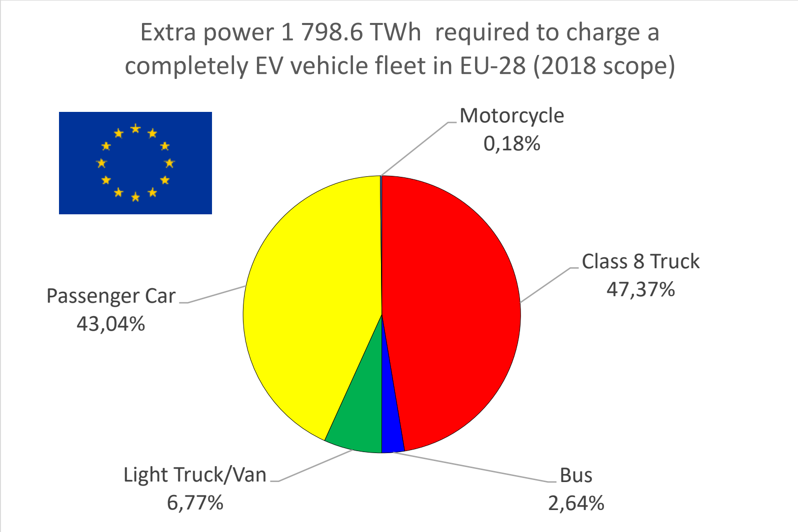


Figure 18.15. How the different parts of the European (EU-28) self-propelled EV vehicles fleet make up the extra required 2 710.8 TWh power generation to charge batteries in Scenario A

Table 18.23. How the different parts of the European (EU-28) self-propelled EV vehicles fleet make up the extra required 2 710.8 TWh power generation to charge batteries in Scenario A

Vehicle Class	TeraWatt-hours needed to power EU-28 transport fleet if all vehicles were EV (assuming grid efficiency loss) (TWh)
Class 8 Truck	269.6
Bus	15.0
Light Truck/Van	38.5
Passenger Car	247.7
Motorcycle	0.6
Total	571.4

Table 18.24. Mass of batteries required to be manufactured to install in vehicles for the entire EU-28 self-propelled vehicle fleet to be completely EV (2018 number of vehicles)

Task for Battery Banks to Support	Needed Capacity of Batteries (TWh)	Mass of batteries @ 230Wh/kg (million tonnes)	Proportion (%)
Complete EV Self Propelled Vehicle fleet	14.4	62.5	94.7 %
Storage Power Station to manage intermittency of supply (48 hours)	0.81	3.53	5.3 %
Sum Total	15.21	66.06	100.0 %

18.6.3 Chinese scope phase out of petroleum based ICE vehicles and substitution with EV vehicles

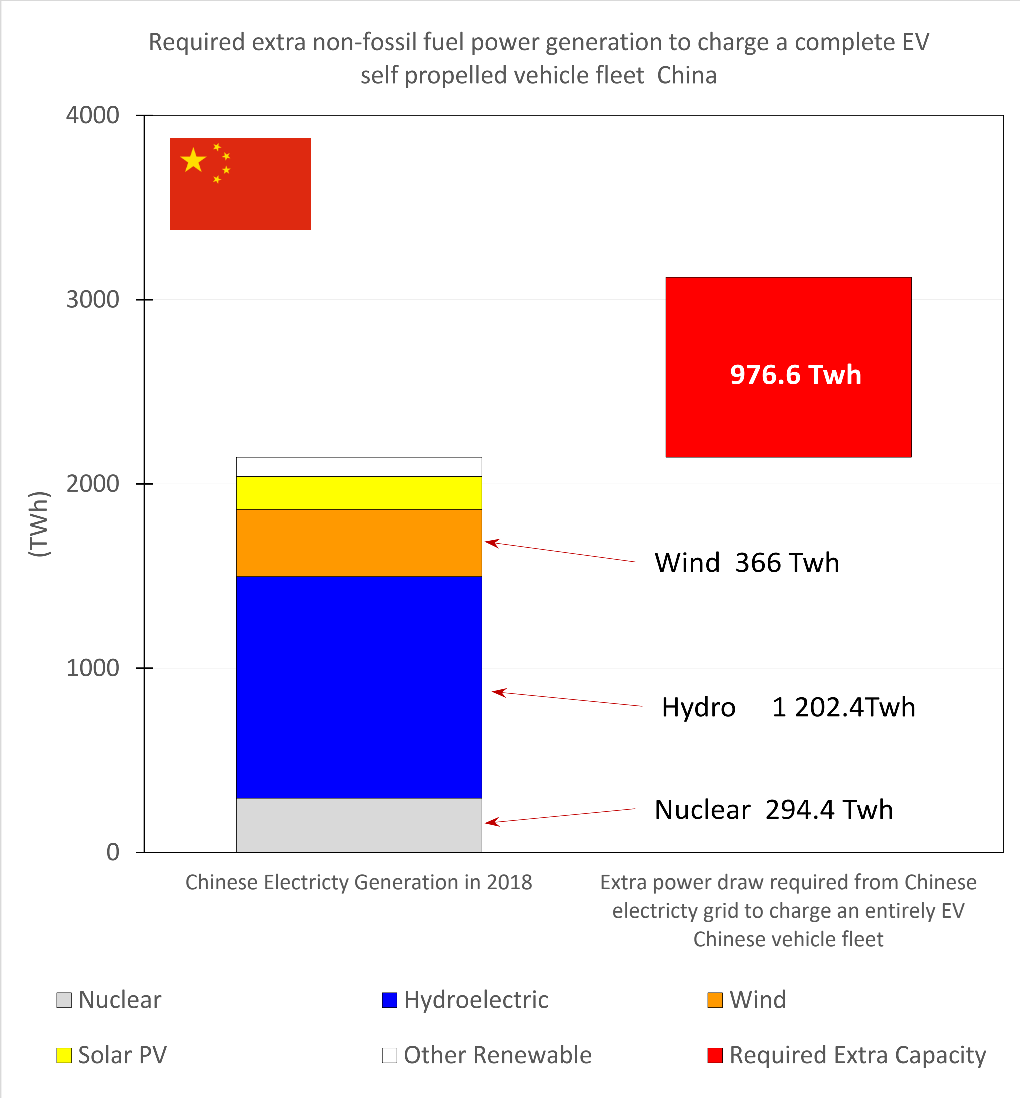


Figure 18.16. Required extra power generation to charge a completely EV Chinese vehicle fleet

Table 18.25. Estimated number of new power stations required to phase out petroleum fueled ICE vehicles – China (Source: Appendix B, BP Statistical Review of World Energy, Global Energy Observatory)

Power Generation System 	Chinese electricity production in 2018 (BP Statistical Review of World Energy 2019)	2018 ratio percent of all Chinese electrical non-fossil fuel power systems	Expanded extra required capacity to phase out petroleum	Average Installed Plant Capacity in 2018 (Global Energy Observatory)	Power Produced by a Single Average Plant in 2018	Estimated number of required additional new power plants of average size to phase out petroleum
	(kWh)	(%)	(kWh)	(MW)	(kWh)	(number)
Nuclear	2.94E+11	13.72%	1.34E+11	2 046.5 MW	1.28E+10	10
Hydroelectric	1.20E+12	56.06%	5.47E+11	225.4 MW	1.33E+09	413
Wind	3.66E+11	17.06%	1.67E+11	37. 2 MW	8.12E+07	2,051
Solar PV	1.78E+11	8.28%	8.08E+10	33.1 MW	3.30E+07	2,446
Other Renewable	1.05E+11	4.88%	4.77E+10	76.97 MW	7.70E+07	619
Total (kWh)	2.15E+12		9.77E+11			5,539
Total (TWh)	2,145					

Table 18.26. Estimated number of 100 MW power storage stations to be built in China to address renewable source intermittency of supply

Power Generation System	Expanded extra required annual Chinese capacity to phase out petroleum (kWh)	Expanded extra required capacity in a 48 hour cycle to phase out petroleum (kWh)	Number of 100 MWh capacity power storage stations to meet power generation in a 48 hour cycle in China (number)	Mass of Li-Ion batteries @230 Wh/kg (tonnes)
Wind	1.67E+11	9.13E+08	9,130	3.97E+06
Solar PV	8.08E+10	4.43E+08	4,428	1.93E+06
Total Storage Capacity	2.47E+11 247.4 TWh	1.36 TWh Summed Battery Capacity	13,558 number of storage stations	5,894,925 tonnes of batteries

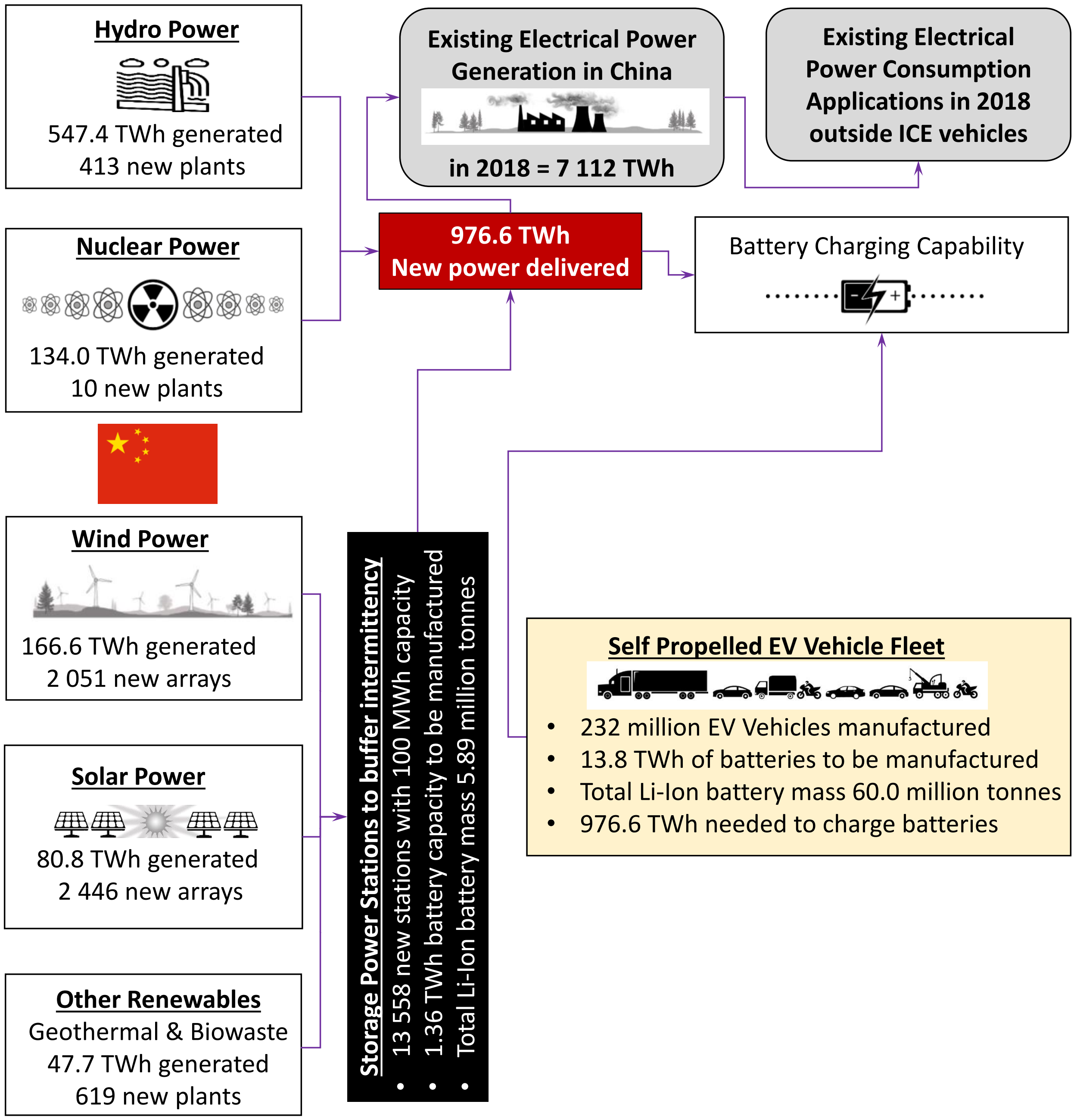


Figure 18.17. Estimated requirements for Global Scenario A – Phase out petroleum ICE technology and substitute with EV technology for a Chinese self-propelled vehicle fleet of the size and scope of 2018 (Images: Tania Michaux,)

Figures 18.17 and 18.18 shows how the extra power grid capacity of 2 866.0 TWh is proportionally split between the different parts of the Chinese self-propelled vehicle fleet (assuming the size and scope of the fleet in 2018).

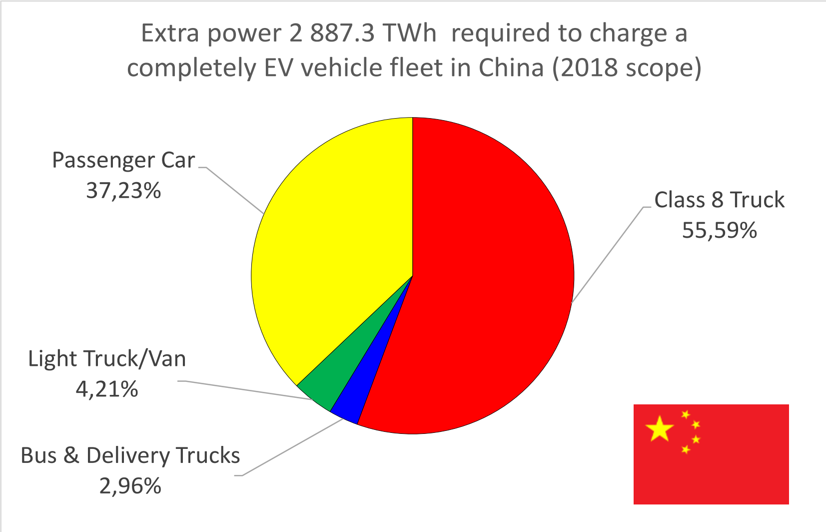


Figure 18.18. How the different parts of the Chinese self-propelled EV vehicles fleet make up the extra required 2 710.8 TWh power generation to charge batteries in Scenario A

Table 18.27. How the different parts of the European Chinese self-propelled EV vehicles fleet make up the extra required 2 867.3 TWh power generation to charge batteries in Scenario A

Vehicle Class 	KiloWatt-hours needed to power Chinese transport fleet if all vehicles were EV (accounting for transmission loss) (TWh)
Class 8 Truck	645.6
Bus & Delivery Trucks	29.8
Light Truck/Van	30.6
Passenger Car	270.3
Motorcycles	0.3
Total	976.3

Table 18.28. Mass of batteries required to be manufactured to install in vehicles for the entire Chinese self-propelled vehicle fleet to be completely EV (2018 number of vehicles)

Task for Battery Banks to Support 	Needed Capacity of Batteries (TWh)	Mass of batteries @ 230Wh/kg (million tonnes)	Proportion (%)
Complete EV Self Propelled Vehicle fleet	13.8	60.0	91.0 %
Storage Power Station to manage intermittency of supply (48 hours)	1.36	5.89	9.0 %
Sum Total	15.15	65.86	100.0 %

18.6.4 RoW scope phase out of petroleum based ICE vehicles and substitution with EV vehicles

Table 18.29. Estimated number of new power stations required to phase out petroleum fueled ICE vehicles – Rest of World (Data compiled from Table 8.4)
(Source: Appendix B, BP Statistical Review of World Energy, Global Energy Observatory)

Power Generation System	Rest of World (RoW) production in 2018 (BP Statistical Review of World Energy 2019) (kWh)	2018 ratio percent of all RoW electrical non-fossil fuel power systems (%)	Expanded extra required capacity to phase out petroleum (kWh)	Average Installed Plant Capacity in 2018 (Global Energy Observatory) (MW)	Power Produced by a Single Average Plant in 2018 (kWh)	Estimated number of required additional new power plants of average size to phase out petroleum (number)
Nuclear	7.30E+11	30.23%	1.49E+12	2 046.5 MW	1.28E+10	116
Hydroelectric	2.36E+12	46.92%	2.31E+12	225.4 MW	1.33E+09	1,741
Wind	2.48E+11	14.59%	7.18E+11	37. 2 MW	8.12E+07	8,834
Solar PV	1.82E+11	6.48%	3.19E+11	33.1 MW	3.30E+07	9,648
Other Renewable	1.75E+11	1.80%	8.85E+10	76.97 MW	7.70E+07	1,150
Total (kWh)	3.69E+12		4.92E+12			21,489
Total (TWh)	3,692					

Table 18.30. Estimated number of 100 MW power storage stations to be built in rest of World (RoW) to address renewable source intermittency of supply

Power Generation System	Expanded extra required annual RoW capacity to phase out petroleum (kWh)	Expanded extra required capacity in a 48 hour cycle to phase out petroleum (kWh)	Number of 100 MWh capacity power storage stations to meet power generation in a 48 hour cycle in RoW (number)	Mass of Li-Ion batteries @230 Wh/kg (tonnes)
Wind	7.18E+11	3.93E+09	39,325	1.71E+07
Solar PV	3.19E+11	1.75E+09	17,467	7.59E+06
Total Storage Capacity	1.04E+12 1036.4 TWh	5.7 TWh Summed Battery Capacity	56,791 number of storage stations	24,691,750 tonnes of batteries

Table 18.31. How the different parts of the Rest of World (RoW) self-propelled EV vehicles fleet make up the extra required 4918.7 TWh power generation to charge batteries in Scenario A

Vehicle Class (RoW)	TeraWatt-hours needed to power RoW transport fleet if all vehicles were EV (assuming grid efficiency loss) (TWh)
Class 8 Truck	1594.8
Transit Bus	414.6
Refuse Truck	171.4
Paratransit Shuttle	141.0
Delivery Truck	37.4
School Bus	51.6
Light Truck/Van	835.3
Light-Duty Vehicle	1036.8
Passenger Car	620.4
Motorcycle	15.4
Total	4,918.7

Table 18.32. Mass of batteries required to be manufactured to install in vehicles for the entire rest of World (RoW) self-propelled vehicle fleet to be completely EV (2018 number of vehicles)

Task for Battery Banks to Support (RoW)	Needed Capacity of Batteries (TWh)	Mass of batteries @ 230Wh/kg (million tonnes)	Proportion (%)
Complete EV Self Propelled Vehicle fleet	57.2	248.8	91.0 %
Storage Power Station to manage intermittency of supply (48 hours)	5.68	24.69	9.0 %
Sum Total	62.90	273.47	100%

18.6.5 Global scope phase out of petroleum based ICE and substitution with EV technology

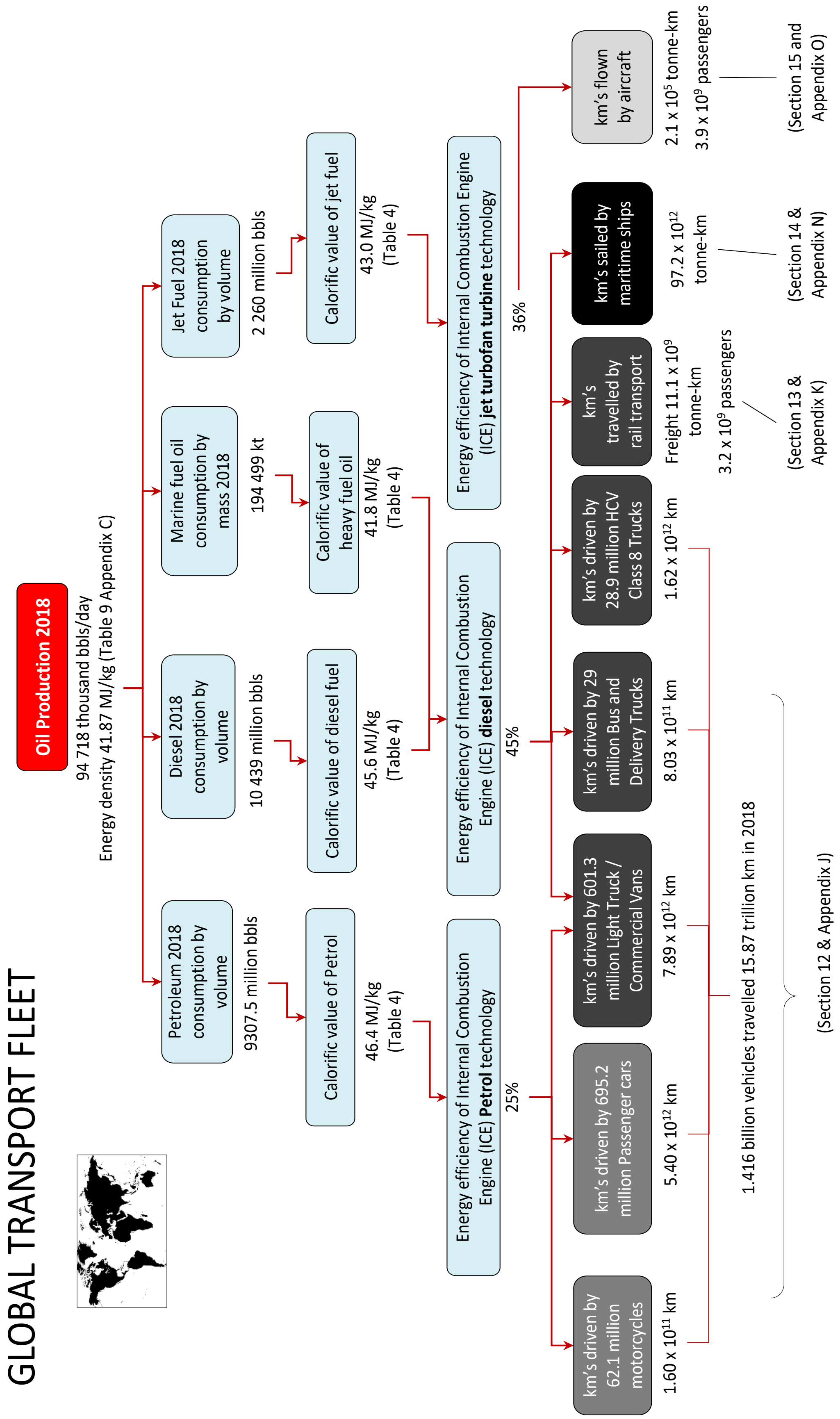


Figure 18.19 - Part 1 – Calculation flow chart for extra power generation required for a completely EV global transport fleet (World Map Image by Clker-Free-Vector-Images from Pixabay)

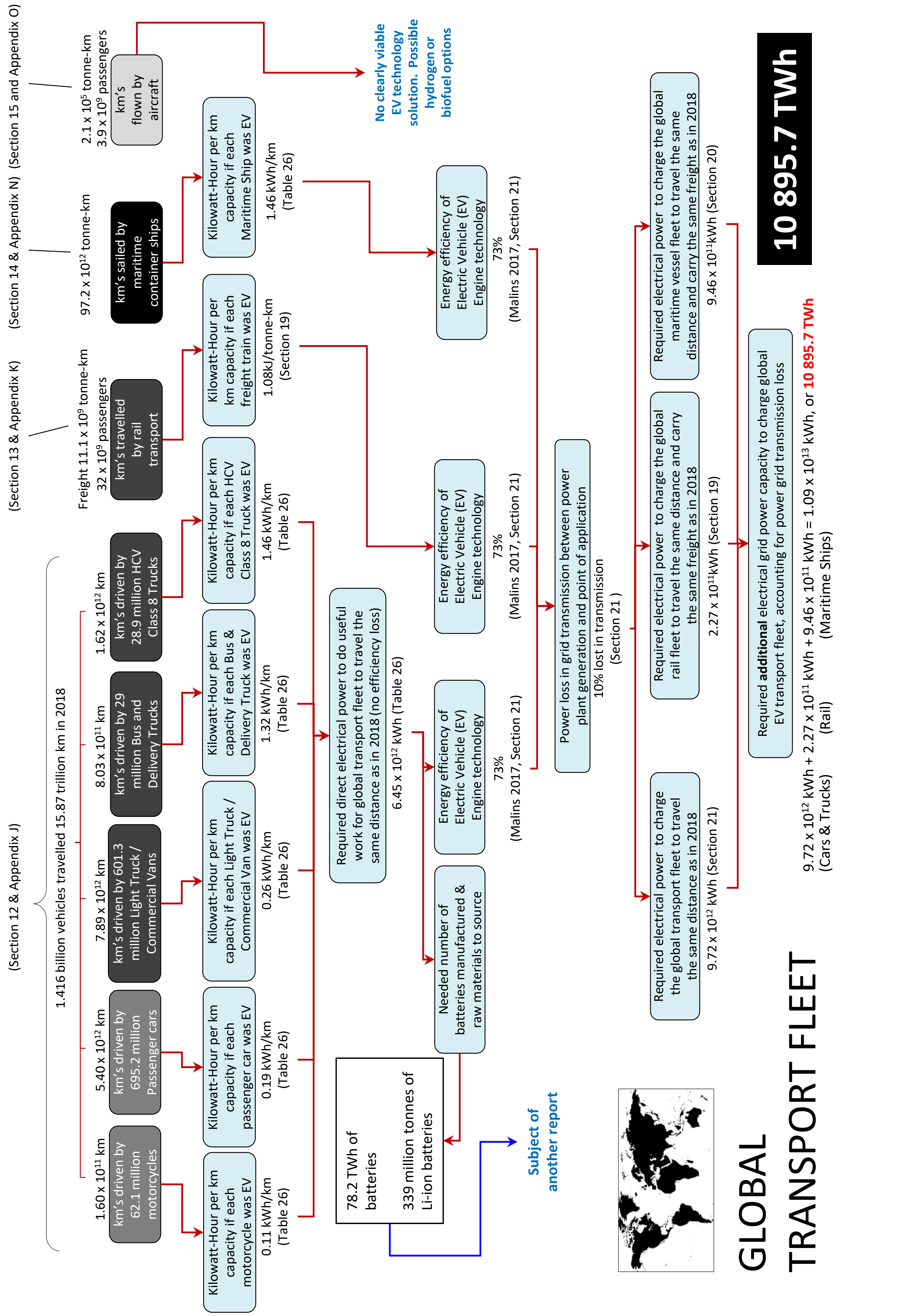


Figure 18.20 - Part 2 – Calculation flow chart for extra power generation required for a completely EV global transport fleet (World Map Image by Clker-Free-Vector-Images from Pixabay)

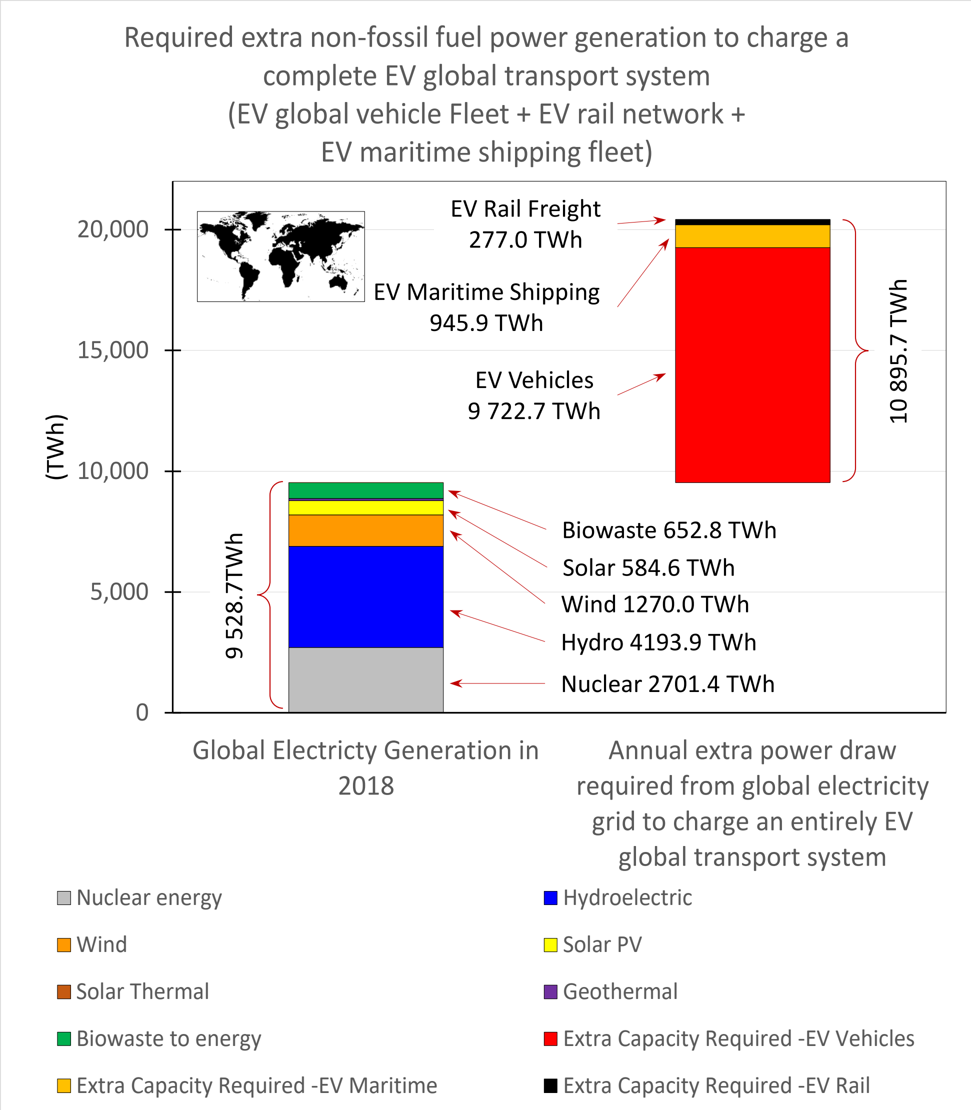


Figure 18.21. Required extra non-fossil fuel power generation to charge a complete EV global transport system (EV global vehicle Fleet + EV rail network + EV maritime shipping fleet)
(World Map Image by Clker-Free-Vector-Images from Pixabay)

Table 18.33. Estimated number of new power stations required to phase out petroleum fuel – Global System
(Source: Appendix B, Agora Energiewende and Sandbag, Global Energy Observatory) (World Map Image by Clker-Free-Vector-Images from Pixabay)

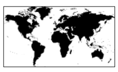
Power Generation System 	Global non-fossil fuel electricity production in 2018 (Appendix B & Agora Energiewende and Sandbag 2019) (kWh)	2018 ratio percent of non-fossil fuel electrical power systems (%)	Expanded extra required capacity to phase out petroleum (kWh)	Global Number Power Plants in 2018 (Global Energy Observatory) (number)	Average Plant Capacity (Global Energy Observatory) (MW)	Power Produced by a Single Average Plant in 2018 (kWh)	Estimated number of required additional new power plants of average size to phase out petroleum (number)
Nuclear	2.70E+12	28.35%	3.09E+12	438	2 046.5 MW	1.28E+10	241
Hydroelectric	4.19E+12	44.00%	4.79E+12	3,163	225.4 MW	1.33E+09	3,617
Wind	1.30E+12	13.68%	1.49E+12	16,048	37. 2 MW	8.12E+07	18,351
Solar PV	5.79E+11	6.08%	6.62E+11	17,526	33.1 MW	3.30E+07	20,041
Solar Thermal	5.50E+09	0.06%	6.29E+09	52	76.9 MW	7.70E+07	82
Geothermal	9.30E+10	0.98%	1.06E+11	108	94.7 MW	6.03E+08	176
Biowaste to energy	6.53E+11	6.85%	7.46E+11	3,800	31.7 MW	3.46E+07	21,585
Total (kWh)	9.53E+12	100.00%	1.09E+13				64,093
Total (TWh)	9,528.7		**10,895.7**				

Table 18.34. Estimated number of 100 MW power storage stations to be built in the global power grid to address renewable source intermittency of supply (World Map Image by Clker-Free-Vector-Images from Pixabay)

Power Generation System	Expanded extra required annual global capacity to phase out petroleum (kWh)	Storage capacity required for a 48 hour time period to manage winter period, with limited sun & wind (kWh)	Number of 100 MWh capacity power storage stations to meet power generation in a 48 hour cycle (number)	Mass of Li-Ion batteries @230 Wh/kg (tonnes)
Wind	1.49E+12	8.17E+09	81,690	3.55E+07
Solar PV	6.62E+11	3.63E+09	36,284	1.58E+07
Total Storage Capacity	2.15E+12 2 153.0 TWh	11.8 TWh Summed Battery Capacity	117,974 number of storage stations	51,292,992 tonnes of batteries

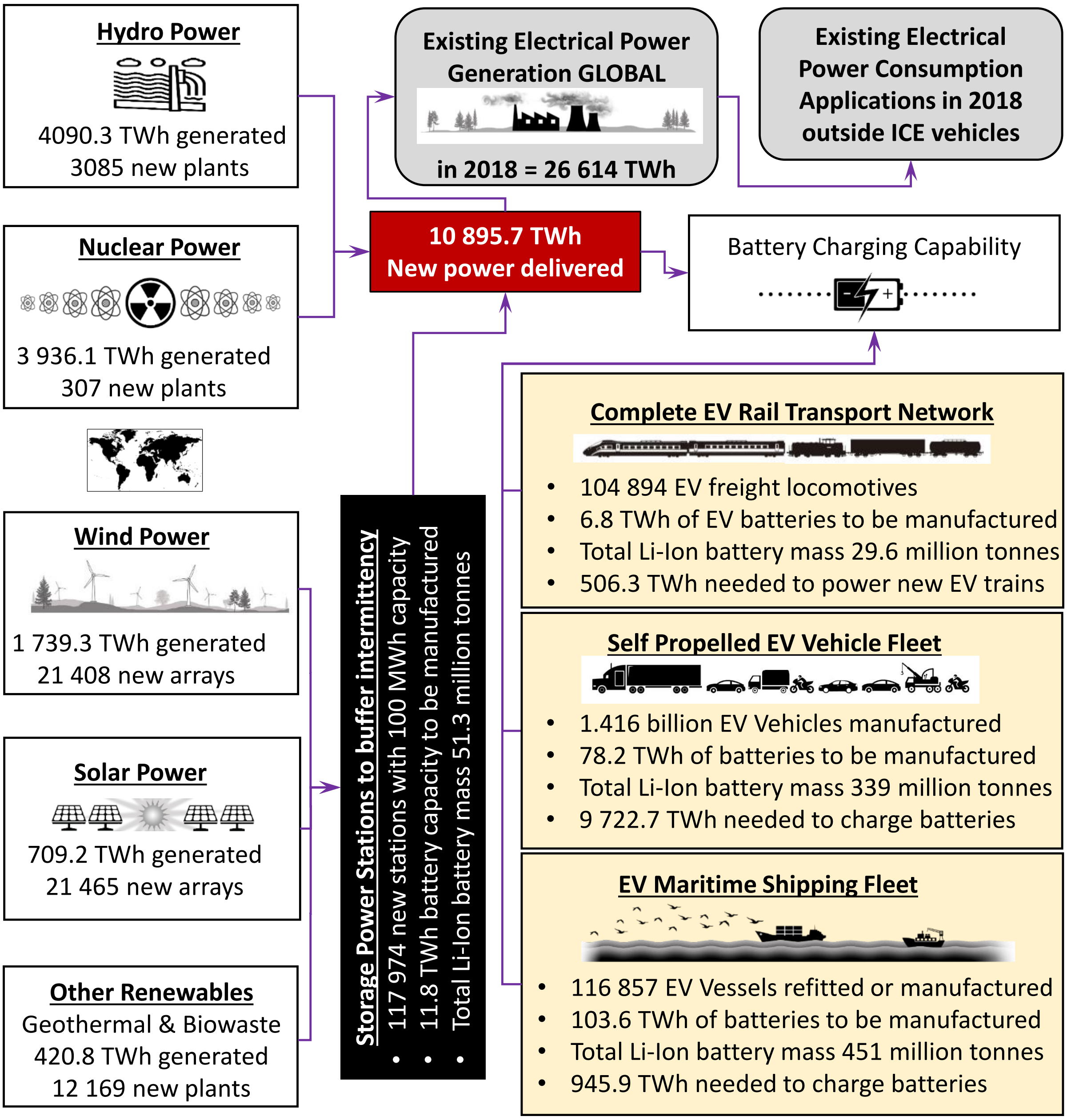


Figure 18.22. Estimated requirements for Global Scenario A – Phase out petroleum ICE technology and substitute with EV technology for a global transport fleet of the size and scope of 2018. Vehicles, Rail and Maritime vessels. (Images: Tania Michaux) (World Map Image by Clker-Free-Vector-Images from Pixabay)

Figures 18.23 to 18.25 shows how the extra power grid capacity of 10 895.7 TWh is proportionally split between the different parts of the global transport fleet (assuming the size and scope of the fleet in 2018).

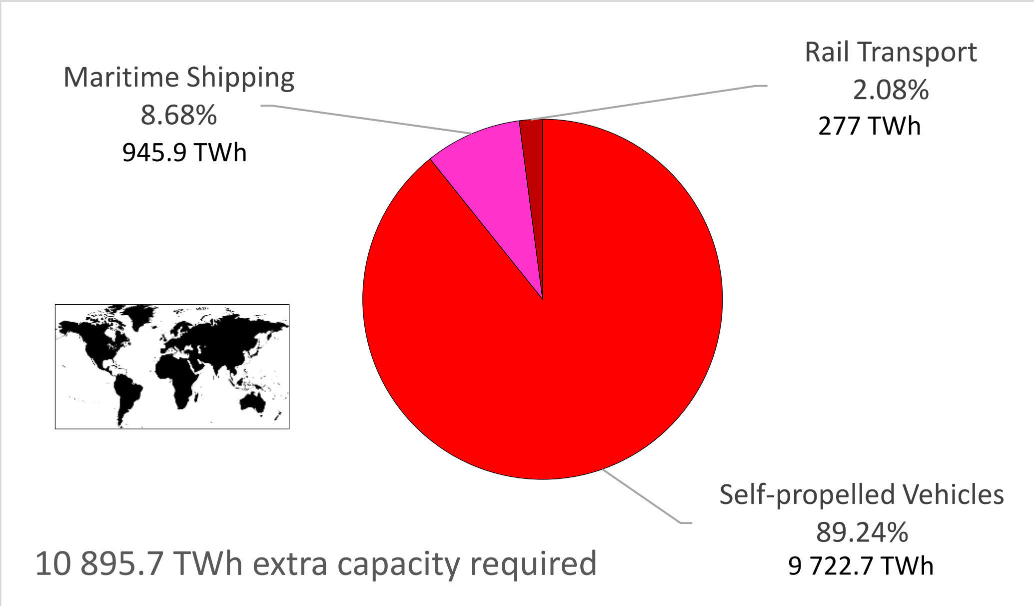


Figure 18.23. How the different parts of the global transport fleet make up the extra required 10 895.7 TWh in Scenario A Split by self-propelled EV vehicles, a complete EV rail transport network and a complete EV maritime fleet (World Map Image by Clker-Free-Vector-Images from Pixabay)

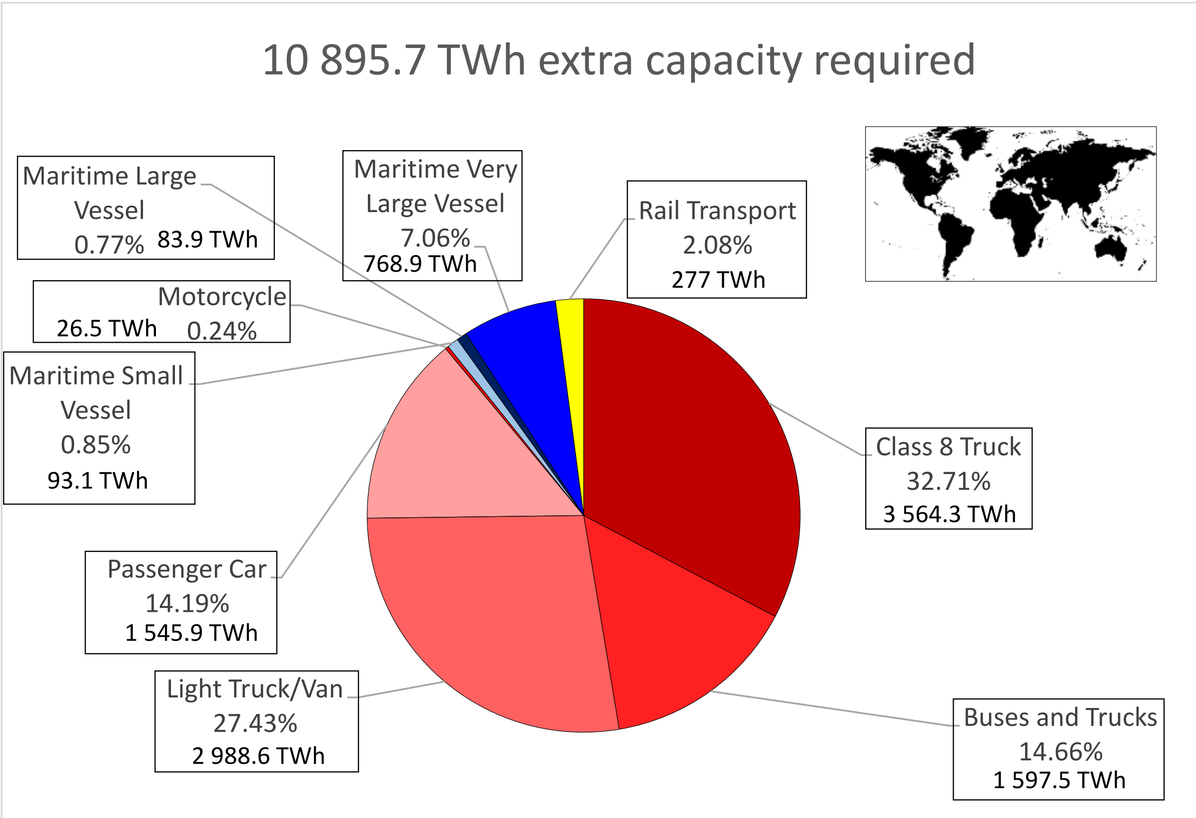


Figure 18.24. How the different parts of the global transport fleet make up the extra required 10 895.7 TWh in Scenario A Split by classes of EV vehicles, a complete EV rail transport network and a complete EV maritime fleet (World Map Image by Clker-Free-Vector-Images from Pixabay)

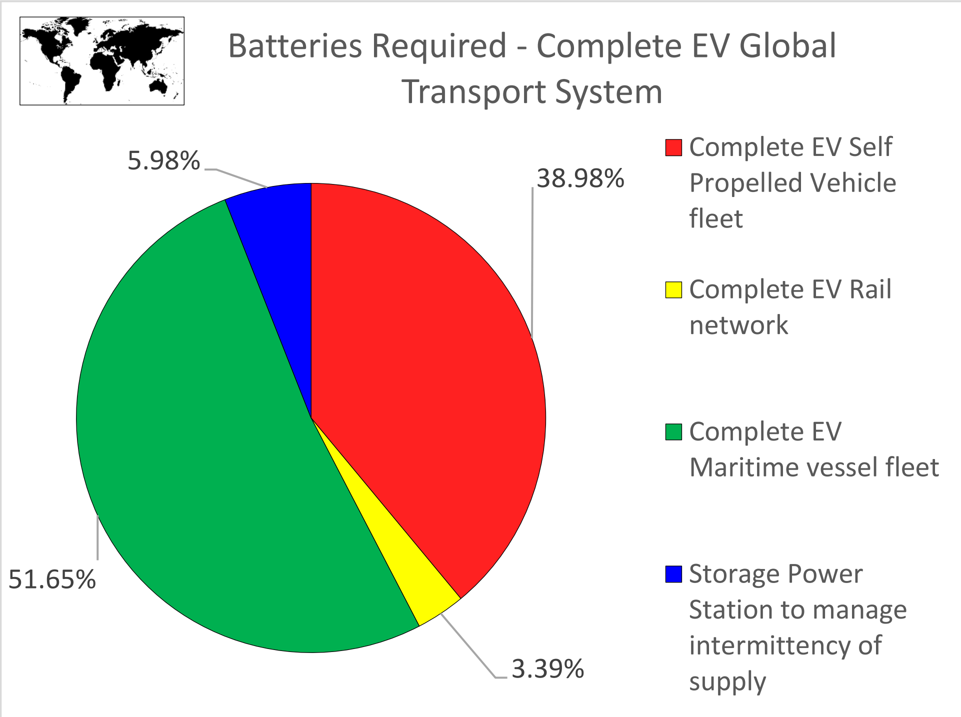
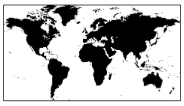


Figure 18.25. Mass of batteries required to be manufactures to install in vehicles, trains, ships, and power storage stations for the entire global transport fleet to be completely EV (2018 number of vehicles)
(World Map Image by Clker-Free-Vector-Images from Pixabay)

Table 18.35. Mass of batteries required to be manufactured to install in vehicles, trains, ships and power storage stations for the entire global transport fleet to be completely EV (2018 number of vehicles)
(World Map Image by Clker-Free-Vector-Images from Pixabay)

Tasks to be powered by Li-Ion batteries 	Needed Capacity of Batteries (TWh)	Mass of batteries @ 230Wh/kg (million tonnes)	Proportion (%)
Complete EV Self Propelled Vehicle fleet	78.2	339	39.0 %
Complete EV Rail network	6.81	29.6	3.4 %
Complete EV Maritime vessel fleet	103.6	451	51.7 %
Storage Power Station to manage intermittency of supply	11.8	51.3	5.9 %
Sum Total	**200.41**	**870.9**	**100.0 %**

18.7 Required infrastructure for Scenario A

Given that the current number of power stations globally in 2018, was 46 423 (Table 8.4), the number of additional power stations to phase out oil and implement the EV revolution is estimated at 64 093 (Table 18.33) is a significant challenge. Currently assigning the needed budget for the maintenance of existing old power stations (nuclear in particular) has been a challenge (EESI 2018), where many of them have been kept operational past their decommissioning date. Building so many new power stations will require a massive effort, comparable to the current military spending budget.

The following infrastructure to make this scenario work is as follows:

- The manufacture of 1.416 billion EV vehicles
    - 28 929 348 Class 8 HCV Trucks
    - 29 002 253 Buses & Delivery trucks
    - 601 327 324 Light Trucks & Commercial Vans
    - 695 160 429 Passenger Cars
    - 62 109 261 Motorcycles

- The manufacture of 1.416 billion Li-Ion batteries, making up 78.2 TWh (339 million tonnes) in batteries for cars & trucks.

- The manufacture of 104 894 Li-Ion batteries, each one 281.9 tonne, making up 6.81 TWh (29.6 million tonnes) in batteries for rail locomotives (Section 19).

- To electrify the part of the rail transport fleet (passenger and freight), 277.0 TWh of extra power capacity would be required to be added to the global electrical power grid. This would be 2.8% of the of the task to phase out the complete ICE transport fleet.

- The Li-Ion batteries for cars, trucks, rail locomotives and maritime ships, would be 188.61 TWh, with a mass of 819.6 million tonnes.

- To electrify the maritime shipping fleet, 101 105 EV powered vessels would have to be constructed. To power these vessels, 103.6 TWh of batteries would need to be manufactured, ranging from 62 tonnes to 50 499 tonnes. If these were Lithium Ion batteries, then 450.5 million tonnes would be required (at 230 Wh/kg).

- Construction and commissioning of the number of electrical power generation stations to deliver the required extra capacity to the grid, estimated 64 093 power stations, providing annually 10 895.7 TWh in extra capacity to the grid.

- Installation of number of EV charging stations throughout the road network equivalent to current gasoline fuel service stations.

- Construction and commissioning of a series of 100 MWh battery storage power stations to manage power fluctuations from wind and solar sources, estimated at 117 974 power stations, when combined, providing a 48 hour buffer with 11.8 TWh in storage capacity to the grid.

18.8 Outcomes of Scenario A

The outcomes of Scenario A are summarized below. The existing global non-fossil fuel power grid has to expand from 9 528.7 TWh annual production, by adding an additional 10 895.7 TWh (annual production) in capacity. This task of phasing out fossil fuel powered ICE vehicle fleet and substituting with Li-Ion powered Electric Vehicles (which are then charged of the electricity grid) is a new task and will be done in addition to existing electricity demand applications.

This means the global non-fossil fuel electrical power generation is required to grow to an annual capacity of 20 424.4TWh (9 528.7 + 10 895.7). As all new power stations will have to be non-fossil fuels, wind and solar power will be among the systems used.

This required 10 895.7 TWh of extra power would be used to charge the batteries of the entire transport fleet, including passenger cars, buses, light trucks, delivery trucks, Class 8 heavy trucks, the remaining part of the rail transport system that is not electric already, and the entire maritime shipping fleet. To phase out the existing ICE transport fleet (using 2018 data), 201.41 TWh of batteries need to be manufactured. This would be 870.9 million tonnes of Lithium Ion batteries (at 230 Wh/kg).

The four largest tasks to phase out the fossil fuel powered ICE transport fleet in the global industrial ecosystem were:

1. To charge a global fleet of **class 8 truck** Electric Vehicles (same size as vehicles of that class in 2018), an estimated 3 564.3 TWh of extra power will need to be delivered to the power grid. This would be 32.71 % of the task to phase out the complete ICE transport fleet.

2. To charge the global fleet of **light truck/commercial van** Electric Vehicles (same size as vehicles of that class in 2018), an estimated 2 988.6 TWh of extra power will need to be delivered to the power grid. This would be 27.43 % of the task to phase out the complete ICE transport fleet.

3. To charge the global fleet of **buses & delivery trucks** Electric Vehicles (same size as vehicles of that class in 2018), an estimated 1 597.5 TWh of extra power will need to be delivered to the power grid. This would be 14.66 % of the task to phase out the complete ICE transport fleet.

4. To charge the global fleet of **passenger cars** Electric Vehicles (same size as vehicles of that class in 2018), an estimated 1 545.9 TWh of extra power will need to be delivered to the power grid. This would be 14.19 % of the task to phase out the complete ICE transport fleet.

The required mass of each vehicle class was calculated for each vehicle class. It became clear that any application that involves transporting a large cargo over a long distance, would require a very large battery. The required mass of some of these batteries would pose a number of practical limitations and problems. For example:

- The EV Class 8 truck battery was estimated as 1956.5 kg in mass.

- For an EV train hauling 3 000 tonnes a distance of 804.6 km, the EV freight locomotive battery banks were required to be 65 000 kWh, which were 289.1 tonnes in mass (Section 19).

- For an EV Large Maritime shipping vessel hauling a full load of cargo, with only have a range of 8 890 km, battery banks were required to be 4 977 740 kWh, which were 21 642 tonnes in mass (Section 20).

- For an EV Very Large Maritime shipping vessel hauling a full load of cargo, with only have a range of 8 890 km, battery banks were required to be 11 614 726 kWh, which were 50 499 tonnes in mass (Section 20). The size of this battery bank was so large that there was only 36.1 % left of the Gross Tonnage carrying capacity for cargo.

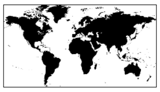
- For a very large maritime shipping vessel, with a range of 8 890 km have a battery bank mass 50 499 tonnes (11 614 726 kWh). The size of this battery bank was so large that there was only 25.8 % left of the Gross Tonnage carrying capacity for cargo. The shipping route between Shanghai and Hamburg is 22 737 km. For an EV ship of this specification, it would have to stop twice for recharging to complete this route and deliver its cargo.

The implications of these points suggest the following. Large payload cargos being transported long distances should not be EV but be powered by some other power system (Hydrogen cells for example). If this cannot be made practical, then these transport vehicle types would not be deployed in any large numbers. Maritime ships, rail freight locomotives and Class 8 trucks should all be something other than EV. If each of these vehicles were powered by hydrogen cells, they could be more viable as the required hydrogen tank would much lighter in mass and smaller in volume than the battery required for the equivalent EV vehicle (see Sections 19 and 20).

Any vehicle of short range application (passenger cars, motorcycle, commercial vans, buses, delivery trucks) should be EV.

If Scenario A was applied in full, then 10 895.7 TWh of extra electrical power generation annual capability would be required to be commissioned and connected to the grid. This extra capacity would be delivered with only non-fossil fuel power generation systems. Table 18.36 shows an estimate of the number of power stations needed to phase out the fossil fuel powered ICE transport fleet, using the same proportion of power generation systems reported in 2018. The far right hand side column shows the existing power plant fleet as reported in 2018 for comparison and understanding of the size and scale of the task ahead.

Table 18.36. Estimated global number of non-fossil fuel electrical power generation stations to phase out the petroleum fueled ICE transport fleet use (World Map Image by Clker-Free-Vector-Images from Pixabay)

Power Generation System 	Expanded extra required capacity to phase out petroleum fueled ICE (kWh)	Estimated number of required **additional** new power plants of average size to phase out petroleum (number)	**Existing** global Number Power Plants in 2018 (Global Energy Observatory) (number)
Nuclear	3.09E+12	241	438
Hydroelectric	4.79E+12	3,617	3,163
Wind	1.49E+12	18,351	16,048
Solar PV & Solar Thermal	6.68E+11	20,123	17,526
Biomass, Tidal & Geothermal	8.53E+11	21,761	3,960
Total (kWh)	1.09E+13	64,093	41,135
Total (TWh)	**10,895.7**		

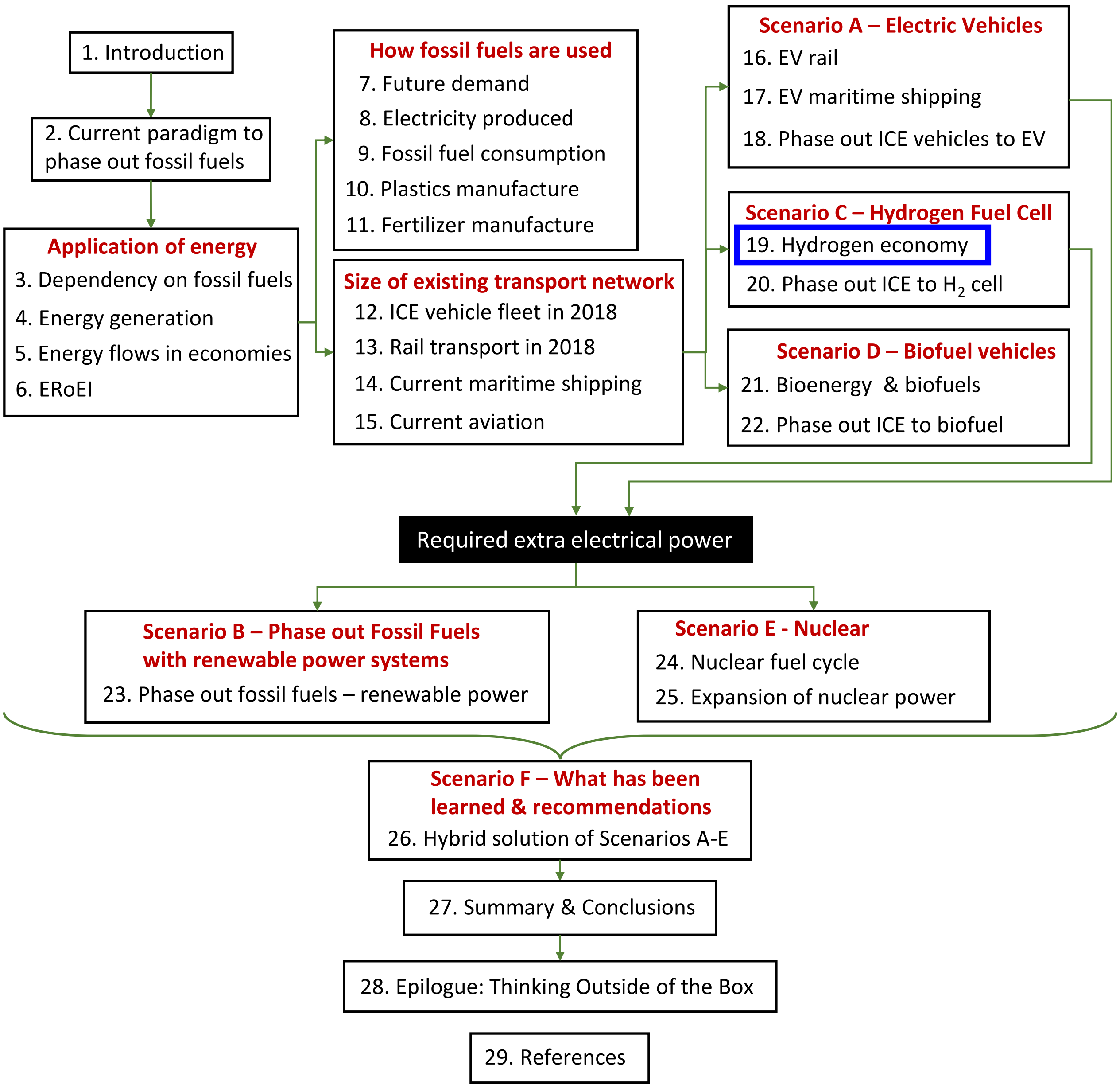
For this to work, a fundamental change in how our industrial systems are managed is needed. Currently, the global system is having difficulty maintaining the existing fleet of power stations. The time period required to design and construct a single coal fired power station is 3-6 years. For a new nuclear power plant, the incubation time period is closer to 10 to 15 years. This suggests that the 2050 climate neutral target (European Commission 2019) task is much greater than current planners understand as shown in Tables 18.17 and 18.28.

It is to be remembered that the numbers shown in this section are for Scenario A – Phase out ICE technology systems and complete substitution with EV technology systems. This involves just the removal of petroleum fuel from the transport fleet. To completely phase out fossil fuels, requires the removal of coal, gas, and petrochemical manufacturing. This is discussed in Scenario B – The complete phasing out of fossil fuels and complete substitution with non-fossil fuel power generation (see Section 23).

19 THE HYDROGEN ECONOMY AS A POSSIBLE SUBSTITUTE FOR FOSSIL FUELS

The hydrogen economy is now often promoted as a replacement system to phase out fossil fuels. Hydrogen is to be manufactured, stored then used as a fuel in a power cell (also called hydrogen fuel cell, or H-cell). A hydrogen fuel cell vehicle is now in competition of the Electric Vehicle as a substitution option to phase out Internal Combustion Engine (ICE) vehicles.

The purpose of Section 19 is to provide a summary of how hydrogen is used now, how it is manufactured and how power fuel cells function.



Assessment of the Extra Capacity Required of Alternative Energy Electrical Power Systems to Completely Replace Fossil Fuels

The Hydrogen Economy refers to the proposed strategy of using hydrogen as a low-carbon energy source – replacing petroleum products as a transport fuel for Internal Combustion Engine (ICE) vehicles (Hydrogen Council 2020, IRENA 2019, IRENA 2018 FCH 2019, COAG 2019, and ITM 2017). Also, hydrogen could be used as a substitute for natural gas as a heating fuel. Hydrogen is attractive because whether it is burned to produce heat or reacted with air in a fuel cell to produce electricity, the only byproduct is water.

Hydrogen is not an energy source though, so much as an energy carrier or storage medium. Hydrogen is not found in pure form in the natural environment. This means that hydrogen fuel needs to be produced from other compounds such as natural gas, biomass, alcohols, or water. In all cases it takes energy to convert these into pure hydrogen.

One of the most potentially useful ways to use hydrogen is in electric cars or buses in conjunction with a fuel cell which converts the hydrogen into electricity.

At the moment, hydrogen is most commonly produced from natural gas. In this situation, a typical fuel cell car generates 70–80g CO_2 for each kilometer driven – similar to a modern gasoline hybrid or to a battery electric vehicle charged with today's UK grid electricity.

These emissions can be reduced towards zero if the hydrogen is produced using low-carbon electricity sources such as renewables, nuclear to electrolyze water. A potential downside is that much less electricity is harvested from hydrogen in a fuel cell than the electricity required to produce that same volume of hydrogen.

It is the flexibility that hydrogen offers that makes it so potentially useful within future low-carbon energy systems. It can be produced from a wide variety of resources and can be used in a wide range of applications, such as power generation, as a transport fuel for low carbon vehicles, for the chemical industry, and for low carbon heating. Also, hydrogen is already used extensively in the chemical industry. This means that technology for hydrogen production, handling, and distribution on a large scale, is mature.

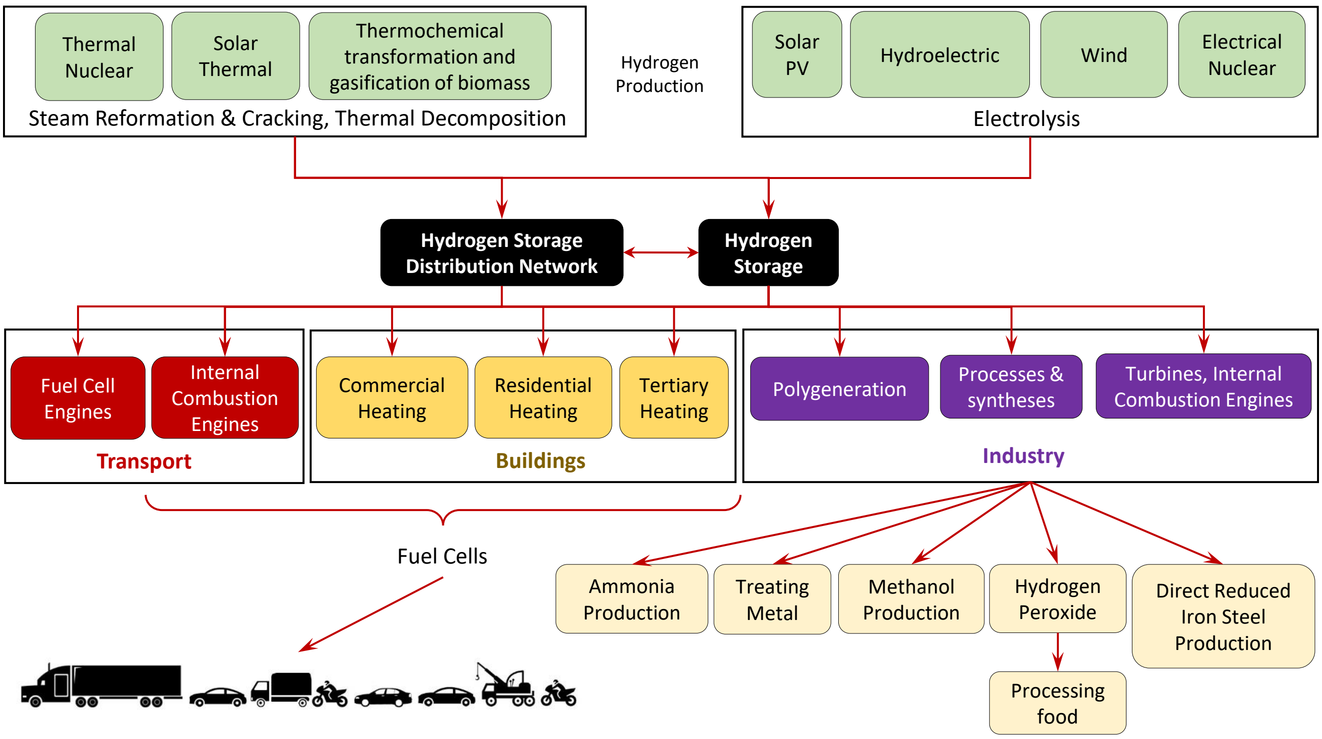


Figure 19.1. The proposed hydrogen economy
(Image: Simon Michaux)

19.1 Existing Hydrogen Demand Consumption by Application

Conventional demand for hydrogen is to resource mostly two applications (Table 19.1 and Figure 19.3).

The largest market share is used for the conversion of heavy petroleum fractions into lighter ones via hydrocracking. Hydrocracking is usually performed on heavy gas oils and residues, to remove feed contaminants (nitrogen, sulfur, metals) and to convert them into lighter fractions including diesel gasoils. The chemistry involves the conversion of heavy molecular weight compounds to lower molecular weight compounds through carbon-carbon bond breaking and hydrogen addition.

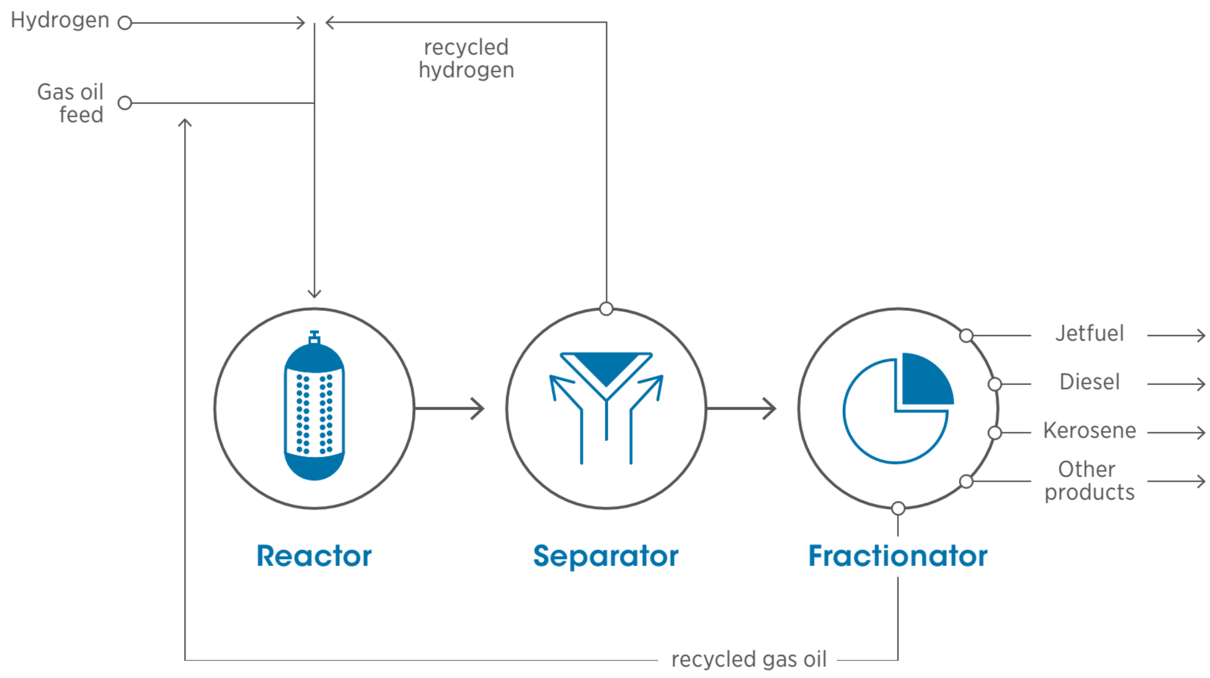


Figure 19.2. Process flow chart for hydrocracking the role of hydrogen
(Source: EIA 2019) (Copyright License: https://www.eia.gov/about/copyrights_reuse.php)

Hydrogen is also used in other processes including the aromatization process, hydrodesulfurization the refining of petroleum products. The second largest market share application is the production of ammonia via the Haber process (Appl 1982), which is used predominantly in the production of petrochemical fertilizers.

Table 19.1. Hydrogen Use and Application (Source: IEA 2019 –The Future of Hydrogen, EIA Hydrogen)

Application	Use (Million Tonnes)	Use (%)
Ammonia Production	31,5	43 %
Refining	38,2	52 %
Other Uses	4,2	6 %
Sum Total	73,9	100 %

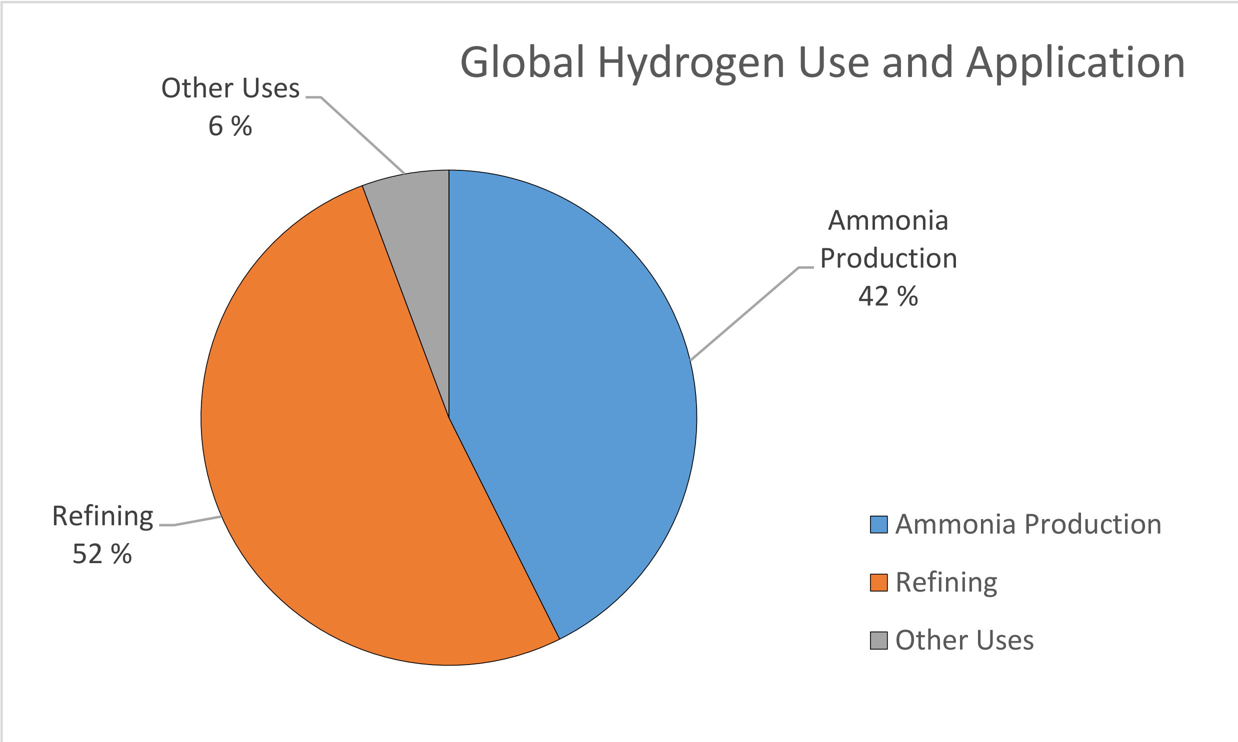
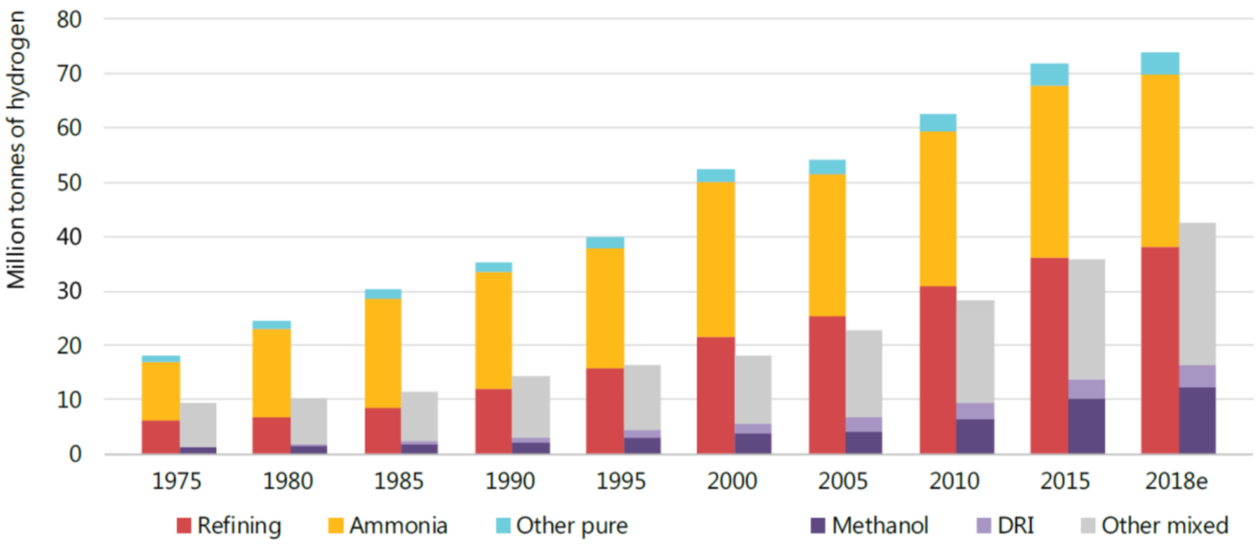


Figure 19.3. Hydrogen Use and Application (Source: IEA 2019 –The Future of Hydrogen, EIA Hydrogen)

Figure 19.4 shows how the hydrogen market has evolved between 1975 and 2018.



Notes: DRI = direct reduced iron steel production. Refining, ammonia and "other pure" represent demand for specific applications that require hydrogen with only small levels of additives or contaminants tolerated. Methanol, DRI, and "other mixed" represent demand for applications that use hydrogen as part of a mixture of gases, such as synthesis gas, for fuel or feedstock.

Figure 19.4. Estimated global annual demand for hydrogen in 2018 (pure or as part of mixed gases) by application. (Source: IEA 2019 –The Future of Hydrogen)

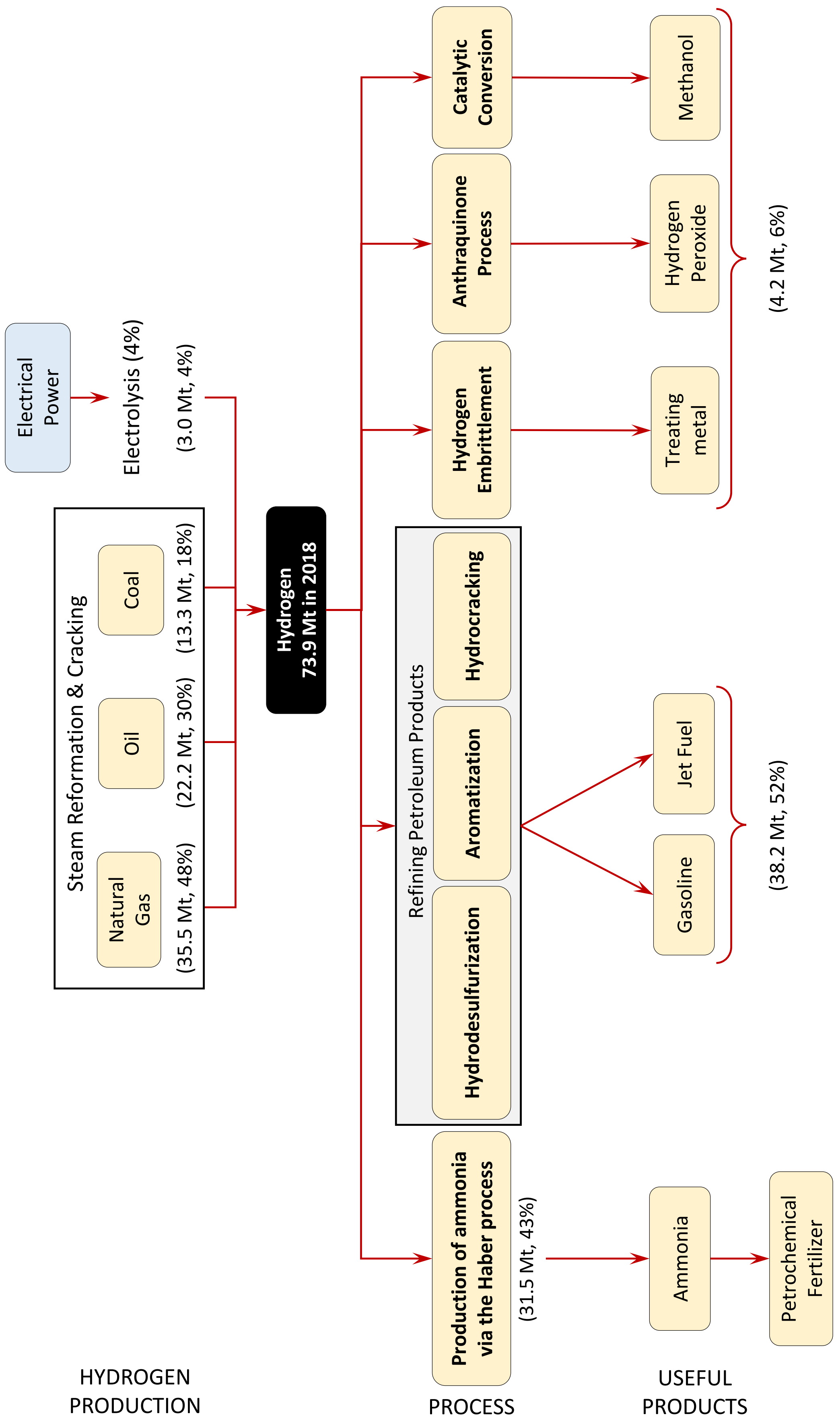


Figure 19.5. Existing hydrogen production and applications
(Image: Simon Michaux)

19.2 Hydrogen production

Hydrogen production can be divided into three segments (USDoE 2019):

- *Merchant* hydrogen—hydrogen generated on site or in a central production facility and sold to a consumer by pipeline, bulk tank, or cylinder truck delivery.

- *Captive* hydrogen—hydrogen produced by the consumer for internal use.

- *By-product* hydrogen—hydrogen that is recovered from by-product process streams and can be consumed by the same company (as with captive) or sold to another company (as with merchant).

Both merchant and captive hydrogen production can be considered to be the primary saleable product of the refining process, while by-product hydrogen is the result of processes that are not for the purpose of producing hydrogen. So, merchant hydrogen can include hydrogen produced from steam methane reforming or water electrolysis. It can also include hydrogen that was produced as a byproduct, then sold as a commercial product to a third party. Captive hydrogen can include an industrial site producing (which could be with steam methane reforming, water electrolysis) and then using hydrogen gas in the same process plant, with no transport. In this instance, hydrogen was produced in an industrial process, where it still was the primary desired product. Examples of captive hydrogen production include steam reforming of hydrocarbons and ammonia dissociation (which is common in the metals industry) (USDoE 2019).

Hydrogen is produced as the by-product of many processes, one example of which is brine electrolysis for chlorine and sodium hydroxide production (USDoE 2019). By-product hydrogen can be vented, sold as merchant hydrogen, or captured and used on site.

Based on which segments are included in accounting for hydrogen production, estimates can vary (USDoE 2019). For example, some sources do not include by-product hydrogen because hydrogen production is not the primary saleable product.

Hydrogen is produced from four main raw materials and methods: natural gas, oil, coal, and electrolysis using electricity (Table 19.2 and Figure 19.6), with fossil fuels accounting for 96%.

Table 19.2. Hydrogen Production (Source: IEA 2019 –The Future of Hydrogen, EIA Hydrogen)

Raw Material Source	Production	
	(Million Tonnes)	(%)
Natural Gas	35,5	48 %
Oil	22,2	30 %
Coal	13,3	18 %
Electrolysis	3,0	4 %
Sum Total	73,9	100 %

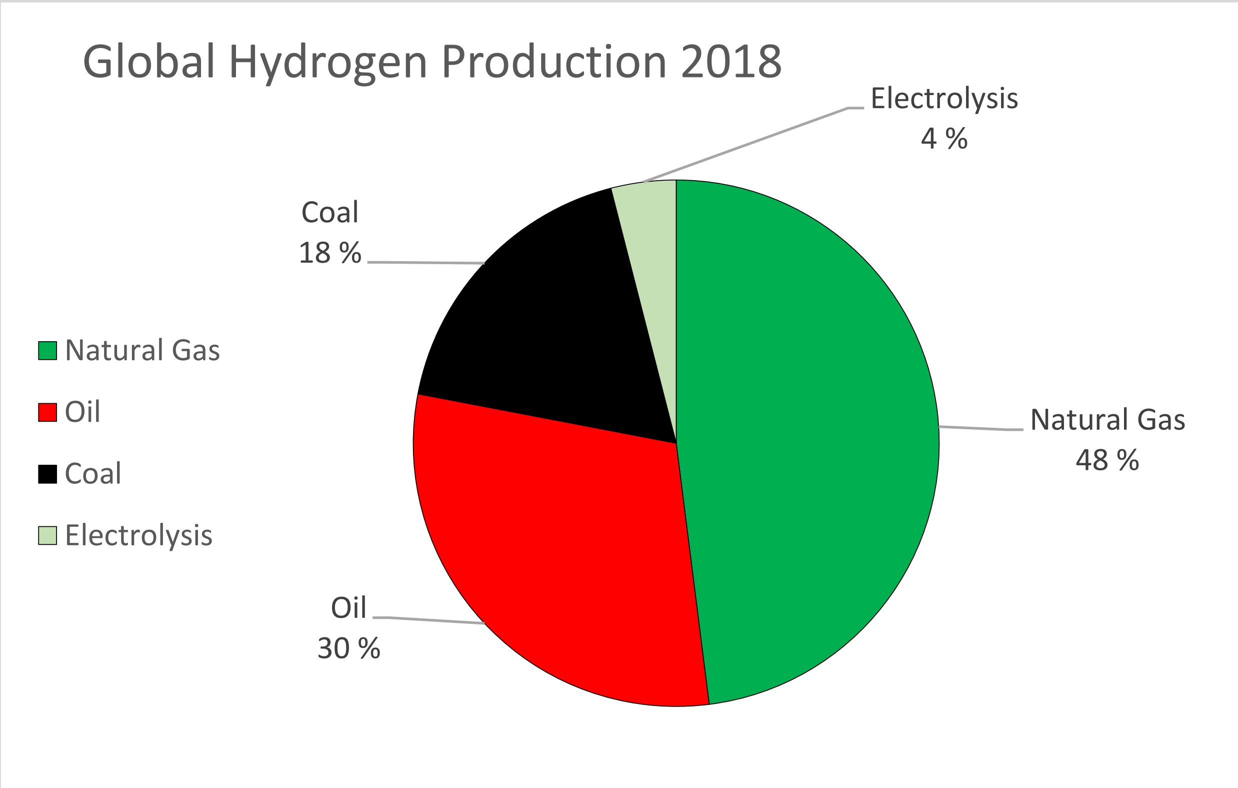


Figure 19.6. Hydrogen Production (Source: IEA 2019 –The Future of Hydrogen, EIA Hydrogen)

19.2.1 Hydrogen production with steam reforming

Steam reforming is a hydrogen production process from natural gas. This method is currently the most economically viable source of hydrogen (IRENA 2019).

This process consists of heating the gas to between 700–1100 °C in the presence of water vapor steam and a nickel metal catalyst (Rostrup-Nielsen 2005). The resulting endothermic reaction breaks up the methane molecules and forms carbon monoxide CO and hydrogen H_2. The carbon monoxide gas can then be passed with steam over iron oxide or other oxides and undergo a water gas shift reaction to obtain further quantities of H_2.

For this process high temperature (700–1100 °C) steam (H_2O) reacts with methane (CH_4) in an endothermic reaction to yield a syngas (U.S. DoE 2008).

$$CH_4 + H_2O \rightarrow CO + 3H_2$$

In a second stage, additional hydrogen is generated through the lower-temperature, exothermic, water gas shift reaction, performed at about 360 °C:

$$CO + H_2O \rightarrow CO_2 + H_2$$

The oxygen (O) atom is stripped from the additional water (in the form of steam) to oxidize CO to CO_2. This oxidation also provides energy to maintain the reaction. Additional heat required to drive the process is generally supplied by burning some portion of the methane feedstock.

This process also produces large volumes of major byproducts like CO, CO_2 and other problematic gases (Press *et al* 2008). Depending on the quality of the feedstock (natural gas, rich gases, naphtha, etc.), one ton of hydrogen produced will also produce 9 to 12 tons of CO_2 (Collodi 2010).

19.2.2 Partial oxidation

Another method of hydrogen production is partial oxidation, using natural gas or other hydrocarbons as a feedstock. A fuel-air or fuel-oxygen mixture is partially combusted resulting in a hydrogen rich syngas. Hydrogen and carbon monoxide are obtained via the water-gas shift reaction (Press *et al* 2008). Carbon dioxide can be co-fed to lower the hydrogen to carbon monoxide ratio.

The partial oxidation reaction occurs when a substoichiometric fuel-air mixture or fuel-oxygen is partially combusted in a reformer or partial oxidation reactor. The chemical reaction takes the general form:

$$C_nH_m + {}^{n}/2\ O_2 \rightarrow nCO + {}^{m}/2\ H_2$$

19.2.3 Production of hydrogen with plasma reforming

A plasma reforming method, developed in the 1980s, called the Kværner-process or Kvaerner carbon black & hydrogen process. This is used for the production of hydrogen and carbon black from liquid hydrocarbons (C_nH_m). Of the available energy of the feed, approximately 48% is contained in the hydrogen, 40% is contained in activated carbon and 10% in superheated steam (Bellona-Hydrogen Report). CO_2 is not produced in the process.

19.2.4 Production of hydrogen with coal gasification

The process of coal gasification uses steam and a carefully controlled concentration of gases to break molecular bonds in coal and form a gaseous syngas—a mixture consisting primarily of carbon monoxide (CO), hydrogen (H_2), carbon dioxide (CO_2), natural gas (CH_4), and water vapour (H_2O)—from coal and water, air and/or oxygen (Hordeski 2007).

This source of hydrogen is advantageous since its main product is coal-derived gas which can be used for fuel. The gas obtained from coal gasification can later be used to produce electricity more efficiently and allow a more effective capture of flue gases than the traditional burning of coal (Lee & Lee 2001).

19.2.5 Production of hydrogen with petroleum coke gasification

Hydrogen can be produced from petroleum coke through gasification, using the same methodology as with coal gasification. The petroleum coke is converted to a hydrogen rich syngas. The syngas consists mainly of hydrogen, carbon monoxide and H_2S, depending on the sulfur content of the coke feed (Gemayel *et al* 2014).

19.2.6 Production of hydrogen with biomass gasification

Biomass is any material that has participated in the growing cycle. This includes agricultural by products, food waste, wood waste as well as trees and grasses grown as energy crops. These feed products would be gasified in the same fashion as coal or petroleum coke.

19.2.7 Production of hydrogen with nuclear power

Nuclear power could be used to mass produce hydrogen. Electricity could be used to power electrolysis. The heat and steam generated by a nuclear plant could be used to thermo-chemically decompose water into hydrogen and oxygen. Thermo-chemical splitting of water occur at temperatures exceeding 750 °C, with a theoretical efficiency of 40-52% in hydrogen production. This method requires more research before it can be applied industrially.

19.2.8 Production of hydrogen with electrolysis of water

Hydrogen can be produced by using electricity to split water into hydrogen and oxygen. The electrolysis of water is 70–80% efficient, with a 20–30% conversion loss (ITM 2017 & FCHJU 2016). In comparison, steam reforming of natural gas has a thermal efficiency between 70–85% (Kalamaras & Efstathiou 2013). The efficiency temperature for water electrolysis to operate is between 50–80 °C, where in comparison, steam methane reforming requires temperatures between 700–1100 °C (U.S. DoE 2018).

There are three main types of electrolysis cells (Badwal *et al* 2013).

- Alkaline electrolysis cells (AEC)
- Polymer electrolyte membrane cells (PEM)
- Solid oxide electrolyzer cells (SOEC)

19.2.8.1 Alkaline electrolyzers (AEC)

Alkaline electrolyzers have been used by industry for nearly a century, for example in the manufacture of chlorine. These cells generally use nickel catalysts and can be economically cheaper, but less efficient (Ahmad *et al* 2018). AEC is a type of electrolyzer that is characterized by having two electrodes operating in a liquid alkaline electrolyte solution of potassium hydroxide (KOH) or sodium hydroxide (NaOH). These electrodes are separated by a diaphragm, separating the product gases and transporting the hydroxide ions (OH^-) from one electrode to the other.

This technique produces very clean hydrogen gas, at more than 99.989% purity (Badwal *et al* 2013). Usually an alkaline medium is employed (25–30% KOH). The electrolytic reactions that occur on each electrode are given by the following equations:

At the Cathode: $2H_2O + 2e^- \rightarrow 2OH^- + H_2$

At the Anode: $2OH^- \rightarrow ½O_2 + H^+ + 2e^-$

Overall Fuel Cell balance: $H_2O \rightarrow H_2 + ½O_2$

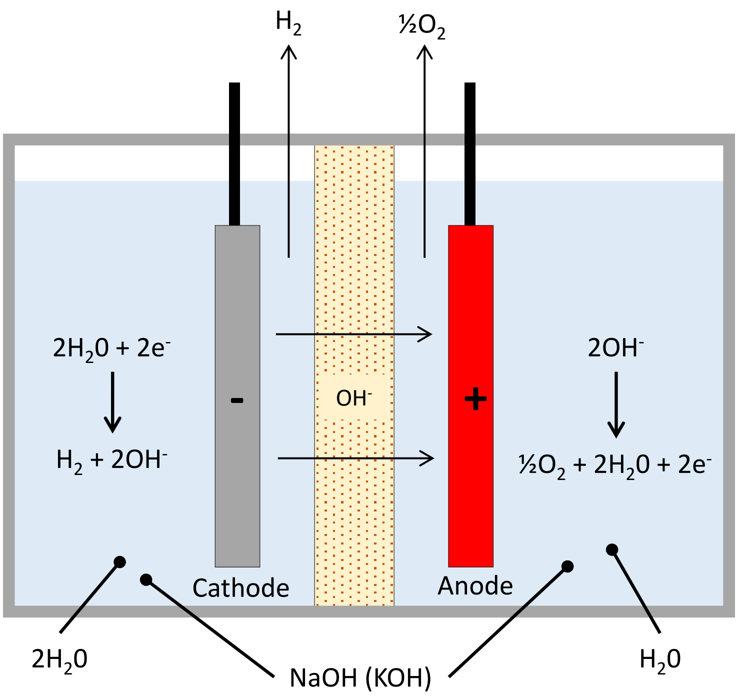


Figure 19.7. Schematic diagram of the alkaline electrolysis cell (Image: Simon Michaux)

AECs optimally operate at high concentrations electrolyte (KOH or potassium carbonate) and at high temperatures, often near 200 °C.

19.2.8.2 Polymer electrolyte membrane cells electrolyzers (PEM)

PEM cells use a proton conductive polymer membrane as electrolyte. PEM's are currently more expensive (they generally use expensive platinum group metal catalysts) but are more efficient and can operate at higher current densities. PEM electrolysis cells typically operate below 100 °C (IRENA 2018). These cells have the advantage of being comparatively simple and can be designed to accept widely varying voltage inputs which makes them ideal for use with renewable sources of energy such as solar PV (Millet 2015).

The basic form of the individual PEM fuel cell contains three primary components: two electrodes (anode and cathode) and a conductive electrolyte (Figure 19.8). In the case of PEM fuel cells, each electrode is comprised of a porous, high-surface area material (for example conductive carbon) impregnated with an electrocatalyst. In 2020, that electrocatalyst is typically platinum or a platinum alloy. Platinum exhibits high activity for hydrogen oxidation and continues to be a frequently used electrocatalyst material.

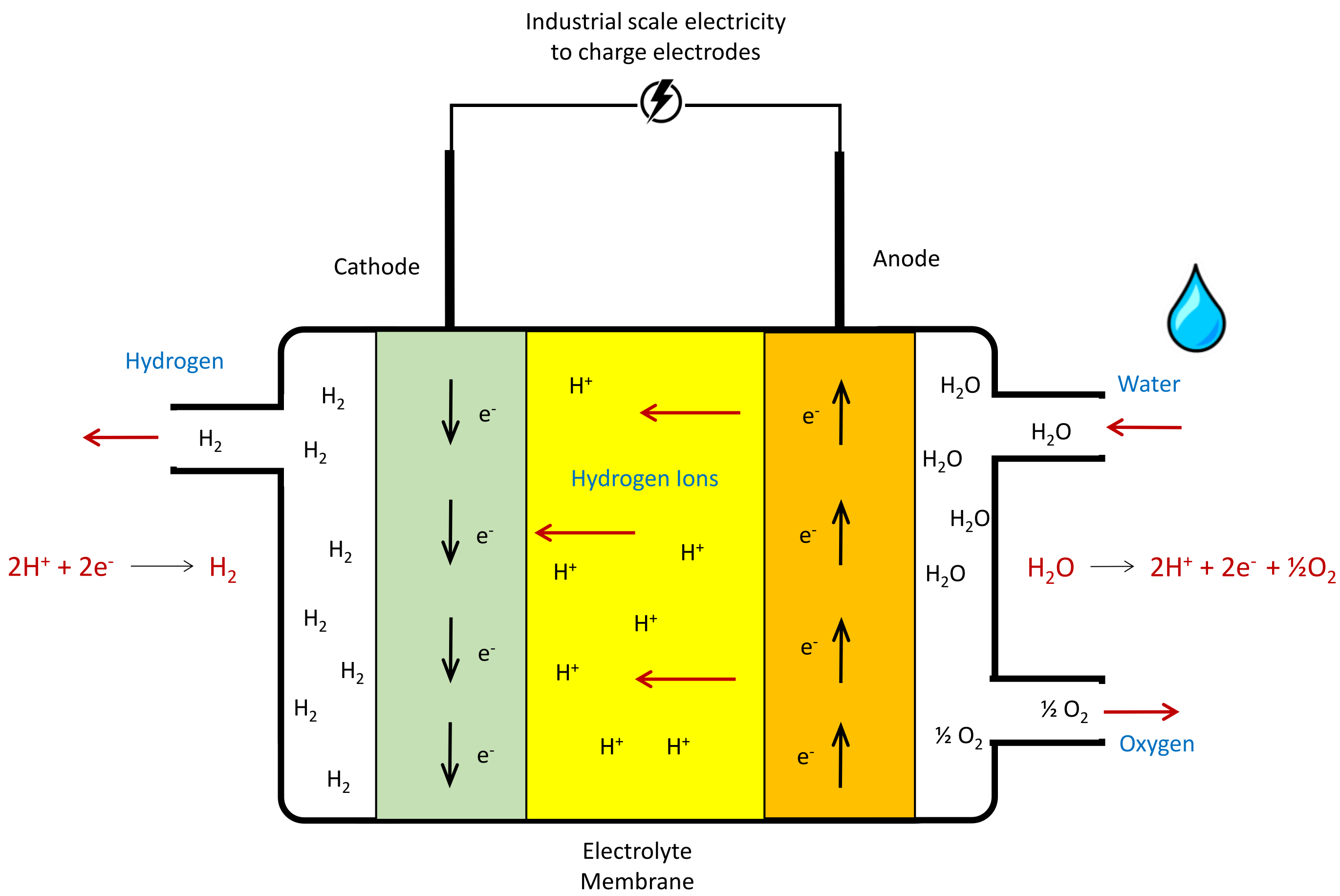


Figure 19.8. Schematic of the individual unit inside a PEM electrolysis cell, splitting water into hydrogen and oxygen to generate hydrogen gas (Image: Simon Michaux)

The negative side is called the anode, while the oxygen side of the fuel cell is positive and is called the cathode. The electrochemical reactions in fuel cell happen simultaneously on both sides of the membrane – the anode and the cathode.

At the heart of a PEM fuel cell is a polymer membrane that has some unique capabilities. It is impermeable to gases, but it conducts protons (hence Proton Exchange Membrane name). The membrane, which acts as the electrolyte, is squeezed between the two porous, electrically conductive electrodes.

Electrical generation in a PEM fuel cell is driven by two primary chemical reactions, as illustrated in red text in Figure 19.8. Electrochemical reactions occur at the surface of the catalyst at the interface between the electrolyte and the membrane.

Water (H_2O) enters at the anode (RHS top of Figure 19.8). There, a chemical reaction causes the hydrogen molecules to separate into positive hydrogen ions (H^+ or protons) and electrons (e^-). The oxygen, which has been split from the water exits the electrolyzer as a gas product (RHS bottom of Figure 19.8).

Each hydrogen atom consists of one electron and one proton. The electrons remain behind and thereby give the anode a negative charge, creating a voltage difference between the anode and the cathode.

This electrochemical reaction is driven by the electric potential between the anode and the cathode, created by the attached battery. The electrons are drawn along the external circuit by the battery, forming a circuit with the cathode. The H^+ protons are conducted through the electrolyte membrane, while the electrons travel through electrically conductive electrodes, through current collectors, and through the outside circuit.

The hydrogen ions (H^+) passes through the electrolyte membrane to the cathode, where they combine with electrons stripped from the cathode to form hydrogen gas (H_2).

The electrolyte material is a polymeric membrane and serves as an ionic conductor (NET 2004). Several key requirements are considered when selecting a fuel cell electrolyte. Desirable properties include high proton conductivity, high chemical and thermal stability, and low gas permeability. Considered materials are can be fluorinated polymers functionalized with sulphonic acid moieties. The electrolytic reactions that occur on each electrode are given by the following equations:

At the Anode (strip e^- from H_2O):	$H_2O \rightarrow H_2 + ½O_2$ Generated by Electrical current
At the Cathode (add e^- to Hydrogen ions):	$H^+ + 2e^- \rightarrow H_2$
Overall Fuel Cell balance:	$H_2O \rightarrow H_2 + ½O_2$

In view of application in the hydrogen economy to produce hydrogen as an energy carrier, PEM water electrolyzers can be operated in a flexible context. These units can accept highly transient power loads (such as those resulting from the use of intermittent energy sources of electricity via PV panels or wind turbines) and can operate over the quasi-entire power load range (10–100%) within seconds with no significant operational constraints. This is not a limitation for the alkaline process. Polymer electrolyte membrane water electrolyzers can also be operated under pressure (50 bars is available in some commercial products; operation under several 100 bars has been reported in the literature) and under pressure differences between the anode and cathode (Millet 2015).

19.2.8.3 Solid oxide electrolyzer cells (SOEC)

SOEC cells operate at high temperatures, typically around 800 °C through a process termed High temperature electrolysis. These cells use ceramic as the electrolyte and can operate on air or natural gas. Where PEM cells us positively charged hydrogen ions to conduct through the polymer membrane, SOEC cells use negatively charged oxygen ions that travel through a porous cathode then through the electrolyte, then through a porous anode, where they combine with hydrogen to form water. The solid ceramic electrolyte is a hermetic barrier between chemical reactants so no hydrogen or water can reach the air side of the fuel cell. This simplifies operation.

The heat energy can be provided from a number of different sources, including waste industrial heat, nuclear power stations or concentrated solar thermal plants. This has the potential to reduce the overall cost of the hydrogen produced by reducing the amount of electrical energy required for electrolysis (IRENA 2018 & IRENA 2019). SOEC technology holds the promise of greater efficiencies compared to AEC and PEM electrolysis. However, SOEC is a less mature technology, only demonstrated at laboratory and small demonstration scale.

Tables 19.3, 19.4 and 19.5 shows a comparison in performance between AEC, PEM and SOEC) cells.

Table 19.3. Comparison between alkaline, PEM, and high-temperature electrolysis (Source: Ahmad et al 2018)

Technology	Advantages	Disadvantages
Alkaline electrolysis (AEC)	Technology: oldest and well established Cost: cheapest and effective Catalyst type: Noble Durability: Long Term Stacks: MW range Efficiency: 70% Commercialized	Current density: Low Degree of purity:Low (crossover of gases) Electrolyte: Liquid and corrosive Dynamics: Low dynamic operation Load range: Low for partial load Pressure: Low operational pressure
PEM electrolysis (PEM)	Current density: High Voltage efficiency: High Load range: Good partial load range System design: Compact Degree of purity: High gas purity Dynamics: High dynamics operation Reponse: Rapid system response	Technology: New and partially established Cost: High cost of components Catalyst: Noble catalyst Corrosion: Acidic environment Durability: Comparatively low Stack: Below MW range Membrane: Limited and costly Commericalization in near term
High-temperature steam electrolysis (SOEC)	Efficiency: 100% Thermal neutral efficiency >100% with hot steam Pressure; High-pressure operation	Technology: In laboratory phase Durability: Low due to high heat, ceramics System design: Bulk system design

Table 19.4. Techno-economic characteristics of AEC and PEM electrolyzers in 2017 and estimated 2025 (Source: IRENA 2018, FCH JU 2017)

Technology	Unit of Measure	AEC Electrolysis cells		PEM Electrolysis cells	
		2017	2025	2017	2025
Efficiency	kWh of electricity per kg of H_2	51	49	58	52
Efficiency (LHV)	(%)	65	68	57	64
Lifetime stack	Operating Hours	80 000 h	90 000 h	40 000 h	50 000 h
CAPEX - total system cost (incl. Power supply and installation costs)	€/kW	750	480	1200	700
OPEX	% of inital CAPEX/year	2 %	2 %	2 %	2 %
CAPEX - stack replacement	€/kW	340	215	420	210
Typical output pressure*	Bar	Atmospheric	15	30	60
System lifetime	Years	20		20	

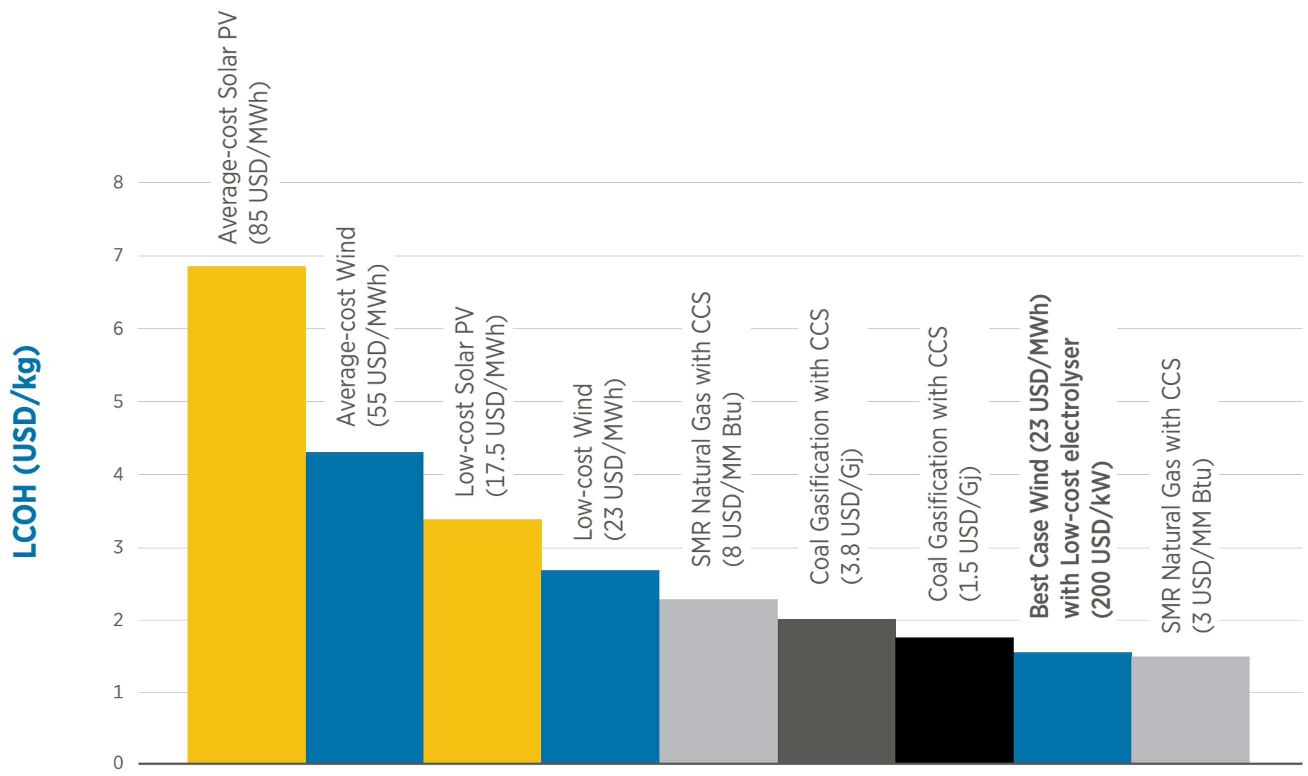
*Higher output pressure leads to lower downstream cost to pressurise the hydrogen for end use.

Notes: H_2 = hydrogen; h = hour; kg = kilogram; kW = kilowatt; kWh = kilowatt hour; LHV = lower heating value; OPEX = operating expenditure; CAPEX and OPEX are based on a 20 MW system.

Table 19.5. Electrolyzers specifications (Source: Thomas 2018)

	Alkaline Electrolyzers (AEC)			Polymer electrolyte membrane Electrolyzers (PEM)		
Unit	HySTAT -15-10	HySTAT -60-10	HySTAT -100-10	HyLYZER -300-30	HyLYZER -1000-30	HyLYZER -5000-30
Output pressure	10 bar.g (27 bar.g optional)			30 bar.g		
Number of cell stacks	1	4	6	1	2	10
Nominal hydrogen flow	15 Nm^3/h	60 Nm^3/h	100 Nm^3/h	300 Nm^3/h	1000 Nm^3/h	5000 Nm^3/h
Nominal input power	80 kW	300 kW	500 kW	1.5 MW	5 MW	25 MW
AC power consumption (utilities included, at nominal capacity)	5.0 - 5.4 kWh/Nm^3			5.0 - 5.4 kWh/Nm^3		
Hydrogen flow range	40-100%	10-100%	5-100%	1-100%		
Hydrogen purity	99.998% O_2 < 2ppm, N_2 < 12 ppm (higher purities optional)			99.998% O_2 < 2ppm, N_2 < 12 ppm (higher purities optional)		
Tap water consumption	< 1.7 liters / Nm^3 Hydrogen			< 1.4 liters / Nm^3 Hydrogen		
Footprint (in shipping containers)	1 x 20 ft	1 x 40 ft	1 x 40 ft	1 x 40 ft	2 x 40 ft	10 x 40 ft

Figure 19.9 shows the cost of producing hydrogen with a range of methods. Figure 19.20 shows the classification of how clean hydrogen is classified.



Notes: Electrolyser capex: USD 840/kW; Efficiency: 65%; Electrolyser load factor equals to either solar or wind reference capacity factors. For sake of simplicity, all reference capacity factors are set at 48% for wind farms and 26% for solar PV systems.

Figure 19.9. Costs of producing hydrogen from renewables and fossil fuels (Source: IRENA Analysis, IRENA 2019)

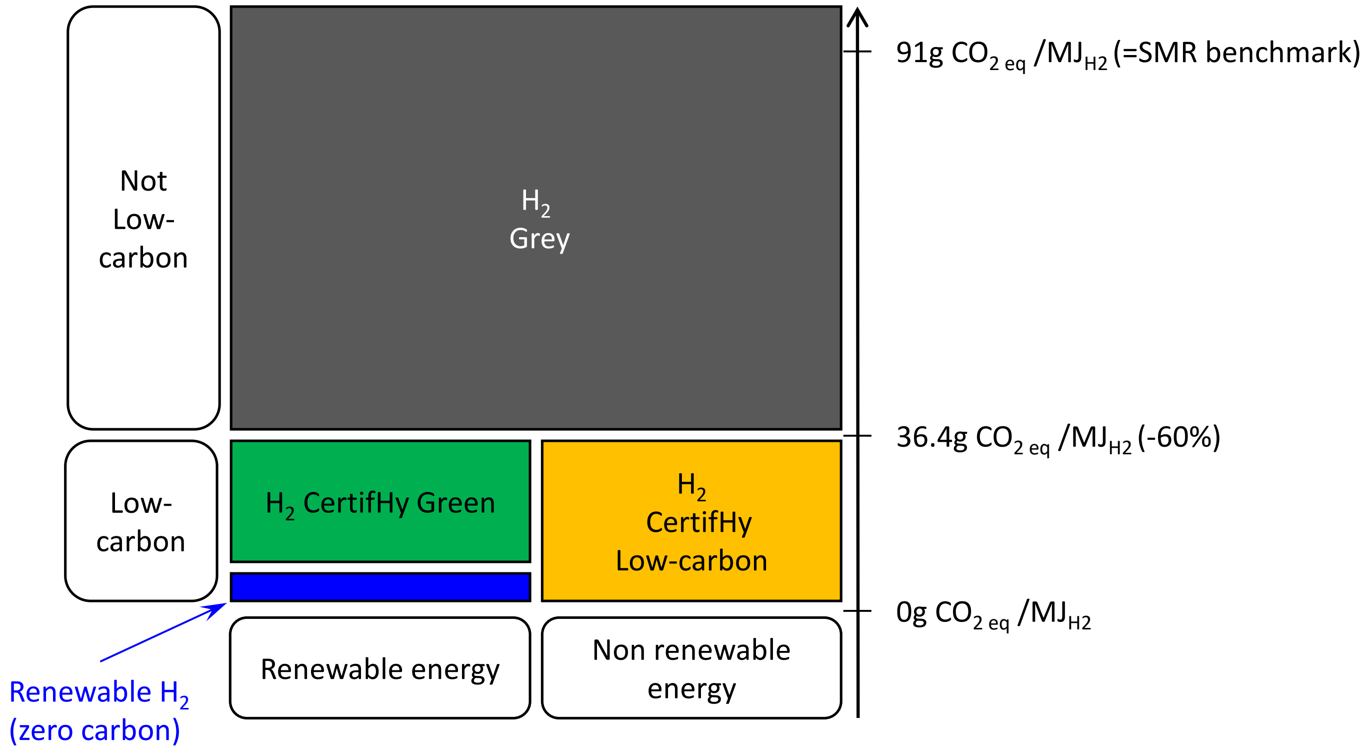


Figure 19.20. 'Clean' Hydrogen definitions (Source: redrawn from Thomas 2018)
(Image: Simon Michaux)

19.3 The Storage and Transport of Hydrogen

A pure hydrogen economy, or a complete replacement of petroleum powered ICE vehicles with hydrogen fuel cell vehicles will require a comprehensive investment in infrastructure. Two key issues will determine the nature of that infrastructure.

- Where the hydrogen is produced
- What form the hydrogen takes in storage on board the vehicle

There are three places where hydrogen can be produced

1. Hydrogen could be produced on board the car or truck
2. Hydrogen could be produced at local fueling stations (similar to current gasoline fueling stations)
3. Hydrogen could be produced at a remote central point, then transported to fueling stations

Hydrogen storage systems need to enable a vehicle to travel 500-600km and fit in small enough volume that does not compromise either passenger space or cargo storage space (ARUP 2019). The driving range requirement will mean that the fuel tank must contain at least 5kg of hydrogen, and be fueled in under 5 minutes at a fuel station. There are several ways to do this.

19.3.1 Liquid Hydrogen

Liquid hydrogen is widely used industrially for the storing and transporting of large quantities of hydrogen gas. A liquid has a much higher energy density than a gas, thus is more efficient to transport. To do this, hydrogen gas has to be stored in a pressurized container. At atmospheric pressure, hydrogen becomes liquid only at a temperature of -253 ^oC, where absolute zero is -273.15 ^oC. Hydrogen in this form can only be stored in a super insulated tank, termed as cryogenic storage. NASA used liquid hydrogen in cryogenic storage to power the Space Shuttle and is the fuel of choice for space exploration for future missions (NASA https://www.nasa.gov/topics/technology/hydrogen/hydrogen_fuel_of_choice.html). This form of storage is only suitable for transport of large quantities hydrogen over a long distance, and/or is not economically viable in the proposed transport system.

Hydrogen gas compressed into a liquid hydrogen in cryogenic tanks has a volumetric density of 70.8 kg of hydrogen per cubic meter (kg of H_2 /m^3) (Zuttel 2004).

19.3.2 Compressed hydrogen

Compressed hydrogen is the most common form of storage. It is this method that will probably be used to store hydrogen on board passenger cars and trucks to service fuel cells. Hydrogen is compressed into a tank to a pressure range between 250 bar (25 000 kpa or kilo-pascals) and 700 bar (70 000 kpa), depending on the application. Even at these high pressures, compressed hydrogen has less energy density than petroleum gasoline does. Increasing compression allows more hydrogen to be stored in the same volume, but more energy is needed inputted to achieve this.

To achieve a mechanical compression of 700 bar requires a multi-stage process, which requires energy equivalent to 10-15% of the calorific energy value of the produced compressed gas. Compressing 1kg of hydrogen gas into 700 bar requires a range between 2.7 and 13.5 kWh of energy, depending on the reference (Rivard *et al* 2019, Gardiner 2009 and Wipke *et al* 2014). Compressed hydrogen has safety implications relating to a flammable gas under pressure. At 700 bar (~10,000 psi) a storage system would have a volume of 3-4 times the volume of gasoline tanks typically found in cars today (DOE, EIA and Wipke *et al* 2014).

Hydrogen gas compressed to a pressure of 700 bar has a volumetric density of 40 kg of hydrogen per cubic meter (kg of H_2 /m^3) (Zuttel 2004).

For the purpose of this report, Scenario C in Section 23 will examine the widespread use of hydrogen, where it requires 2.5 kWh to compress 1 kg of hydrogen to a pressure of 700 bar in a storage tank (Zuttel 2004 and Rivard *et al* 2019). This conservative estimate has been selected to reflect possible future technological advancements in the efficiency of hydrogen storage.

19.3.3 Metal Hydrides

Metal hydrides include several classes of hydrogen containing compounds that could offer a promising means of hydrogen storage. Hydrogen is chemically bonded to one or more metals and is released through a catalyzed reaction, or through heating. Hydrides can be stored in solid form, or in a water based solution. After a hydride has released its hydrogen, a by-product remains in the fuel tank to be either replenished or disposed of.

Hydrides are classified as reversible or irreversible. Reversible hydrides act similarly to sponges soaking up hydrogen into a compact volume. These reversible hydrides are generally solids, alloys or intermetallic compounds. These hydrides can be replenished by adding pure hydrogen at fueling stations. Irreversible hydrides are compounds that undergo reactions with other reagents, such as water, producing a by-product. This process cannot be reversed. To release the hydrogen, the by-product may need to be sent to a chemical processing plant.

This storage method requires more research and development before it can be applied at industrial scale use.

19.3.4 Hydrogen produced at a remote central point

The logistics and engineering for the mass production at a central is the challenge to make this viable. Hydrogen can be produced at an industrial scale, but it needs to be stored then transported to local fueling stations. The production site would have to be close to a very large wind turbine farm or solar panel farm, then delivered to tens of thousands of local fuel distribution stations. There are two options to do this, hydrogen delivered through pipelines and hydrogen delivered with tanker trucks.

19.3.5 Pipelines

There are already many industrial scale pipelines to transport hydrogen all over the world. They tend to be relatively short in length and are located in industrial areas that use large volumes of hydrogen. Pipelines are the preferred option to transport petroleum products in the current industrial ecosystem, so the logistics and technology exists now. Pipelines may well be the least expensive long term option but requires more upfront cost of construction.

Hydrogen pipelines are comparatively expensive as they are prone to leaks and are carrying a fuel that is very diffuse. Hydrogen is very reactive, which causes steel to become very brittle over time. This means hydrogen pipelines will need close maintenance schedules.

19.3.6 Tanker trucks

Tanker trucks are the most common way of delivering hydrogen in the current ecosystem as demand is still very small and specialized compared to a fully-fledged hydrogen economy. This currently is the most flexible solution and could be used to develop the hydrogen economy initially. That being stated this is not very efficient in terms of the movement of hydrogen. Each truck would have to be loaded at the production point, then unloaded at the fuel distribution station. In between each tank truck will consume energy to drive between the production site and the fuel station, further reducing the ERoEI ratio.

19.3.7 Hydrogen produced at local fueling stations

If hydrogen is produced at local fueling stations using electricity (using electrolysis electrolyzers), then no significant new infrastructure will be needed to be constructed. The question will become, will this scale of production be able to keep up with demand for hydrogen, or would it be more effective (economically efficient) to produce the hydrogen at a remote central point at a greater scale. The number of vehicles requiring refueling, each in a timely fashion may quickly exhaust capacity.

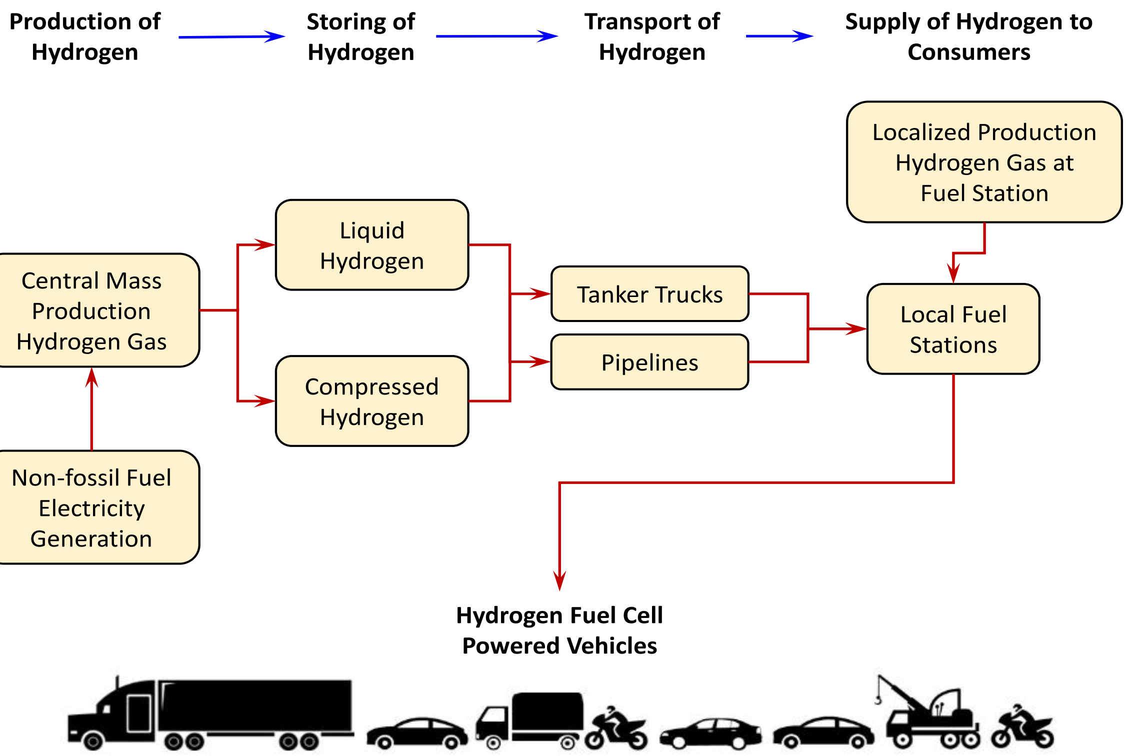


Figure 19.21. Infrastructure of the hydrogen economy
(Image: Simon Michaux)

19.4 The Hydrogen fuel cell to power vehicles

For the purpose of this report, PEM fuel cells are considered as the technology to be used in hydrogen fueled vehicles. There are alternatives but they are not as mature in an economically viable context.

Phosphoric acid fuel cells (PC). These cells use phosphoric acid as the electrolyte. They are the most mature of the fuel cell technology options. They operate at a temperature range of 150-200 ^{0}C and have an electric efficiency of 30 to 35%. That is, 30-35% of the total calorific energy of the feed natural gas is converted into useable electricity. These units generate a considerable amount of heat during operation.

Molten Carbonate fuel cells (MC). These cells use liquid carbonate as the electrolyte. They have been the subject of research and development for some time. These cells have a number of advantages over PC. MC cells operate at a very high temperature of 650 ^{0}C or higher. Heat given off can be sued to make hydrogen internally from a variety of fuels like natural gas, ethanol, and methanol. MC cells operate at an efficiency rate of 47 to 50%. The high temperatures used allow for the use of inexpensive metals like nickel to be used as the catalyst. Also, these fuel cells can tolerate higher levels of contamination of carbon monoxide, which can disrupt the electrochemical reaction in PEM cells. High temperature steam produced by MC cells can be used for industrial purposes.

19.4.1 Polymer electrolyte membrane cells electrolyzers (PEM) Fuel Cell in Vehicles

The basic form of the individual PEM fuel cell is the same as the PEM electrolyzer. It contains three primary components: two electrodes (anode and cathode) and a conductive electrolyte (Figure 19.23). Again, each electrode in the PEM fuel cells, is comprised of a porous, high-surface area material (for example conductive carbon) impregnated with an electrocatalyst (usually platinum).

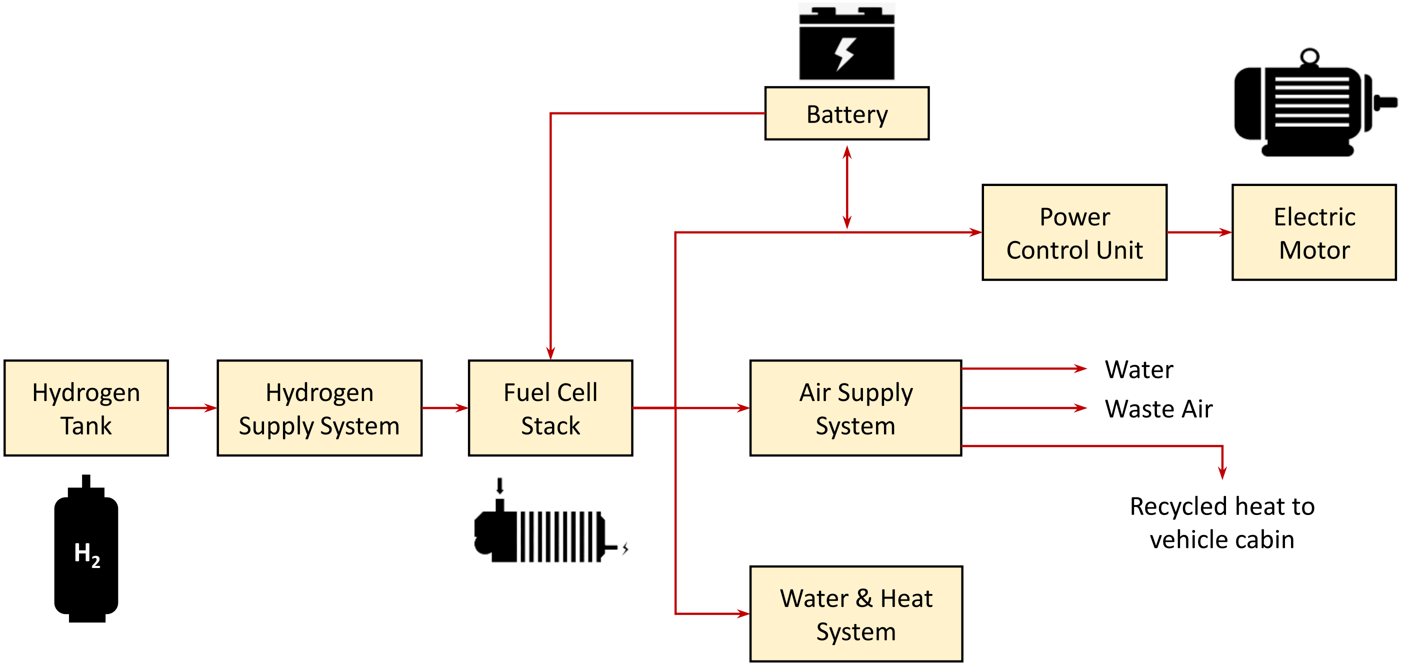


Figure 19.22. Fuel cell operation principle
(Image: Simon Michaux)

The PEM fuel cell works to the same principle as a PEM electrolyzer but instead of stripping electrons from water to generate hydrogen (and consuming electricity to do it), the reverse happens, where electrons are stripped from hydrogen gas and in combining with oxygen to form water, create an electric current.

For fuel cells operating on pure H_2, the fuel (hydrogen, H_2) enters at the anode. There, a chemical reaction causes the hydrogen molecules to separate into positive hydrogen ions (H^+ or protons) and electrons (e^-). This reaction releases heat.

Each hydrogen atom consists of one electron and one proton. The electrons remain behind and thereby give the anode a negative charge, creating a voltage difference between the anode and the cathode. The H^+ protons are conducted through the electrolyte membrane, while the electrons travel through electrically conductive electrodes, through current collectors, and through the outside circuit where they perform useful work and return to the other side of the membrane (forming an electric current). At the same time, oxygen (O_2) enters the fuel cell. The charged ions (H^+ and e^-) combine with oxygen at the cathode, producing water (H_20) and heat (O'Hayre *et al* 2009).

The electrolyte material is a polymeric membrane and serves as an ionic conductor (NET 2004). Several key requirements are considered when selecting a fuel cell electrolyte. Desirable properties include high proton conductivity, high chemical and thermal stability, and low gas permeability. Considered materials are can be fluorinated polymers functionalized with sulphonic acid moieties.

The electrolytic reactions that occur on each electrode are given by the following equations:

At the Anode (strip e^- from H_2):	$H_2 \rightarrow H^+ + 2e^-$
At the Cathode (Combine O_2 to H^+ ions e^-):	$2H^+ + ½O_2 + 2e^- \rightarrow H_2O$
Overall Fuel Cell balance:	$H_2 + (H_2 + ½O_2) \rightarrow (H_2O) + H_2$ Electrical current generated by moving e^-

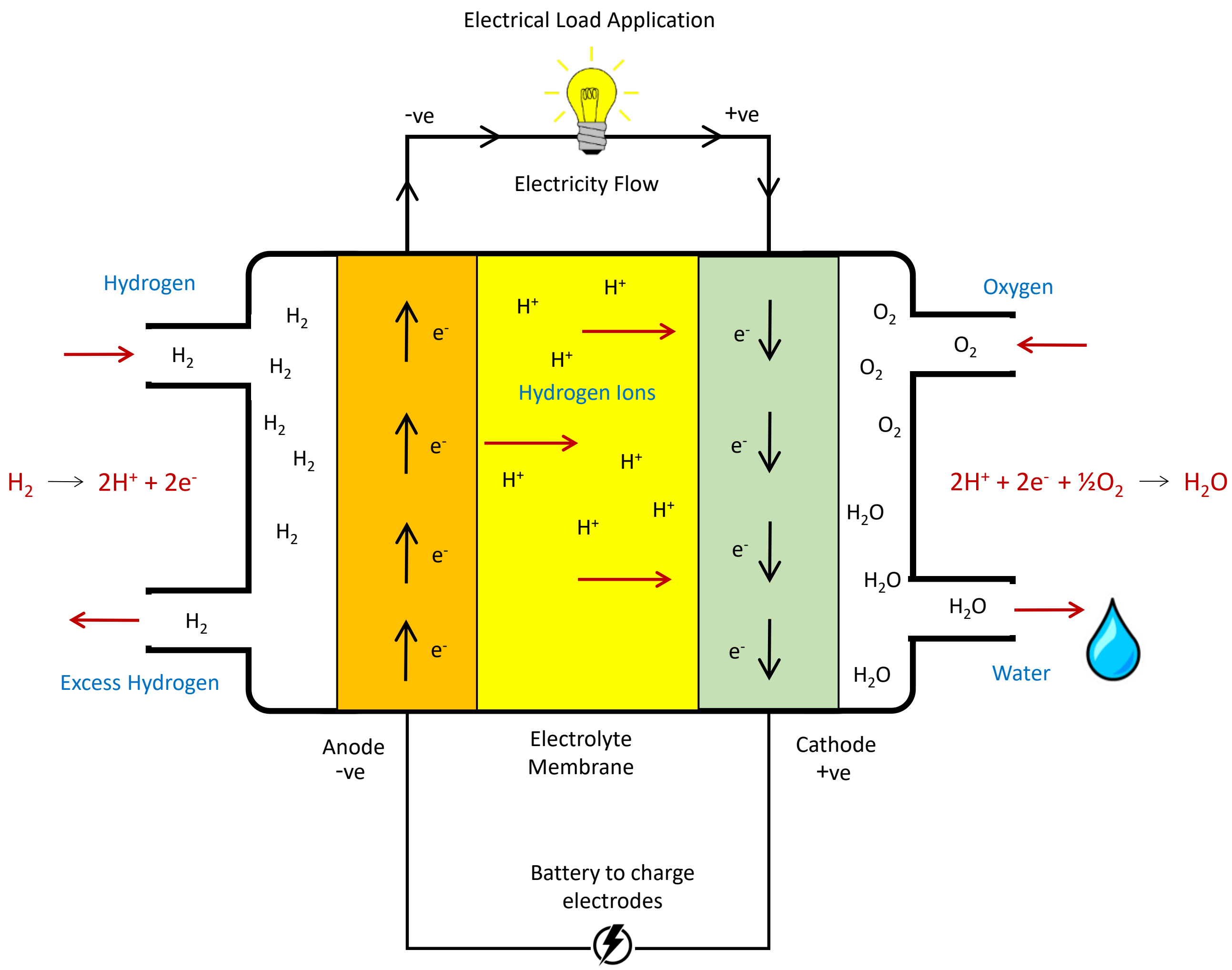


Figure 19.23. Schematic of the individual unit inside a PEM fuel cell in combining hydrogen and oxygen into water to generate electricity (Image: Simon Michaux)

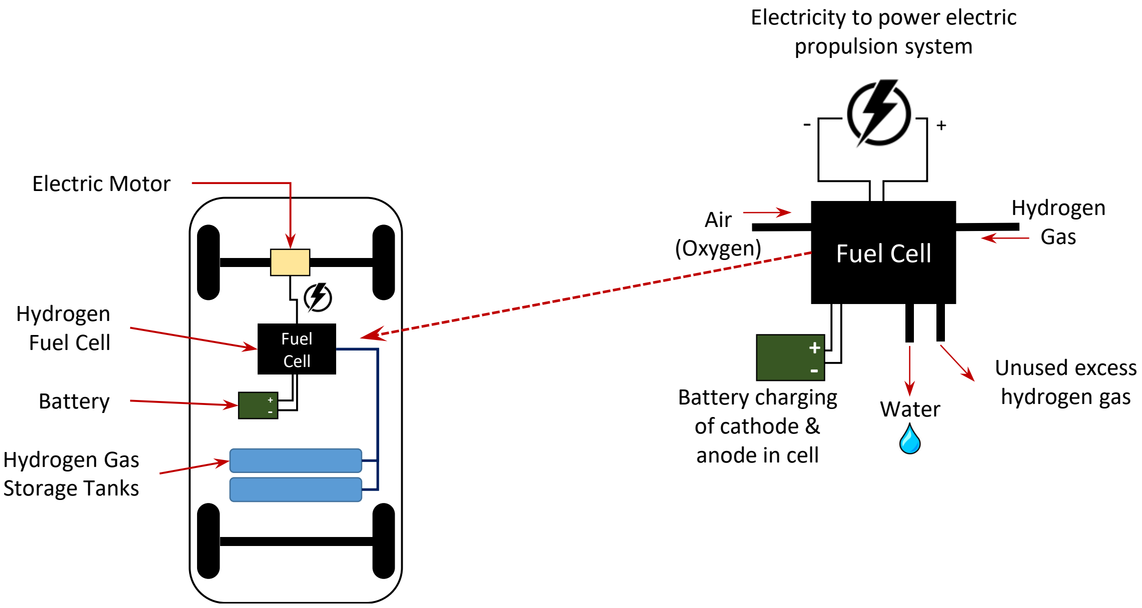


Figure 19.24. Plan view conceptual schematic of a hydrogen cell fuelled passenger car (Image: Simon Michaux)

The PEM fuel cell that is installed into a vehicle is actually an array of many individual PEM cells into what is termed a 'stack' (Figure 19.25).

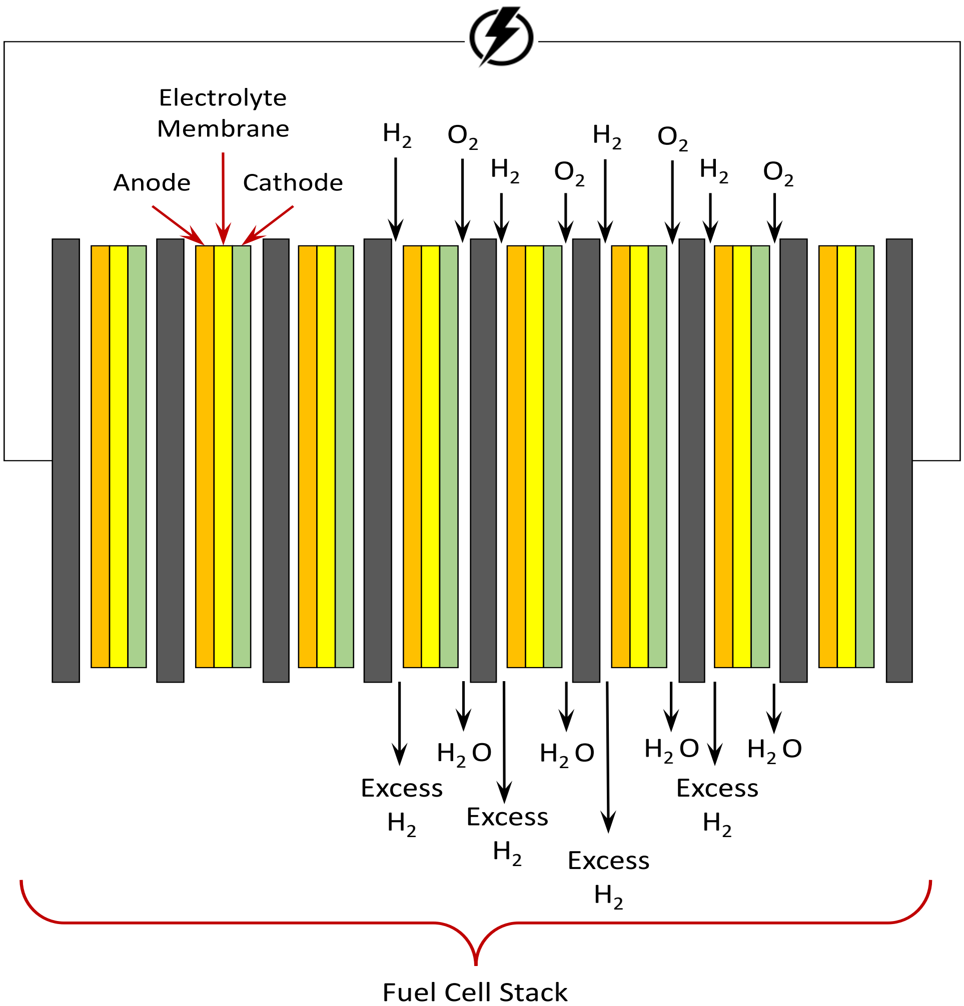


Figure 19.25. Schematic illustrating multiple PEM fuel cells combined in a stack (Image: Simon Michaux)

An example of this technology in action is the Toyota Mirai is a mid-size hydrogen fuel cell vehicle, passenger 4 door sedan. Under the United States Environmental Protection Agency (EPA) cycle, the 2016 model year Mirai has a total range of 502 km on a full tank (4kg of hydrogen in a 122.4 liter tank), with a combined city/highway fuel economy rating of 3.6 L/100 km (0.8 kg/100km, consuming 15 kWh/100km, at a speed of 100km/hr), making the Mirai a very fuel-efficient hydrogen fuel cell vehicle rated by the EPA, and the one with a comparatively long range (Toyota 2014). The Mirai consumes 1kg of hydrogen to produce 15 kWh of electricity.

Figure 26 below shows the energy efficiency of tank to wheels stage of the FCEV system to be 36-45% (Deloitte 2020).

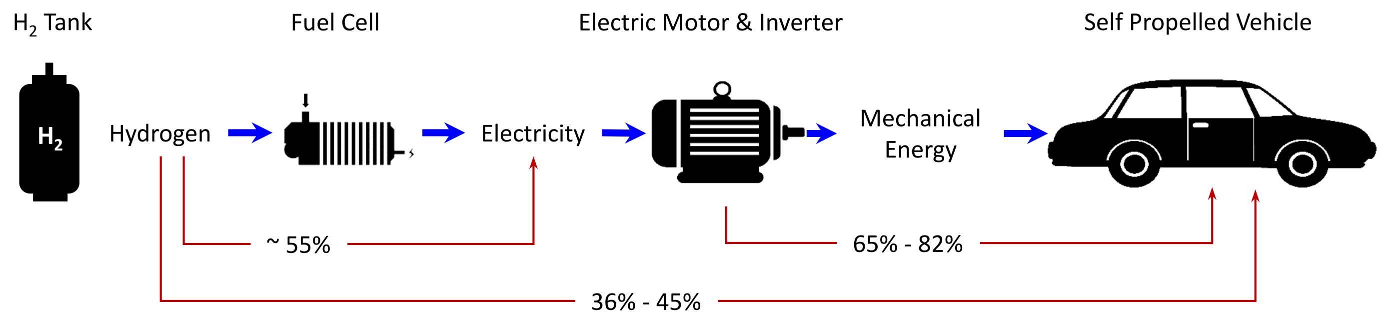


Figure 19.26. Energy efficiency of tank to wheels stage of the FCEV system (Data from Deloitte 2020) (Image: Simon Michaux)

19.5 Onboard hydrogen production

If it became possible to produce hydrogen on board a vehicle as it was consumed from a tank of water, the whole profile of the hydrogen fuel cell technology and what it would mean for the development of the industrial ecosystem would be completely transformed. Currently it is not possible (or at least economically viable). Using the range capability of the Toyota Mirai, an estimate of the needed battery size to convert hydrogen on board is shown below.

- 50 kWh to produce 1kg of hydrogen from 10 liters of water, using a PEM electrolyzer (Table 19.4)
- 4kg of hydrogen would be for the needed driving range of a passenger car = 200 kWh of needed battery power + 40 liters of water
- 200 kWh at a density of 230 Wh/kg for Lithium Ion Batteries (IEA 2019, EV Battery Global Outlook) results in a battery mass of 869 kg.

So, for a passenger car of the performance specifics of the Toyota Mirai to travel 502 km, the following would need to be carried on board during travel:

- A 40 liter tank of water
- A 200 kWh Li-Ion battery, with mass 869 kg
- A hydrogen electrolyzer unit to split H_2 from water
- A fuel cell to use H_2 to generate electricity to power the electric motor

This is far too heavy to be viable in a passenger car.

19.6 The Proposed Hydrogen Economy

In summary of this chapter, the proposed hydrogen economy is shown in Figure 19.27. Hydrogen is produced using electrolysis, powered with non-fossil fuel based electricity. That hydrogen is stored and distributed throughout society to be the basic energy of choice in parallel with electricity. Hydrogen is to be used as a fuel source to power vehicles like passenger cars, trucks, and ships with the use of fuel cells (probably PEM cells). Some hydrogen could also be used in turbines (same technology as gas turbines) to generate electricity and heat, which could be used in a variety of applications domestically and industrially.

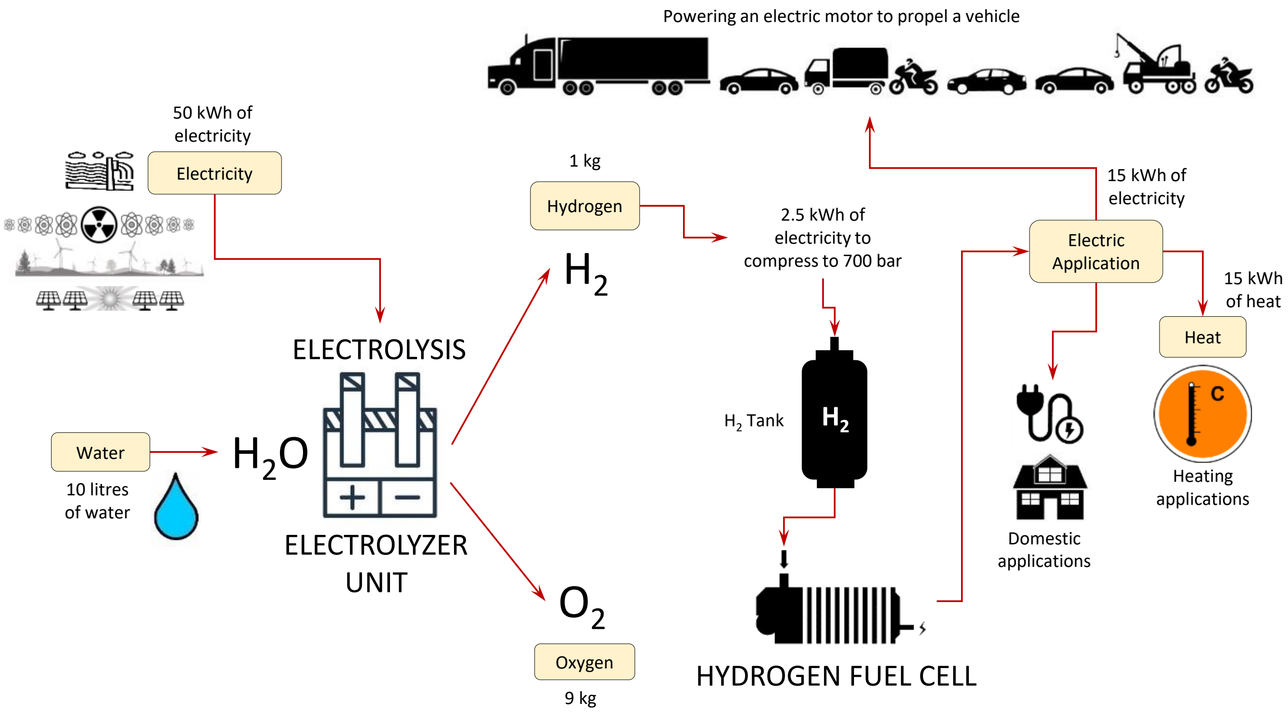


Figure 19.27. Production and use of 1kg of hydrogen in the proposed Hydrogen Economy (Image: Simon Michaux) (Data taken from EIA)

19.6.1 Hydrogen Physics

- 1kg of H_2 ↔ 11.1 Nm^3 ↔ 33.3 kWh (LHV) and 39.4 kWh (HHV)
- High mass energy density (1kg H_2 = 3.77 liters of gasoline)
- Low volumetric density (1 Nm^3 H_2 = 0.34 liters of gasoline)
- (Source: Thomas 2018)

19.6.2 Hydrogen Production from water electrolysis (~ 5 kWh/Nm_2 H_2)

- Power: 1 MW electrolyzer 200 Nm^3/h H_2 ↔ ±18 kg/h H_2
- Energy: +/- 50 kWh of electricity ↔ 1kg H_2 ↔ 11.1 Nm^3 ↔ ±10 liters demineralized water
- Compressed H_2 in tank storage at pressure 700 bar requires 2.5 kWh/kg
- (Source: Thomas 2018)

19.6.3 Power production from a hydrogen PEM fuel cell from hydrogen (+/- 50% efficiency)

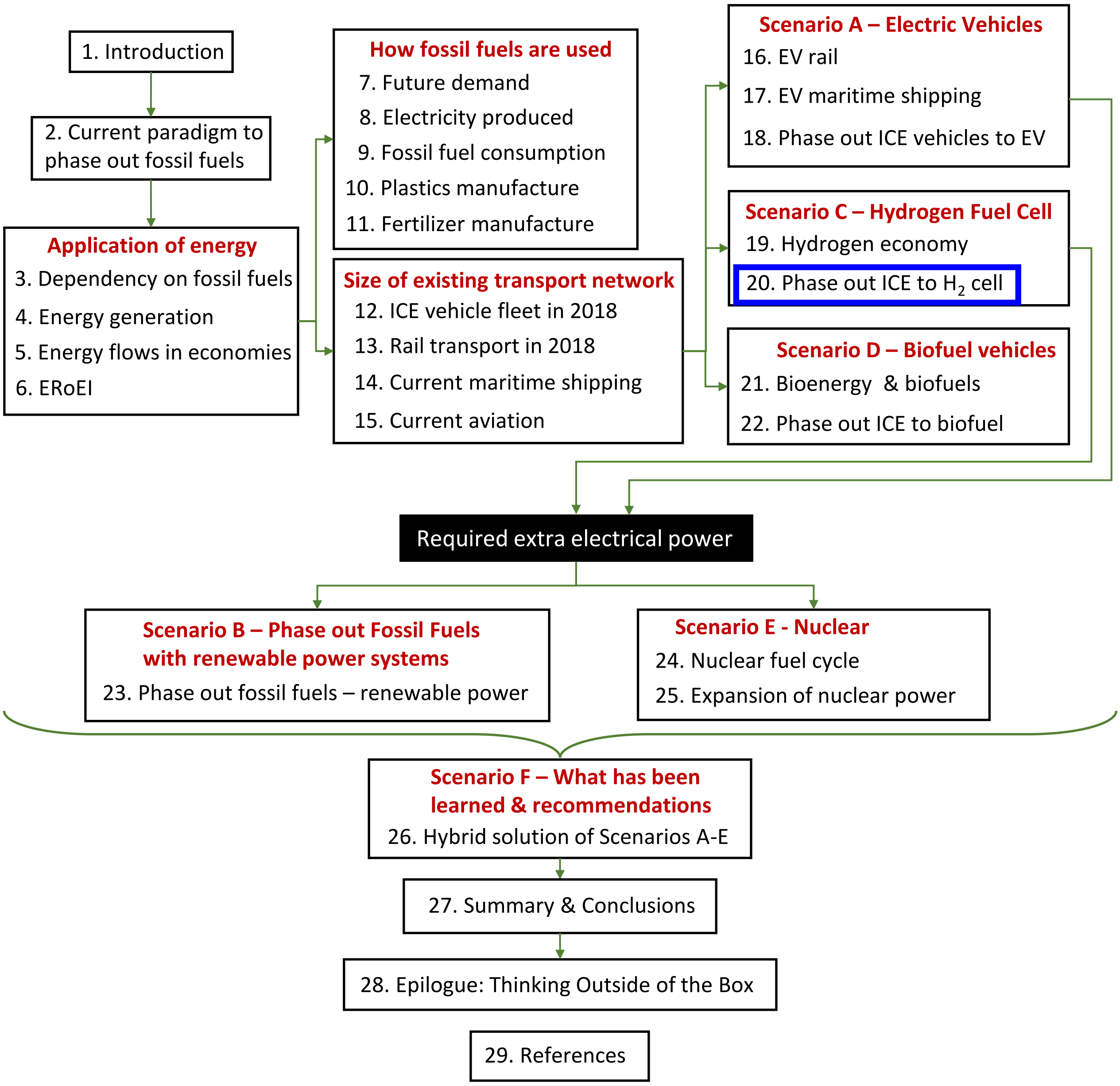
- Energy: 1kg of H_2 ↔ 15 kWh
- (Source: Thomas 2018)

Table 19.6: Hydrogen consumption of H-cell cars, buses, and trucks (Source: Thomas 2018)

FCEV	H_2 Tank	H_2 Consumption	Driving Range
Car (Passenger)	5 kg	1 kg / 100 km	500 km
Bus (12 m)	35 kg	8kg /100km	350 km
Heavy-duty fuel cell truck	5000 -10 000 kg	20 - 45 kg / 100 km	320 - 1300 km

20 SCENARIO C – PHASE OUT ICE TRANSPORT AND SUBSTITUTE WITH HYDROGEN

The purpose of Section 20 is to assemble the data for Scenario C, where all fossil fuel ICE vehicles in the global transport fleet are phased out and are substituted with hydrogen power cell fueled vehicles. The size and scope of the vehicle transport fleet has been estimated in Sections 12, 13, 14 and 15. Each of these vehicles will now have an electric propulsion motor but powered with a hydrogen fuel cell. The required electrical power to be serviced will be taken from estimations developed in Scenario A (Section 18, 17 and 16). To manufacture the needed hydrogen, requirements were taken from Section 19. A logistical comparison between EV and H-cell fleets is done.



Assessment of the Extra Capacity Required of Alternative Energy Electrical Power Systems to Completely Replace Fossil Fuels

Scenario C will now be examined, where all petroleum fueled Internal Combustion Engine (ICE) vehicles will be phased out and hydrogen fueled fuel cell vehicles will be phased in. So, Scenario C will examine the amount of hydrogen needed to fuel the global fleet of cars, trucks, buses, freight trains and maritime shipping, and the extra required quantity of electric power needed from the grid to produce that hydrogen. The number of new non-fossil fuel electric power stations to be constructed will be estimated.

Scenario C will be estimated first for the global transport fleet, in context of self-propelled vehicles (passenger cars, trucks, buses, delivery trucks, and commercial vans), in context of a portion of the rail freight transport and maritime shipping. Then an estimate will be made for self-propelled vehicles only for the United States, Europe (EU-28) and China.

To achieve this, the number of vehicles, the class types of vehicles and kilometers driven in the year 2018 will be taken from Section 21 (Scenario A). Then an estimate of what would the hydrogen consumption (kg/100km) need to be if all of these vehicles where H_2 fuel cell powered and drove the same kilometers.

To determine the consumption of hydrogen per unit distance, an example of each vehicle class using H_2 fuel cell technology would be selected as an average for that class. Results are then summed. The following vehicle classes were examined:

Self-propelled vehicles

- Class 8 Truck
- Bus & Delivery Truck
- Light Truck & Van
- Passenger Car
- Motorcycle

Rail Freight Locomotive

- The required electrical power calculated in Scenario A will now be supplied from a H_2 fuel cell

Maritime Shipping

- Small Vessel
- Medium Vessel
- Large Vessel
- Very Large Vessel

20.1 Hydrogen Fuel Cell Passenger cars

An example of this technology in action is the Toyota Mirai is a mid-size hydrogen fuel cell vehicle, passenger 4 door sedan. Under the United States Environmental Protection Agency (EPA) cycle, the 2016 model year Mirai has a total range of 502 km on a full tank (4kg of hydrogen in a 122.6 liter tank, with a 5.7 wt% storage density), with a combined city/highway fuel economy rating of 3.6 L/100 km (0.8 kg/100km, consuming 15 kWh/100km, at a speed of 100km/hr), making the Mirai a very fuel-efficient hydrogen fuel cell vehicle rated by the EPA, and the one with a comparatively long range (Toyota 2014). The Mirai consumes 1kg of hydrogen to produce 15 kWh of electricity.

20.2 Hydrogen Fuel Cell Heavy Duty Truck

The Hyundai Motor Company have produced and commercialized a heavy duty hydrogen fueled truck (FuelCellsWorks 2020). The first 50 manufactured units are being sent to Switzerland in Q3 of 2020 with a planned total of 1 600 XCIENT trucks to be manufactured by Hyundai by 2025. The XCIENT H-cell fueled truck is powered by a 190 kW hydrogen fuel cell system with dual 95 kW fuel cell stacks. Seven large hydrogen fuel tanks offer a combined storage capacity of 32.09 kg of hydrogen. The driving range of the XCIENT truck is quoted by Hyundai as being 400km (assuming the 4X2 model with refrigerated up-fit configuration while operating 34 tonne truck + trailer). This provides a hydrogen fuel consumption efficiency of 8.02 kg/100km. These specifications were developed based on a balance between the optimal requirements from the potential commercial fleet customers. Refueling time is approximately 8-20 minutes.

Table 20.1. Specifications of the XCIENT Fuel Cell Heavy Duty Truck (Source: Hyundai Motor Company, FuelCellWorks 2020)

Item Model	XCIENT Fuel Cell truck
Vehicle Type	Cargo (Chassis Cab)
Cab Type	Day Cab
Drive System	LHD/4X2
Dimensions (mm)	
Wheel Base	5130
Overall (Chassis Cab)	
Length	9745
Width	2515 (2550 with side protector), Maximum allowable width 2600
Height	3730
Weight (kg)	
Max. Gross Combination Weight	36 000 as pull-cargo
Max. Gross Vehicle Weight	19 000 as rigid truck
Front/Rear	8 000/11 500
Empty Vehicle Weight (Chassis Cab)	9 795
Calculated Performance	
Drive Range	Accuarte range to be confirmed later
Max. Speed	85 km/hr
Powertrain	
Fuel Cell Stack	190 kW (95 kW x 2 EA)
Battery	661 V / 73.2 kWh - by Akasol
Motor/Inverter	350 kW / 3 400 Nm - by Siemens
Transmission	ATM S4500 - by Allison / 6 forward speeds and 1 reverse speed
Rear Axle ratio	4.875
Hyrdogen Tank	
Filling Pressure	350 bar
Capacity	32.09 kg H_2 (available hydrogen amount at SOF 100%)

Note - Hyundai Motor Company reserves the right to change specifications and equipment without prior notice

So, a Class 8 H_2 Fuel Cell Heavy Duty Truck to travel 400 km, it would carry as an energy store a 32.09 kg tank of hydrogen. In comparison, a Class 8 Electric Vehicle Heavy Duty Truck (pure EV) would need a 584 kWh lithium ion battery, of mass of 2.540 tonne (where the energy density of Li-Ion batteries is assumed to be 230 Wh/kg – IEA 2019b). This shows there to be a large difference in mass of an energy storage between the systems.

20.3 Hydrogen Fuel Cell Commercial Van

DHL Express & StreetScooter in collaboration with Ford are in the process of developing a hydrogen fuel cell powered commercial van, called the H_2 Panel Van (ElectricDrive 2019). This vehicle has a 6kg hydrogen fuel tank, and a range of 502 km. The H_2 Panel Van, which is based on the StreetScooter WORK XL delivery vehicle already used by DHL Parcel, features cargo capacity over 10 cubic meters (approx. 100 Express parcels). With a maximum payload of over 800 kg, the H2 Panel Van achieves a maximum permissible weight of 4.25 tonnes.

The Work XL was introduced in August 2017 and has been produced exclusively for Deutsche Post. This Electric Vehicle was based on the Ford Transit, with a cargo volume of 20 cubic meters. This model has a 76 kWh battery, reaches 90 km/h and its range is 205 km (NEDC), carrying a payload of up to 1175 kg (StreetScooter 2019).

So, if the Work XL commercial van has a range of 205 km, and the H2 Panel Van has a range of 500 km, then the added hydrogen fuel cell system has added 297km to the total range of the vehicle. Given that the 6 kg tank of hydrogen has added 297 km, the hydrogen fuel consumption was 2.02kg/100km. For the purposes of this report, the hydrogen fuel consumption of 2.02kg/100km will used to estimate the hydrogen fuel volume requirements for commercial vans and light trucks.

Even though this is a hybrid vehicle, to make the calculation simpler, a full hydrogen system is estimated for Scenario C. Obviously, this calculation could be made more sophisticated with a hybrid system estimate, in a further report with a more hydrogen focused scope.

20.4 Hydrogen Fuel Cell Pickup Truck – Light Duty Vehicle

The Nikola Motor Company showcased a hybrid EV electric pickup truck with a hydrogen fuel cell auxiliary system, called the Badger (Nikola Corporation 2020). Production is slated to begin in 2022. In BEV mode, the Badger range is 482.8 km (300 miles). With assistance of the hydrogen cell auxiliary, that range is extended to 965.6 km (600 miles). So, it can be inferred that the hydrogen cell system can propel the vehicle 482.8 km (300 miles) using the 8 kg of hydrogen in its tank. The hydrogen fuel efficiency could then be estimated at 1.66 kg/100 km.

This Nikola Badger electric pickup light duty vehicle is estimated to deliver following specifications (Nikola Corporation 2020)*:

- 965.6 km (600 miles) on blended FCEV / BEV
- 482.8 km (300 miles) on BEV alone
- Operates on blended FCEV / BEV or BEV only by touch of a button
- 906 HP peak
- 455 HP continuous
- 980 ft. lbs. of torque
- 160 kWh, flooded module - lithium-ion battery
- 120 kW fuel cell
- 8 kg hydrogen fuel tank
- Advanced Supercapacitor Launch Assist that blends with lithium ion and fuel-cell
- -20F operating environments without major performance or SOC losses
- Towing capacity of over 8,000 pounds
- Operating targets without motor stalls up to 50% grade
- 15 kW power export outlet
- Compatible with industry standard charging for BEV mode
- Five seats
- Truck dimensions: 5900 mm long x 1850 mm tall x 2160 mm wide a 1560 mm bed width

*Specs may vary according to FCEV or BEV-only mode, temperature, elevation, tires, wheels, software packages, production requirements, hardware and/or regulations.

For the purpose of this report, the H_2 fuel efficiency of a light duty vehicle is estimated at 1.66 kg/100km. Even though this is a hybrid vehicle, to make the assumption calculation simpler, a full hydrogen system is estimated for Scenario C. Obviously, this calculation could be made more sophisticated with a hybrid system estimate, in a further report with a more hydrogen focused scope.

20.5 Hydrogen Fuel Cell Bus

Battery electric and fuel cell buses are currently pre-commercial technologies and are not yet mass market products. There are now a number of models of hydrogen fuel cell buses in development and are nearly ready for full commercialization. Some of these models are listed.

- Van Hool Exqui.City 18 FC
- Toyota-Hino FCHV-BUS
- Hyundai ElecCity
- Foton Motor BJ6123FCEVCH-1
- Mercedes-Benz (Daimler AG) Citaro fuel-cell bus
- Yutong ZK6125FCEVG1

The average hydrogen consumption of an FCEV bus is estimated to be 8.0 kg/100km (Hope-Morley *et al* 2017), with an estimated average H_2 tank capacity of 27 kg.

20.6 Hydrogen Fuel Cell Trains

A proportion of the rail transport system is already electric EV based. To phase out petroleum fueled ICE engines in the global rail network, and phase in electric motor propulsion, an estimated needed electrical power would be 2.27 x 10^{11} kWh (see Section 19). In Scenario A, this extra power requirement was met with electric batteries, charged of the local electrical power grid.

In Scenario C, this extra electrical power requirement to be delivered to the electric motors on board each train locomotive, is to be generated by H_2 supplied fuel cells splitting water. As shown in Section 16, a PEM fuel cell can generate 15 kWh from 1 kg of hydrogen, with a waste output of water and heat (Thomas 2018).

Thus, to generate 2.27 x 10^{11} kWh of electrical power, the global rail system (at the same scope as 2018) would require 1.51 x 10^{10} kg (15.13 million tonnes) of hydrogen to be manufactured, stored and then carried on trains as they operate.

To estimate how much each train would be required to carry in a hydrogen tank, a freight train running an average distance is used. This example does not account for extra hydrogen consumption due to the extra torque required to pull such a heavy load but will use the average distance (see Section 19 and Section 13). According to the AAR (Association of American Railroads http://www.aar.org/), an average example, a train might haul 3 000 tonnes of freight 804.6 km (500 miles) and consume approximately 11 541 liters (3,049 gallons) of diesel fuel. So, a hydrogen fueled PEM cell will be used to estimate replacing this example.

If this train was a fully electric EV system, it would have an approximately 73% energy efficiency (IEA 2019b). To do the same amount of useful physical work (47 341.6 kWh), an EV system would require from a battery bank 64 851.6 kWh (Section 19).

In 2017, a PEM fuel cell produced approximately 15 kWh (Thomas 2018) from 1 kg of hydrogen. So the estimated mass of hydrogen required to be stored in a tank aboard a locomotive train pulling 3 000 tonnes of freight 804.6 km, would be 4 323.4 kg, or 4.32 tonnes.

So, for an EV freight train to replace a diesel locomotive, it would need to have a 65 000 kWh battery bank (estimated). Using an estimated energy density for a lithium ion battery technology of 230 kg per Wh of capacity (IEA 2019b), a 65 000 kWh battery would have a mass of 281 963 kg, or 281.9 tonnes.

This means that the energy store load carried by a freight locomotive, if it was a pure EV system, that energy store would be a 281.9 tonne lithium ion battery, whereas if this system was a hydrogen fuel cell, then the energy store would be 4.32 tonne. This difference in mass makes the hydrogen fuel cell system useful for any long range transport distance.

20.7 Hydrogen Fuel Cell Maritime Shipping

In Scenario A, fossil fuel powered ICE engines were to be phased out and substituted by EV electric systems with electric motors (see Section 21). The electric power required to do useful work in the maritime transport of goods and passengers is shown in Table 20.2 and 20.3 for Large and Very Large Vessels (which transported most of the bulk commodities in 2018).

Table 20.2. Large Vessel energy consumption and required, hydrogen quantity needed for tonne-km transport of commodities in global maritime trade (data taken from Table 20.22) (World Map Image by Clker-Free-Vector-Images from Pixabay)

Commodity 	Large Vessel Proportion of Cargo Transport in 2018 (25 000 GT to 59 999 GT) (billions of tonne-km)	Energy Consumed by EV system per tonne-km for Large Vessel rate 2.63 x 10^6 kW/tonne-km (kWh)	Needed kg of hydrogen @15 kWh/1kg to supply fuel cell on vessel (kg)
Chemicals	719,4	1,89E+09	1,26E+08
Gas	not transported		
Oil	not transported		
Other dry cargo	2 911,9	7,65E+09	5,10E+08
Containers	6 174,1	1,62E+10	1,08E+09
Minor dry bulk	7 748,9	2,04E+10	1,36E+09
Main bulks	11 480,0	3,02E+10	2,01E+09
Sum	29 034,3 billions of tonne-km	7,63E+10 kWh	5,09E+09 kg of hydrogen

Table 20.3. Very Large Vessel energy consumption and required, hydrogen quantity needed for tonne-km transport of commodities in global maritime trade (data taken from Table 20.22) (World Map Image by Clker-Free-Vector-Images from Pixabay)

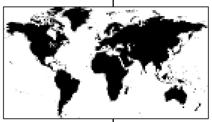
Commodity 	Very Large Vessel Proportion of Cargo Transport in 2018 (>60 000 GT) (billions of tonne-km)	Energy Consumed by EV system per tonne-km for Large Vessel rate 3.42 x 10^6 kW/tonne-km (kW)	Needed kg of hydrogen @15 kWh/1kg to supply fuel cell on vessel (kg)
Chemicals	1 068,2	1,73E+10	1,15E+09
Gas	not transported		
Oil	not transported		
Other dry cargo	4 323,8	7,01E+10	4,67E+09
Containers	9 167,7	1,49E+11	9,90E+09
Minor dry bulk	11 506,0	1,86E+11	1,24E+10
Main bulks	17 046,0	2,76E+11	1,84E+10
Sum	43 111,6 billions of tonne-km	6,99E+11 kWh	4,66E+10 kg of hydrogen

So the mass of hydrogen to fuel the global maritime fleet transporting commodities the same distance in the year 2018 would be estimated to be 5.09 x 10^{10} kg (Very Large Vessels – Table 20.2) + 4.66 x 10^{10} kg (Very Large Vessels – Table 20.3), equaling 5.17 x10^{10} kg.

$$5.09 \times 10^{9}\ \text{kg} + 4.66 \times 10^{10}\ \text{kg} = 5.17 \times 10^{10}\ \text{kg} \quad \text{(51.66 million tonnes)}$$

The size and capacity of the electric propulsion EV system of each of the major maritime shipping vessels was estimated in Section 20. For a series of example shipping routes, the amount of useful work done was estimated, shown below in Table 20.4 (Table 20.10 in Section 20).

Table 20.4. Estimation of energy consumption for an EV system for each ship route, by shipping class (World Map Image by Clker-Free-Vector-Images from Pixabay)



Origin	Destination	Distance in kilometers (km)	Estimated time at sea (days)	Useful work done in this route if propulsion was EV			
				Small Vessel (100 GT to 499 GT) EV work efficiency @ 73% (kW)	Medium Vessel (500 GT to 24 999 GT) EV work efficiency @ 73% (kW)	Large Vessel (25 000 GT to 59 999 GT) EV work efficiency @ 73% (kW)	Very Large Vessel (>60 000 GT) EV work efficiency @ 73% (kW)
Port of Shanghai (China)	Port of Hamburg (Germany)	22 737	25,6	1 459 772,0	4 583 005,0	12 730 569,3	29 704 661,8
Port of Hamburg (Germany)	Port of Melbourne (Australia)	24 765	27,8	1 588 197,6	4 986 201,9	13 850 560,8	32 317 975,2
Port of Hamburg (Germany)	Port of Osaka (Japan)	24 074	27,1	1 545 389,1	4 851 802,9	13 477 230,3	31 446 870,7
Port of Hamburg (Germany)	Port Hong Kong	21 142	23,8	1 357 031,4	4 260 447,4	11 834 576,2	27 614 011,1
Port of Amsterdam (Netherlands)	Port Los Angelas (United States)	19 037	21,4	1 220 044,0	3 830 370,7	10 639 918,7	24 826 476,9
Port of Amsterdam (Holland)	Port of Singapore	17 368	19,6	1 117 303,5	3 507 813,2	9 743 925,5	22 735 826,2
Port of Shanghai (China)	Port Los Angelas (United States)	35 688	40,1	2 290 258,0	7 190 345,0	19 973 180,7	46 604 088,2
Port of Shanghai (China)	Port of Cape Town (South Africa)	17 131	19,3	1 100 180,0	3 454 053,6	9 594 593,3	22 387 384,4

Table 20.5 shows the estimated size of the needed battery in the vessel class to travel the examined shipping route. This battery was calculated to be large enough to power the electric propulsion system. That same electric propulsion system could be supplied with electricity generated by a PEM fuel cell unit. So, for each 1 kg of hydrogen, 15 kWh of energy is generated (Thomas 2018). So that needed quantity of kWh can be calculated into the needed mass of hydrogen the vessel would need to carry in a storage tank. It was also assumed that to compress hydrogen into 700 bar pressure storage will require 2.5 kWh/kg (Zuttel 2004 and Rivard *et al* 2019).

The far RHS column in Table 20.5 shows the calculated mass of the battery for a purely EV system. As can be seen the difference in mass is considerable. The comparison of the needed energy store shown in Table 20.5 demonstrates how the hydrogen economy certainly has its place and has the capacity to make maritime shipping viable once more.

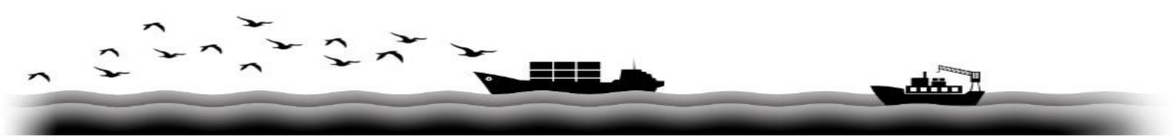
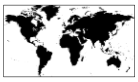


Table 20.5. Estimated size of battery bank and range in maritime shipping vessels, by class (World Map Image by Clker-Free-Vector-Images from Pixabay)

Vessel Class Size 	Estimated Size of Battery in Vessel (kWh)	Reference in Section 20	Estimated Range (km)	Mass of Battery if system was pure EV (kg)
Small Vessel (100 GT to 499 GT)	14,270	Table 20.17	222	62,000
Medium Vessel (500 GT to 24 999 GT)	358,397	Table 20.17	1,778	1,558,000
Large Vessel (25 000 GT to 59 999 GT)	4,977,740	Table 20.17	8,890	21,642,000
Very Large Vessel (>60 000 GT)	11,614,726	Table 20.17	8,890	50,499,000

Table 20.6. Estimated size of hydrogen tank and range required in maritime shipping vessels, by class (World Map Image by Clker-Free-Vector-Images from Pixabay)

Vessel Class Size 	Needed kg of hydrogen @15 kWh/1kg (kg)	Estimated volume of H_2 tank at 700 bar (40kg of H_2 /m^3) (m^3)	Estimate weight of tank with H_2 storage denisty of 5.7% (kg)	Estimated volume of Liquid H_2 cryogenic tank (70.8 kg of H_2 /m^3) (m^3)	Estimate weight of cryogenic tank with liquid H_2 storage denisty of 14% (kg)	Estimated Range (km)
Small Vessel (100 GT to 499 GT)	951	23.8	16,689.5	13.4	6,795.0	222
Medium Vessel (500 GT to 24 999 GT)	23,893	597.3	419,178.1	337.5	170,665.4	1,778
Large Vessel (25 000 GT to 59 999 GT)	331,849	8,296.2	5,821,917.8	4,687.1	2,370,352.3	8,890
Very Large Vessel (>60 000 GT)	774,315	19,357.9	13,584,474.9	10,936.7	5,530,821.9	8,890

20.8 Hydrogen Fuel Cell Aviation

Hydrogen has shown promise in context of a relatively small mass of energy storage for long journeys in Heavy Duty trucks, rail freight and maritime shipping. There is potential for hydrogen to be applied in aviation as well.

A hydrogen aircraft would be an airplane that uses hydrogen fuel as a power source. Hydrogen can either be burned in a jet engine, or other kind of internal combustion engine, or can be used to power a fuel cell to generate electricity to power a propeller. There are a few engineering limitations that require to be resolved, however.

A jet fuel ICE powered aircraft can store fuel in its wings. Due to the nature of what is required to store hydrogen in a tank, concept aircraft that are currently designed with the hydrogen fuel tanks carried inside the fuselage. This reduces space for passengers and cargo.

It could be possible that the aircraft is propelled by an electric turbine, powered by a PEM H_2 fuel cell. If so, it is not clear what fuel efficiency (kg of H_2 consumed per 100km) the aircraft would return in performance.

For this reason, the aviation hydrogen economy was not considered in calculations in this report.

20.9 The size of the global hydrogen economy

Tables 20.7 and 20.8 shows the assembled numbers from the previous few sections to have an estimate of hydrogen consumption per 100km, for each vehicle class. Yes, this is an estimate and there will be in reality variability in each vehicle class. For the purposes of this report, these average estimates will be used to project into each vehicle class.

Table 20.7. Hydrogen fuel cell vehicle examples used to estimate fuel efficiency for vehicle classes – Part 1 (World Map Image by Clker-Free-Vector-Images from Pixabay)

Vehicle Class 	Consumption of hydrogen if vehicle was a FCEV (kg/100 km)	Example Vehicle used to estimate whole class	Reference
Class 8 Truck	8.02	XCIENT H-cell fuelled heavy duty truck	Hyundai Motor Company & FuelCellWorks 2020
Transit Bus + Refuse Truck + Paratransit Shuttle + Delivery Truck + School Bus	8.0	Mercedes-Benz (Daimler AG) Citaro fuel-cell bus	Hope-Morley et al 2017
Light Truck/Van +	2.02	H2 Panel Van (Hybrid, H_2 conusmption estimated)	ElectricDrive 2019 & StreetScooter 2019
Light-Duty Vehicle	1.66	Nikola Badger (Hybrid, H_2 conusmption estimated)	Nikola Corporation (2020)
Passenger Car	0.8	Toyota Mirai	Toyota 2014
Motorcycle	N/A		

Table 20.8. Hydrogen fuel cell vehicle examples used to estimate fuel efficiency for vehicle classes – Part 2 (World Map Image by Clker-Free-Vector-Images from Pixabay)

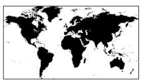
Vehicle Class 	Example Vehicle used to estimate whole class	Estimated Range (km)	Size of H_2 tank (kg)	Estimated volume of H_2 tank at 700 bar (40kg of H_2 /m^3) (m^3)	Estimate weight of H_2 tank with storage denisty of 5.7% (kg)
Class 8 Truck	XCIENT H-cell fuelled heavy duty truck	400	32.09	0.802	563.0
Transit Bus + Refuse Truck + Paratransit Shuttle + Delivery Truck + School Bus	Mercedes-Benz (Daimler AG) Citaro fuel-cell bus	216	27	0.675	473.7
Light Truck/Van +	H2 Panel Van (Hybrid, H_2 conusmption estimated)	297	6	0.150	105.3
Light-Duty Vehicle	Nikola Badger (Hybrid, H_2 conusmption estimated)	482.8	8	0.200	140.4
Passenger Car	Toyota Mirai	502	4	0.100	70.2
Motorcycle					

Table 20.9 shows the estimated quantity of hydrogen for the number of vehicles in each class to travel the same number of kilometers as what was done in 2018. An estimate the total mass of hydrogen is summed together.

So, the estimated mass of hydrogen to fuel self-propelled vehicles in the global fleet for the year 2018 (estimating the needed annual consumption of the current system) is 6.60×10^8 kg of H_2 (660.2 million tonnes). This is a merging of Table 20.8 with Table 12.7 (Section 12).

Table 20.9. Estimated required volume of hydrogen to be consumed by all self-propelled vehicles in GLOBAL FLEET in 2018, as if they were all hydrogen fuel cells (World Map Image by Clker-Free-Vector-Images from Pixabay)

Vehicle Class 	Number of Self Propelled Vehicles in 2018 Global Fleet (number)	Total km driven by class in 2018 Global Fleet (km)	Consumption of hydrogen if vehicle was a FCEV (kg/100 km)	Consumption of hydrogen if vehicle was a FCEV (kg/km)	Quantity of H_2 for all global vehicles in that class to travel the same distance as was done in 2018 (kg)	Quantity of H_2 for all global vehicles in that class to travel the same distance as was done in 2018 (tonnes)
Class 8 Truck	28,929,348	1.62E+12	8.02	0.0802	1.30E+11	1.30E+08
Transit Bus + Refuse Truck + Paratransit Shuttle + Delivery Truck + School Bus	29,002,253	8.03E+11	8.00	0.08	6.43E+10	6.43E+07
Light Truck/Van + Light-Duty Vehicle	601,327,324	7.89E+12	2.02	0.0202	1.59E+11	1.59E+08
Passenger Car	695,160,429	5.40E+12	0.80	0.008	4.32E+10	4.32E+07
Motorcycle	62,109,261	1.60E+11	N/A			
Total	1,416,528,615	1.59.E+13			3.97.E+11	3.97.E+08
	1.416 billion Number of vehicles	15.87 trillion km travelled in 2018				396.8 million tonnes of hydrogen to be consumed in one year

Table 20.10 shows the summed estimated consumption in the global hydrogen economy, accounting for existing H_2 demand (73.9 million tonnes in 2018), self-propelled vehicles, rail, and maritime transport systems.

So, the global hydrogen economy is estimated to consume 502.6 million tonnes each year (based on 2018 figures). Assuming a very conservative estimate of 50 kWh to produce 1kg of hydrogen using a PEM electrolyzer (see Table 16.4 in Section 16), and 2.5 kWh/kg to compress the hydrogen into 700 bar pressure storage tanks, an estimated quantity of 26 964.4 TWh of electricity will be required to manufacture the annual needed mass of hydrogen. These conservative numbers (50 kWh/kg and 2.5 kWh/kg) were selected to reflect future innovation in efficiency).

Table 20.10. The size of the hydrogen economy in terms of required annual mass of H_2 (based in 2018 scope) (World Map Image by Clker-Free-Vector-Images from Pixabay)

Consumption Task 	Hydrogen (million tonnes)	Hydrogen (kg)	Required Electric power to manufacture H_2 with electrolysis (@ 50kWh/kg) (kWh)	Required Electric power to compress H_2 into tanks at 700 barr pressure (@ 2.5 kWh/kg) (kWh)	Required annual electric power generation assuming 10% grid transmission loss between power station and electrolysis unit and compression unit (kWh)
Existing hydrogen global annual demand for industrial applications (73.9 Mt -refining applications)	35.7	3.57E+07	1.79E+09	N/A	1.96E+09
Hydrogen required to fuel the global fleet of passenger cars 	43.2 396.8 million tonnes of hydrogen	4.32E+10	2.16E+12	1.08E+11	2.49E+12
Hydrogen required to fuel the global fleet of commercial vans and light trucks 	159.4	1.59E+11	7.97E+12	3.98E+11	9.20E+12
Hydrogen required to fuel the global fleet of buses and delivery trucks 	64.25	6.43E+10	3.21E+12	1.61E+11	3.71E+12
Hydrogen required to fuel the global fleet of Class 8 Heavy Duty trucks 	129.9	1.299E+11	6.50E+12	3.25E+11	7.50E+12
Hydrogen required to fuel the global fleet rail transport 	18.5	1.85E+10	9.23E+11	4.62E+10	1.07E+12
Hydrogen required to fuel the global maritime shipping fleet 	51.66	5.17E+10	2.58E+12	1.29E+11	2.98E+12
Hydrogen required to fuel the global aviation fleet	N/A				
Total	502.6 million tonnes of H_2				2.70E+13 26 964.4 TWh

Table 20.11 shows the estimated number of new power stations to be constructed to implement Scenario C. An extra **26 964.4 TWh** of electric power capacity will need to be delivered each year. It is not appropriate to apply gas and coal power stations to do this as they are fossil fuels. So, the new capacity will be required to be developed using non-fossil fuel systems like wind, solar, hydro, and nuclear or biowaste. In practical terms, any new capacity will be sourced from a range of these systems. To get a rough estimate of the number of needed power stations, the assumption is made that the same proportion of non-fossil fuel power generation stations will be used to develop this extra capacity. So, using the same methods as used in Figure 21.9 in Section 21 (Scenario A), where the needed capacity of 26 964.4 TWh will be spread across the non-fossil fuel power systems in the same proportions they were in 2018. Once again this is a broad assumption.

Table 20.12 after that shows the needed new power stations if Scenario C was fully developed, and all gas and coal applications were phased out and replaced with non-fossil fuel power systems. The methodology to do this is the same as is shown in Section 22 (Scenario B). The combined needed power to do this is:

26 964.4 (global Scenario C) + 19 958.7 (global substitution for gas & coal) = 46 923 TWh

Table 20.11. Estimated number of new power stations to be constructed to deliver the extra required annual electrical power capacity to phase out petroleum ICE technology and substitute with H_2 Fuel Cell technology in the GLOBAL system (World Map Image by Clker-Free-Vector-Images from Pixabay)

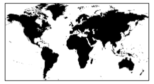
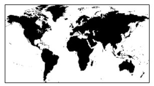
Power Generation System 	Global non-fossil fuel electricity production in 2018 (Appendix B & Agora Energiewende and Sandbag 2019) (kWh)	2018 ratio percent of non-fossil fuel electrical power systems (%)	Expanded extra required electrical power capacity to phase out petroleum ICE technology and substitute with H_2 Fuel Cell technology (kWh)	Global Number Power Plants in 2018 (Global Energy Observatory) (number)	Average Plant Capacity (Global Energy Observatory) (MW)	Power Produced by a Single Average Plant in 2018 (kWh)	Estimated number of required additional new power plants of average size to phase out petroleum ICE technology and substitute with H_2 Fuel Cell technology (number)
Nuclear	2.70E+12	28.35%	7.64E+12	438	2 046.5 MW	1.28E+10	597
Hydroelectric	4.19E+12	44.00%	1.19E+13	3,163	225.4 MW	1.33E+09	8,950
Wind	1.30E+12	13.68%	3.69E+12	16048 (est)	37. 2 MW	8.12E+07	45,414
Solar PV	5.79E+11	6.08%	1.64E+12	17526 (est)	33.1 MW	3.30E+07	49,598
Solar Thermal	5.50E+09	0.06%	1.56E+10	52	76.97 MW	7.70E+07	202
Geothermal	9.30E+10	0.98%	2.63E+11	108	94.7 MW	6.03E+08	436
Biowaste to energy	6.53E+11	6.85%	1.85E+12	3,800	31.7 MW	3.46E+07	53,418
Total (kWh)	9.53E+12		2.70E+13				158,615
Total (TWh)	9,529		26,964				new power stations to be constructed

Table 20.12. Estimated number of new power stations to be constructed to expanded extra required annual electrical power capacity to phase out petroleum ICE technology and substitute with H_2 Fuel Cell technology AND phase out gas & coal fossil fuels in the GLOBAL system (World Map Image by Clker-Free-Vector-Images from Pixabay)

Power Generation System 	Global non-fossil fuel electricity production in 2018 (Appendix B & Agora Energiewende and Sandbag 2019) (kWh)	2018 ratio percent of non-fossil fuel electrical power systems (%)	Expanded extra required electrical power capacity to phase out petroleum ICE technology and substitute with H_2 Fuel Cell technology AND phase out gas & coal fossil fuels (kWh)	Global Number Power Plants in 2018 (Global Energy Observatory) (number)	Average Plant Capacity (Global Energy Observatory) (MW)	Power Produced by a Single Average Plant in 2018 (kWh)	Estimated number of required additional new power plants of average size to phase out petroleum ICE technology and substitute with H_2 Fuel Cell technology AND phase out gas & coal fossil fuels (number)
Nuclear	2.70E+12	28.35%	1.33E+13	438	2 046.5 MW	1.28E+10	1,039
Hydroelectric	4.19E+12	44.00%	2.06E+13	3,163	225.4 MW	1.33E+09	15,575
Wind	1.30E+12	13.68%	6.42E+12	16048 (est)	37. 2 MW	8.12E+07	79,029
Solar PV	5.79E+11	6.08%	2.85E+12	17526 (est)	33.1 MW	3.30E+07	86,309
Solar Thermal	5.50E+09	0.06%	2.71E+10	52	76.97 MW	7.70E+07	352
Geothermal	9.30E+10	0.98%	4.58E+11	108	94.7 MW	6.03E+08	759
Biowaste to energy	6.53E+11	6.85%	3.21E+12	3,800	31.7 MW	3.46E+07	92,958
Total (kWh)	9.53E+12		4.69E+13				276,020
Total (TWh)	9,529		46,923				

So, to implement Scenario C, 158 615 new power stations will be needed to be constructed (Table 20.11).

20.10 The size of the United States hydrogen economy for self-propelled vehicles

Table 20.13 below shows the number of self-propelled vehicles in the United States by class and how many kilometers they travelled in the year 2018. Using the consumption of hydrogen if each of these vehicles was a H_2 fuel cell vehicle (Table 20.8 merged with Table 12.2 in Section 12), the total mass of hydrogen for the whole U.S. vehicle fleet was estimated.

Table 20.13. Estimated required volume of hydrogen to be consumed by all U.S. self-propelled vehicles in 2018, as if they were all hydrogen fuel cells

Vehicle Class 	Number of Self Propelled Vehicles in 2018 U.S. Fleet (number)	Total km driven by class in 2018 U.S. Fleet (km)	Consumption of hydrogen if vehicle was a FCEV (kg/100 km)	Consumption of hydrogen if vehicle was a FCEV (kg/km)	Quantity of H_2 for all U.S. vehicles in that class to travel the same distance as was done in 2018 (kg)	Quantity of H_2 for all U.S. vehicles in that class to travel the same distance as was done in 2018 (tonnes)
Class 8 Truck	4 694 851	4,79E+11	8,02	0,0802	3,84E+10	3,84E+07
Transit Bus +	2 517 520	1,38E+11	8,00	0,08	1,10E+10	1,10E+07
Refuse Truck +	1 850 465	7,45E+10				
Paratransit Shuttle +	1 678 668	6,13E+10				
Delivery Truck +	959 133	2,00E+10				
School Bus	888 223	1,72E+10				
Light Truck/Van	82 569 993	1,59E+12	2,02	0,0202	3,22E+10	3,22E+07
Light-Duty Vehicle	79 237 170	1,47E+12	1,66	0,0166	2,44E+10	2,44E+07
Passenger Car	78 293 789	1,43E+12	0,80	0,008	1,15E+10	1,15E+07
Motorcycle	16 223 409	6,15E+10	N/A			
Total	268 913 221	5,34E+12			1,17,E+11	1,17,E+08
	269 million vehicles number of vehicles	5.3 trillion km travelled in 2018				117.5 million tonnes of hydrogen to be consumed in one year

So, the size and scope of this part of the annual hydrogen economy in the United States would require 117.5 million tonnes of hydrogen to be produced and delivered to the distribution fueling stations. Assuming 50 kWh/kg to produce hydrogen with electrolysis, and 2.5 kWh/kg to compress the hydrogen into 700 bar pressure storage tanks, the estimated quantity of electricity to produce the estimated annual required mass of hydrogen for the United States, would be 6 783.6 TWh (Table 20.14).

Table 20.14. Estimated extra required annual electrical power required to manufacture and deliver in storage enough hydrogen to phase out petroleum ICE technology and substitute with H_2 Fuel Cell technology in the United States

Vehicle Class 	Number of Self Propelled Vehicles in 2018 U.S. Fleet (number)	Total km driven by class in 2018 U.S. Fleet (km)	Quantity of H_2 for all U.S. vehicles in that class to travel the same distance as was done in 2018 (kg)	Required Electric power to manufacture H_2 with electrolysis (@ 50kWh/kg) (kWh)	Required Electric power to compress H2 into tanks at 700 barr pressure (@ 2.5 kWh/jg) (kWh)	Required electric power generation,a ssuming 10% grid transmission loss between power station and electrolysis unit (kWh)
Class 8 Truck	4,694,851	4.79E+11	3.84E+10	1.92E+12	9.61E+10	2.22E+12
Transit Bus +	2,517,520	1.38E+11	1.10E+10	5.51E+11	2.76E+10	6.37E+11
Refuse Truck +	1,850,465	7.45E+10				
Paratransit Shuttle +	1,678,668	6.13E+10				
Delivery Truck +	959,133	2.00E+10				
School Bus	888,223	1.72E+10				
Light Truck/Van	82,569,993	1.59E+12	3.22E+10	1.61E+12	8.05E+10	1.86E+12
Light-Duty Vehicle	79,237,170	1.47E+12	2.44E+10	1.22E+12	6.09E+10	1.41E+12
Passenger Car	78,293,789	1.43E+12	1.15E+10	5.73E+11	2.87E+10	6.62E+11
Motorcycle	16,223,409	6.15E+10	N/A			
Total	268,913,221	5.34E+12	1.17.E+11	5.87E+12	2.94E+11	6.78E+12
	269 million vehicles number of vehicles	5.3 trillion km travelled in 2018	117.5 million tonnes of hydrogen			6,783.6 TWh

The estimated number of new non-fossil fuel power stations to be constructed in the United States, using the same method as Figure 21.9 in Section 21, is shown in Table 20.15 below.

Table 20.15. Estimated number of new power stations to be constructed to deliver the extra required annual electrical power capacity to phase out petroleum ICE technology and substitute with H_2 Fuel Cell technology in the United States

Power Generation System	U.S. electricity production in 2018 (BP Statistical Review of World Energy 2019) (kWh)	2018 ratio percent of all U.S. electrical non-fossil fuel power systems (%)	Expanded extra required capacity to phase out ICE petroleum and substitute with H Cell technology (kWh)	Average Installed Plant Capacity in 2018 (Global Energy Observatory) (MW)	Power Produced by a Single Average Plant in 2018 (kWh)	Estimated number of required additional new power plants of average size to phase out petroleum ICE technology and substitute with H_2 Fuel Cell technology (number)
Nuclear	8.50E+11	52.77%	3.58E+12	2 046.5 MW	1.28E+10	280
Hydroelectric	2.89E+11	17.93%	1.22E+12	225.4 MW	1.33E+09	917
Wind	2.78E+11	17.25%	1.17E+12	37. 2 MW	8.12E+07	14,401
Solar PV	9.71E+10	6.03%	4.09E+11	33.1 MW	3.30E+07	12,382
Other Renewable	9.70E+10	6.02%	4.09E+11	76.97 MW	7.70E+07	5,310
Total (kWh)	1.61E+12		6.78E+12			33,290
Total (TWh)	1,610					

20.11 The size of the European EU-28 hydrogen economy for self-propelled vehicles

Table 20.16 below shows the number of self-propelled vehicles in European Union (EU-28) by class and how many kilometers they travelled in the year 2018. Using the consumption of hydrogen if each of these vehicles was a H_2 fuel cell vehicle (Table 20.6 merged with Table 12.3 in Section 12), the total mass of hydrogen for the whole EU-28 vehicle fleet was estimated.

Table 20.16. Estimated required volume of hydrogen to be consumed by all EU-28 self-propelled vehicles in 2018, as if they were all hydrogen fuel cells

Vehicle Class	Number of Self Propelled Vehicles in 2018 EU-28 Fleet (number)	Total km driven by class in 2018 EU-28 Fleet (km)	Consumption of hydrogen if vehicle was a FCEV (kg/100 km)	Consumption of hydrogen if vehicle was a FCEV (kg/km)	Quantity of H_2 for all EU-28 vehicles in that class to travel the same distance as was done in 2018 (kg)	Quantity of H_2 for all EU-28 vehicles in that class to travel the same distance as was done in 2018 (tonnes)
Class 8 Truck	5,716,322	1.23E+11	8.02	0.0802	9.83E+09	9.83E+06
Bus	657,714	7.56E+09	8.00	0.08	6.05E+08	6.05E+05
Light Truck/Van	27,413,946	1.11E+11	2.02	0.0202	2.24E+09	2.24E+06
Passenger Car	222,683,327	8.56E+11	0.80	0.008	6.85E+09	6.85E+06
Motorcycle	4,548,655	3.62E+09	N/A			
Total	261,019,964	1.10E+12			1.95.E+10	1.952.E+07
	261 million vehicles	1.1 trillion km travelled in 2018				19.5 million tonnes of hydrogen to be consumed in one year

So, the size and scope of this part of the annual hydrogen economy in the Europe (EU-28) would require 19.5 million tonnes of hydrogen to be produced and delivered to the distribution fueling stations. Assuming 50 kWh/kg to produce hydrogen with electrolysis, and 2.5 kWh/kg to compress the hydrogen into 700 bar pressure storage tanks, the estimated quantity of electricity produces the estimated annual required mass of hydrogen for the Europe (EU-28), would be 1 127.4 TWh (Table 20.17).

Table 20.17. Estimated extra annual capacity of electrical power to manufacture the need volume of hydrogen, to phase out petroleum ICE technology and substitute with H_2 Fuel Cell technology in Europe (EU-28)

Vehicle Class	Number of Self Propelled Vehicles in 2018 EU-28 Fleet (number)	Total km driven by class in 2018 EU-28 Fleet (km)	Quantity of H_2 for all EU-28 vehicles in that class to travel the same distance as was done in 2018 (kg)	Required Electric power to manufacture H_2 with electrolysis (@ 50kWh/kg) (kWh)	Required Electric power to compress H_2 into tanks at 700 bar pressure (@ 2.5 kWh/kg) (kWh)	Required electric power generation assuming 10% grid transmission loss between power station and electrolysis unit and compression unit (kWh)
Class 8 Truck	5,716,322	1.23E+11	9.83E+09	4.91E+11	2.46E+10	5.68E+11
Bus	657,714	7.56E+09	6.05E+08	3.02E+10	1.51E+09	3.49E+10
Light Truck/Van	27,413,946	1.11E+11	2.24E+09	1.12E+11	5.61E+09	1.30E+11
Passenger Car	222,683,327	8.56E+11	6.85E+09	3.42E+11	1.71E+10	3.95E+11
Motorcycle	4,548,655	3.62E+09				
Total	261,019,964	1.10E+12	1.95E+10			1.13E+12
	261 million vehicles	1.1 trillion km travelled in 2018	19.5 million tonnes of hydrogen			1,127.4 TWh

The estimated number of new non-fossil fuel power stations to be constructed in Europe, using the same method as Figure 21.9 in Section 21, is shown in Table 20.18 below.

Table 20.18. Estimated number of new power stations to be constructed to deliver the extra required annual electrical power capacity to phase out petroleum ICE technology and substitute with H2 Fuel Cell technology in Europe EU-28

Power Generation System	EU-28 electricity production in 2018 (BP Statistical Review of World Energy 2019) (kWh)	2018 ratio percent of all EU-28 electrical non-fossil fuel power systems (%)	Expanded extra required capacity to produce the needed mass of H2 to pahse out petroleum (kWh)	Average Installed Plant Capacity in 2018 (Global Energy Observatory) (MW)	Power Produced by a Single Average Plant in 2018 (kWh)	Estimated number of required additional new power plants of average size to phase out petroleum ICE technology and substitute with H_2 Fuel Cell technology (number)
Nuclear	8.27E+11	42.33%	4.77E+11	2 046.5 MW	1.28E+10	37
Hydroelectric	3.45E+11	17.64%	1.99E+11	225.4 MW	1.33E+09	150
Wind	3.79E+11	19.38%	2.18E+11	37. 2 MW	8.12E+07	2,689
Solar PV	1.28E+11	6.54%	7.37E+10	33.1 MW	3.30E+07	2,231
Other Renewable	2.76E+11	14.12%	1.59E+11	76.97 MW	7.70E+07	2,068
Total (kWh)	1.95E+12		1.13E+12			7,175
Total (TWh)	1,955					

20.12 The size of the Chinese hydrogen economy for self-propelled vehicles

Table 20.19 below shows the number of self-propelled vehicles in China by class and how many kilometers they travelled in the year 2018. Using the consumption of hydrogen if each of these vehicles was a H_2 fuel cell vehicle (Table 20.6 merged with Table 12.4 in Section 12), the total mass of hydrogen for the whole Chinese vehicle fleet was estimated.

Table 20.19. Estimated required volume of hydrogen to be consumed by all Chinese self-propelled vehicles in 2018, as if all vehicles in all classes were all hydrogen fuel cells

Vehicle Class	Number of Self Propelled Vehicles in 2018 Chinese Fleet (number)	Total km driven by class in 2018 Chinese Fleet (km)	Consumption of hydrogen if vehicle was a FCEV (kg/100 km)	Consumption of hydrogen if vehicle was a FCEV (kg/km)	Quantity of H_2 for all Chinese vehicles in that class to travel the same distance as was done in 2018 (kg)	Quantity of H_2 for all Chinese vehicles in that class to travel the same distance as was done in 2018 (tonnes)
Class 8 Truck	7,095,300	2.9E+11	8.02	0.0802	2.35E+10	2.35E+07
Bus + Delivery Truck	1,243,900	1.5E+10	8.00	0.08	1.20E+09	1.20E+06
Light Truck/Van + Other Vehicle Type	18,419,000	8.8E+10	2.02	0.0202	1.78E+09	1.78E+06
Passenger Car	203,689,500	9.4E+11	0.80	0.008	7.55E+09	7.55E+06
Motorcycle	1,864,600	1.79E+09	N/A			
Total	232,312,300	1.34E+12				3.407.E+07
	232 million vehicles	Travelled 1.34 trillion km travelled in 2018				34.1 million tonnes of hydrogen to be consumed in one year

So, the size and scope of this part of the annual hydrogen economy in the China would require 98.35 million tonnes of hydrogen to be produced and delivered to the distribution fueling stations. Assuming 50 kWh/kg to produce hydrogen with electrolysis, and 2.5 kWh/kg to compress the hydrogen into 700 bar pressure storage tanks, the estimated quantity of electricity produces the estimated annual required mass of hydrogen for China, would be 1 967.4 TWh (Table 20.20).

Table 20.20. Estimated number of new power stations to be constructed to deliver the extra required electrical power capacity to phase out petroleum ICE technology and substitute with H_2 Fuel Cell technology in China

Vehicle Class	Number of Self Propelled Vehicles in 2018 Chinese Fleet (number)	Total km driven by class in 2018 Chinese Fleet (km)	Quantity of H2 for all EU-28 vehicles in that class to travel the same distance as was done in 2018 (kg)	Required Electric power to manufacture H_2 with electrolysis (@ 50kWh/kg) (kWh)	Required Electric power to compress H2 into tanks at 700 barr pressure (@ 2.5 kWh/jg) (kWh)	Required electric power generation,a ssuming 10% grid transmission loss between powere station and electrolysis unit (kWh)
Class 8 Truck	7,095,300	2.9E+11	2.35E+10	1.18E+12	5.88E+10	1.36E+12
Bus + Delivery Truck	1,243,900	1.5E+10	1.20E+09	5.98E+10	2.99E+09	6.91E+10
Light Truck/Van + Other Vehicle Type	18,419,000	8.8E+10	1.78E+09	8.91E+10	4.46E+09	1.03E+11
Passenger Car	203,689,500	9.4E+11	7.55E+09	3.78E+11	1.89E+10	4.36E+11
Motorcycle	1,864,600	1.79E+09				
Total	232,312,300	1.34E+12	3.41.E+10			1.97E+12
	232 million number of vehicles	Travelled 1.34 trillion km travelled in 2018				1,967.4 TWh

The estimated number of new non-fossil fuel power stations to be constructed in China, using the same method as Figure 21.9, is shown in Table 20.21 below.

Table 20.21. Estimated number of new non-fossil fuel power stations to be constructed in China to implement Scenario C

Power Generation System 	Chinese electricity production in 2018 (BP Statistical Review of World Energy 2019) (TWh)	2018 ratio percent of all Chinese electrical non-fossil fuel power systems (%)	Expanded extra required capacity to phase out petroleum with H-cells (kWh)	Average Installed Plant Capacity in 2018 (Global Energy Observatory) (MW)	Power Produced by a Single Average Plant in 2018 (kWh)	Estimated number of required additional new power plants of average size to phase out petroleum ICE technology and substitute with H_2 Fuel Cell technology (number)
Nuclear	2.94E+11	13.72%	2.70E+11	2 046.5 MW	1.28E+10	21
Hydroelectric	1.20E+12	56.06%	1.10E+12	225.4 MW	1.33E+09	832
Wind	3.66E+11	17.06%	3.36E+11	37. 2 MW	8.12E+07	4,132
Solar PV	1.78E+11	8.28%	1.63E+11	33.1 MW	3.30E+07	4,927
Other Renewable	1.05E+11	4.88%	9.60E+10	76.97 MW	7.70E+07	1,248
Total (kWh)	2.15E+12		1.97E+12			11,160

20.13 Comparison between the electric EV solution and the Hydrogen Economy solution to substitute for petroleum fueled ICE

This section directly compares the full electric vehicle for the global fleet to a fully hydrogen powered H_2 fuel cell vehicle global fleet. Table 20.22 compares the quantity of electricity required to charge the batteries of an entirely EV global fleet of vehicles (Scenario A) compared to the electricity required to produce the required annual mass of hydrogen needed to fuel an entirely H_2 fuel cell global fleet of vehicles (Scenario C). As can be observed, the hydrogen solution requires between 2 and 4 times the electricity for it to be implemented. This has important implications. To deliver this extra electricity, 2 to 4 times the installed capacity in power (Table 20.22) generation needs to be constructed. This is not a trivial matter.

Figure 20.1 shows a required electrical power direct comparison between the EV Scenario A and the fuel cell Scenario C against what electric power was generated in the year 2018.

Figure 20.2 expands upon Figure 20.1 where the extra power required to charge a fully EV vehicle fleet (Scenario A) is compared against the extra power needed to charge the EV fleet but also phase out fossil fuel power generation entirely and substitute with non-fossil fuel power (17 086.1 TWh from Scenario B). If gas for heating (2816 TWh) and coal for steel production (56.5 TWh) was included, then the total non-transport contribution from Scenario B would be 19 958.7 TWh. Both of these were then compared to the hydrogen economy of fuel cell vehicles (Scenario C), and then against a hydrogen fuel cell vehicle fleet with a fully non-fossil fuel power generation system. Of the power generated in 2018, only 9 528.7 TWh was non-fossil fuels, which means that all other capacity has to be built from that base level.

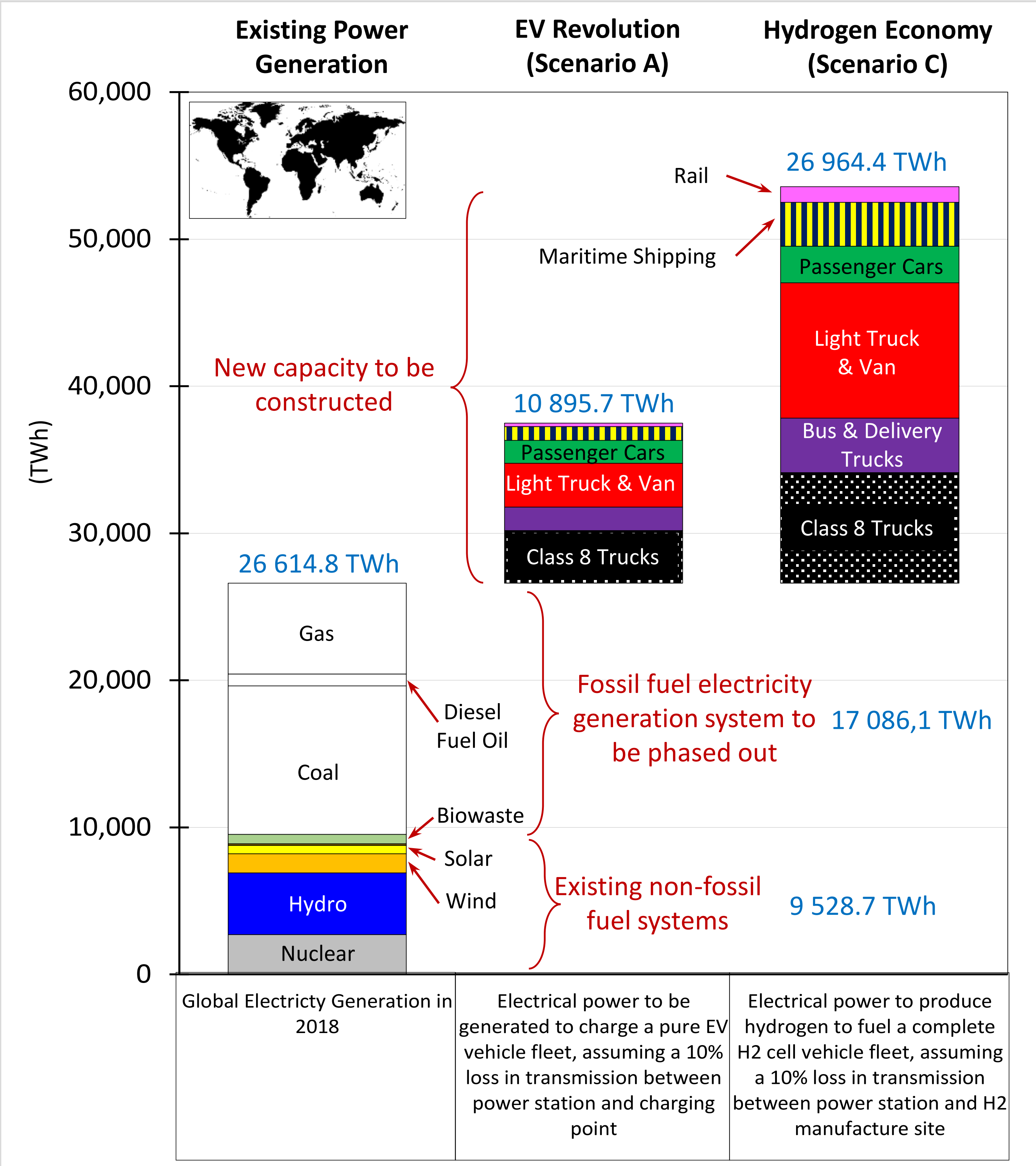


Figure 20.1. Comparison of the global size of the hydrogen economy power requirements (Scenario C) to the complete global electric vehicle fleet power requirements (Scenario A), and power production in 2018
(Image: Simon Michaux) (World Map Image by Clker-Free-Vector-Images from Pixabay)

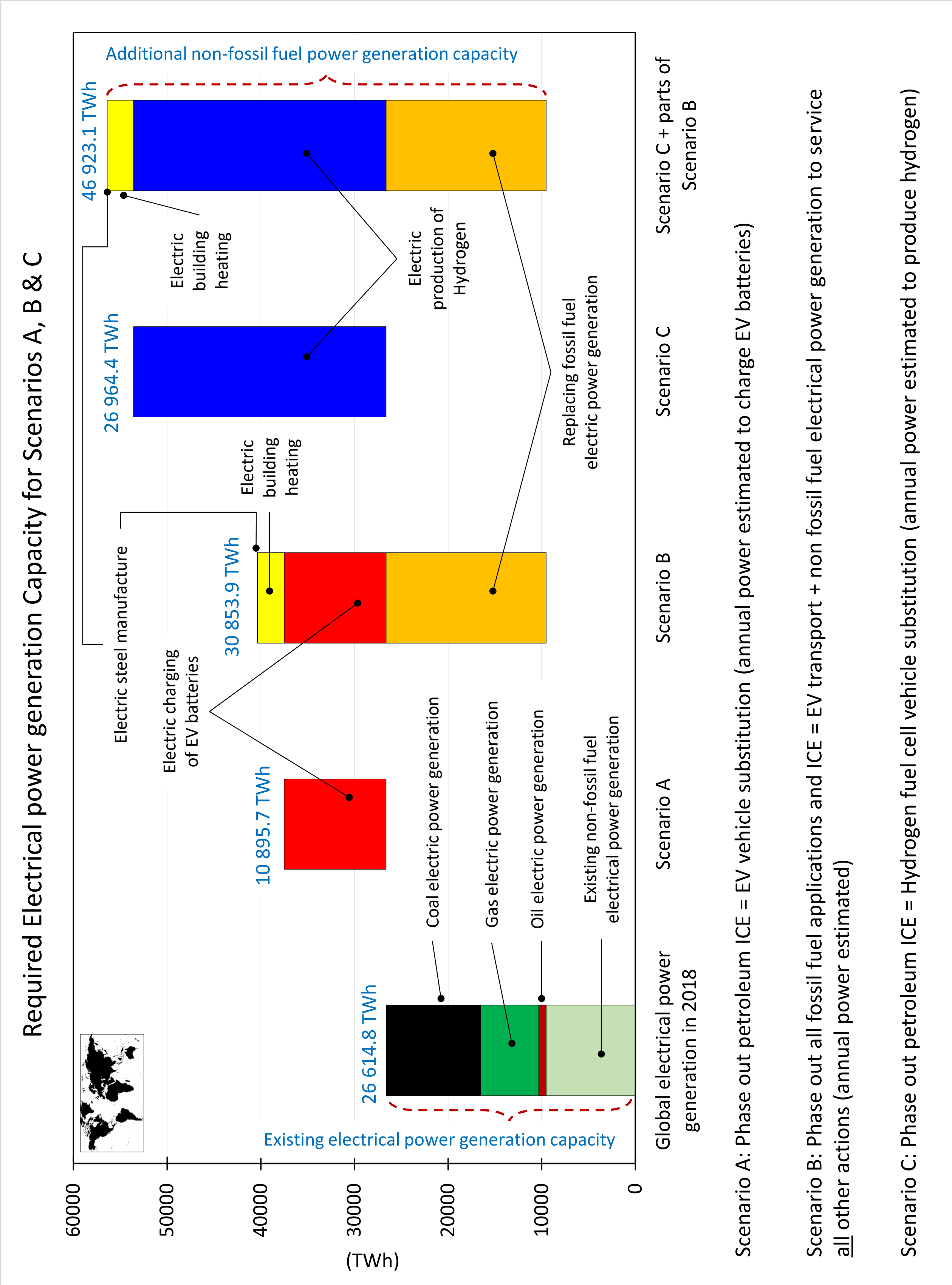


Figure 20.2. Extra non-fossil fuel electrical power to be constructed for Scenarios A, B and C (Image: Simon Michaux) (World Map Image by Clker-Free-Vector-Images from Pixabay)

Table 20.22. Comparison the annual electrical power to be generated to charge a global fleet of pure EV vehicles to the electrical power to produce the annual mass of hydrogen to fuel a global complete H_2 cell vehicle fleet

Vehicle	Required annual electrical power to be generated to charge a global fleet of pure EV vehicles, assuming a 10% loss in transmission between power station and charging point (TWh)	Electrical power to produce the annual required mass of hydrogen to fuel a global complete H_2 cell vehicle fleet, assuming a 10% loss in transmission between power station and H_2 manufacture site (TWh)	Ratio of electric power needed to charge a global fleet of pure EV vechicles to the electric power needed to produce enough of H_2 to power a global fleet of Fuel Cell vehicles
Class 8 Truck	3,564.3	7,503.7	2.1
Bus & Delivery Truck	1,597.5	3,710.4	2.3
Light Truck & Van	2,988.6	9,203.9	3.1
Passenger Car	1,545.9	2,494.5	1.6
Motor Cycle	26.5		N/A
Maritime Shipping	945.9	2,983.4	3.2
Rail Transport	226.6	1,066.5	4.7
Sum Total	10,895.2	26,962.4	2.5
			Average Ratio

Table 20.23 shows the mass of energy storage required to be on board the vehicle while operating. The mass of the battery needed to power the EV vehicle was compared against the mass of the H_2 fuel tank needed to power the fuel cell vehicle, for each vehicle class. The mass of the needed hydrogen tank was assumed to have a storage density for 700 bar compressed hydrogen to be 5.7 wt% (similar to the Toyota Mirai passenger car). It is clear that the hydrogen fuel cell solution has a much lighter mass energy storage than the EV solution, by an average multiplier of 3.2.

Table 20.23. Comparison the estimated mass of energy storage of an EV vehicle (a Lithium-Ion Battery) to the estimated mass of the energy storage of a fuel cell vehicle (compressed H_2 tank at 700 bar pressure) of the same class doing a similar task

Vehicle	Scenario A - EV Vehicles		Scenario C - Hydrogen Fuel Cell Vehicles	Ratio between mass of EV battery and mass of H_2 tank
	Estimated needed capacity of the EV battery in the vehicle (kWh)	Estimated mass of lithium ion battery in vehicle, @230 Wh/kg (kg)	Estimated weight of 700 bar pressure compressed hydrogen storage tank @ 5.7 wt% storage density (kg)	
Class 8 Truck	450.0	1,957	563	3.5
Bus & Delivery Truck	227.5	896	474	1.9
Light Truck & Van	42.1	183	123	1.5
Passenger Car	46.8	203	70	2.9
Motor Cycle	21.5	80	N/A	N/A
Rail Freight Locomotive	65,000	282,609	75,789	3.7
Maritime Shipping				
Small Vessel	14,269.5	62,041	16,689	3.7
Medium Vessel	358,397.3	1,558,249	419,178	3.7
Large Vessel	4,977,739.7	21,642,347	5,821,918	3.7
Very Large Vessel	11,614,726.0	50,498,809	13,584,475	3.7
			Average:	3.2

Table 20.24 shows the same comparison as Table 20.23, but instead of compressed hydrogen gas, storage is in the form of liquid hydrogen in cryogenic tanks. This has been presented as liquid hydrogen has a much smaller mass and volume of storage system for the same unit of mass of hydrogen fuel. The EV storage system mass ratio to liquid hydrogen storage system is approximately 9:1. This would be important for the large long range vehicles like very large ships. The engineering and logistics of liquid hydrogen are much more complex than compressed hydrogen gas. The viability of the system should consider all of these things.

Table 20.24. Comparison the size of energy storage of an EV vehicle (a Lithium-Ion Battery) to the size of the energy storage of a fuel cell vehicle (cryogenic liquid H2 tank) of the same class doing a similar task

Vehicle	Estimated needed capacity of the EV battery in the vehicle (kWh)	Estimated mass of lithium ion battery in vehicle, @230 Wh/kg (kg)	Estimated mass of cryogenic liquid hydrogen storage tank @14 wt% storage density (kg)	Ratio between mass of EV battery and mass of cryogenic liquid H_2 tank
Rail Freight Locomotive	65,000	282,609	30,857	9.2
Maritime Shipping				
Small Vessel	14,269.5	62,041	6,795	9.1
Medium Vessel	358,397.3	1,558,249	170,665	9.1
Large Vessel	4,977,739.7	21,642,347	2,370,352	9.1
Very Large Vessel	11,614,726.0	50,498,809	5,530,822	9.1

This has clear implications. A fuel cell vehicle will be able to have a much greater range and capacity to carry cargo and passengers than an EV. So, the fuel cell is more appropriate for long range and cargo transport applications.

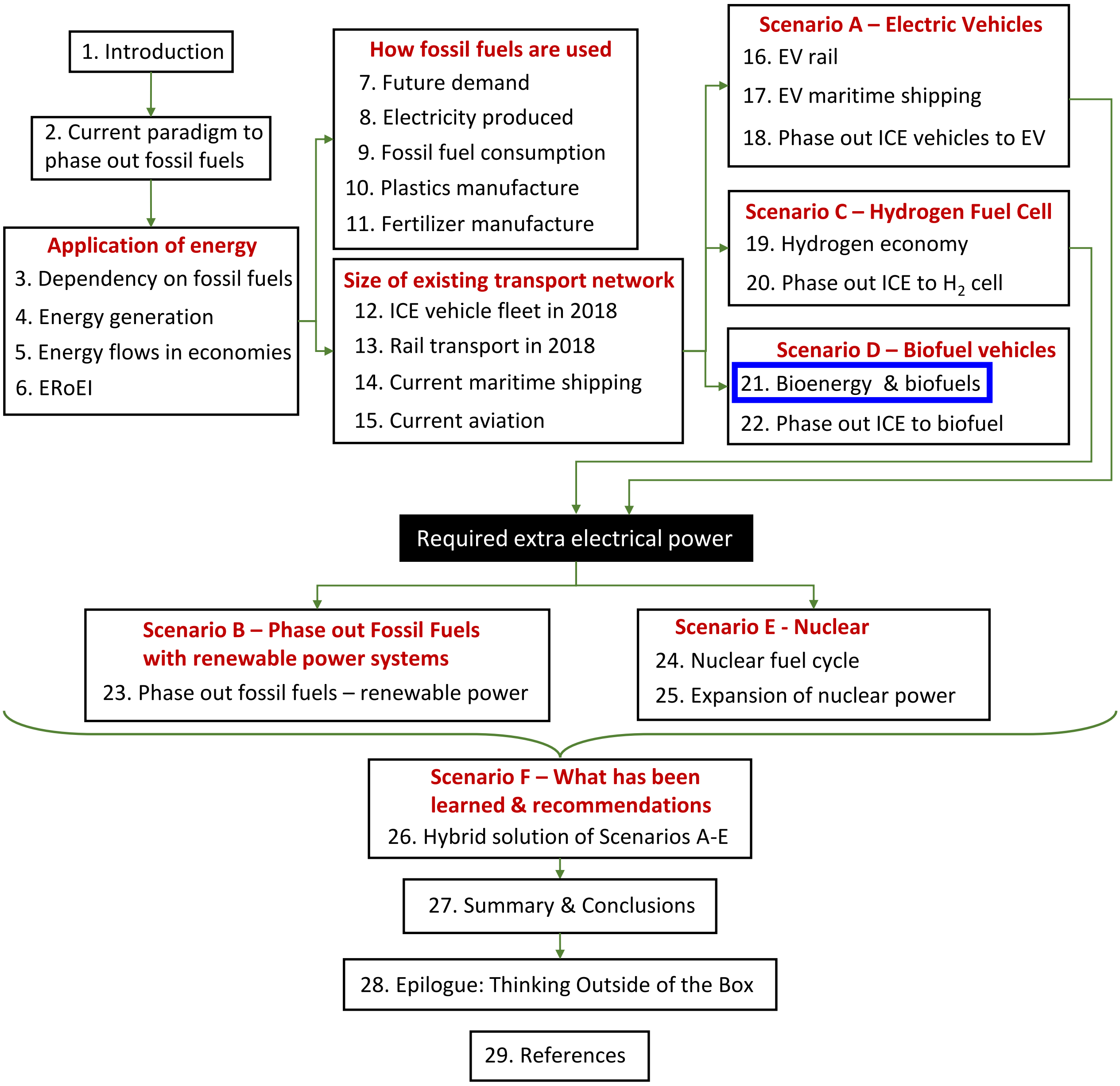
20.14 Outcomes of Scenario C

The outcome learnings of Scenario C are as follows:

- Hydrogen is not an energy source, but an energy carrier.
- To make the hydrogen, 50 kWh are needed for every 1 kg of hydrogen produced. A further 2.5 kWh is required to compress it into a 700 bar pressurized storage unit.
- For each 1kg of hydrogen, 15 kWh of electricity can be generated by a fuel cell
- To power the global transport fleet (same scope as 2018) with hydrogen fuel cells, 26 964.4 TWh of electrical power would be required annually to manufacture the hydrogen gas. This would have to be capacity in addition to existing power demands.
- This is approximately 2.5 times the electrical power required to charge the lithium ion batteries of an entirely electric global transport fleet (same scope as 2018) to travel the same distance and perform the same tasks (the outcome of Scenario A was 10 895.7 kWh).
- The comparison of the mass of the storage systems between EV batteries and compressed hydrogen tanks showed that the battery mass was approximately 3.2 times the mass of the hydrogen tank mass. If liquid hydrogen in cryogenic tanks was compared to the battery mass of the equivalent EV system, the ratio was approximately 9.1 times.

21 BIOENERGY AND BIOFUELS AS AN ENERGY SOURCE

Bioenergy is considered to be a genuinely sustainable and renewable energy source and has been promoted in many studies as the most effective solution to phase out fossil fuels. Bioenergy can take the form of biomass being combusted in a CHP plant to produce heat and electricity, or in the form of a biomass feedstock biochemically processed to produce a fuel that can be used in ICE engine technology. This section will examine each of the major biomass to energy processes.



Assessment of the Extra Capacity Required of Alternative Energy Electrical Power Systems to Completely Replace Fossil Fuels

Bioenergy is considered to be a genuinely sustainable and renewable energy source and has been promoted in many studies as the most effective solution to phase out fossil fuels. Bioenergy is defined as energy made from a natural biomass or biofuel. Biomass is any organic material which has absorbed sunlight and stored it in the form of chemical energy. Examples are wood, energy crops and waste from forests, yards, or farms (EIA 2018 June 18). As a fuel it may include wood, wood waste, straw, manure, sugarcane, and many other by-products from a variety of agricultural processes. Biomass and bioenergy are promoted as useful in that the feedstock can be sustainably replenished without harming the environment or depleting finite nonrenewable resources.

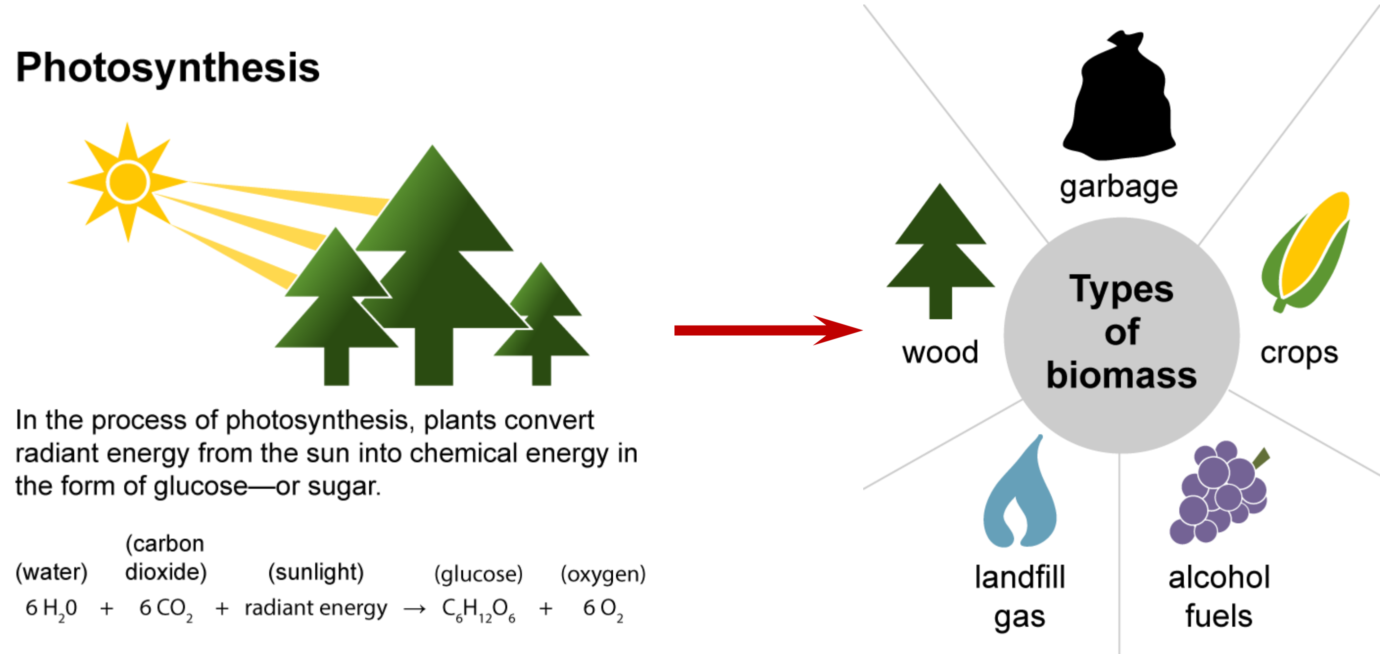


Figure 21.1. Source of biomass, which is then converted into energy
(Source: EIA, and National Energy Education Project)
(Copyright License: https://www.eia.gov/about/copyrights_reuse.php)

Biofuel is defined as liquid or gaseous fuels, used for transportation, that is manufactured from biomass resources. Some of the biofuels are termed 'Drop-in biofuels' which are functionally equivalent to petroleum fuels and fully compatible with the existing petroleum infrastructure (Karatzos *et al* 2014). These drop-in biofuels require no ICE engine modification of the vehicle (U.S. DoE: Renewable Hydrocarbon Biofuels, Efficiency & Renewable Energy).

The global production of biomass from the planetary environment in 2008 was 170 billion metric tonnes (Shen *et al* 2009). The global human population has been harvesting only 3.5% of this, which is in turn split up into food production, lumber/wood products and feedstock for chemicals (Figure 21.2).

Proposed expansions of the use of bioenergy to support industrialization are often not compared to the available planetary biomass feedstock capacity, sustainable or otherwise (Friedemann 2021). If all plant matter in the global planetary environment was harvested in one single step and processed in a combined heat and power (CHP) biowaste to energy plant, only 94 EJ (exajoules) of energy would be produced (Patzek 2005). To put this in context the annual consumption of primary energy for just the United States in the year 2019, was 94.65 EJ, and the global annual primary energy consumption in 2019 was 583.90 EJ (BP Statistical Review of World Energy 2020). So, if all biomass growing in the environment, all over the entire planet was harvested all at once, it would produce the energy requirements of just the United States!

On an annual basis, the global industrial ecosystem consumes a quantity of fossil fuel energy, that is approximately equal to 400 times the planetary environments total annual plant growth, including the microscopic plants in the ocean (Dukes 2003). This thought experiment comparison was done to highlight that while bioenergy may well be the most sustainable and renewable energy source of all of the methods currently available, it will not be able to completely replace all other energy generation systems (Smil 2011). This will be the subject of Scenario D in Chapter 22.

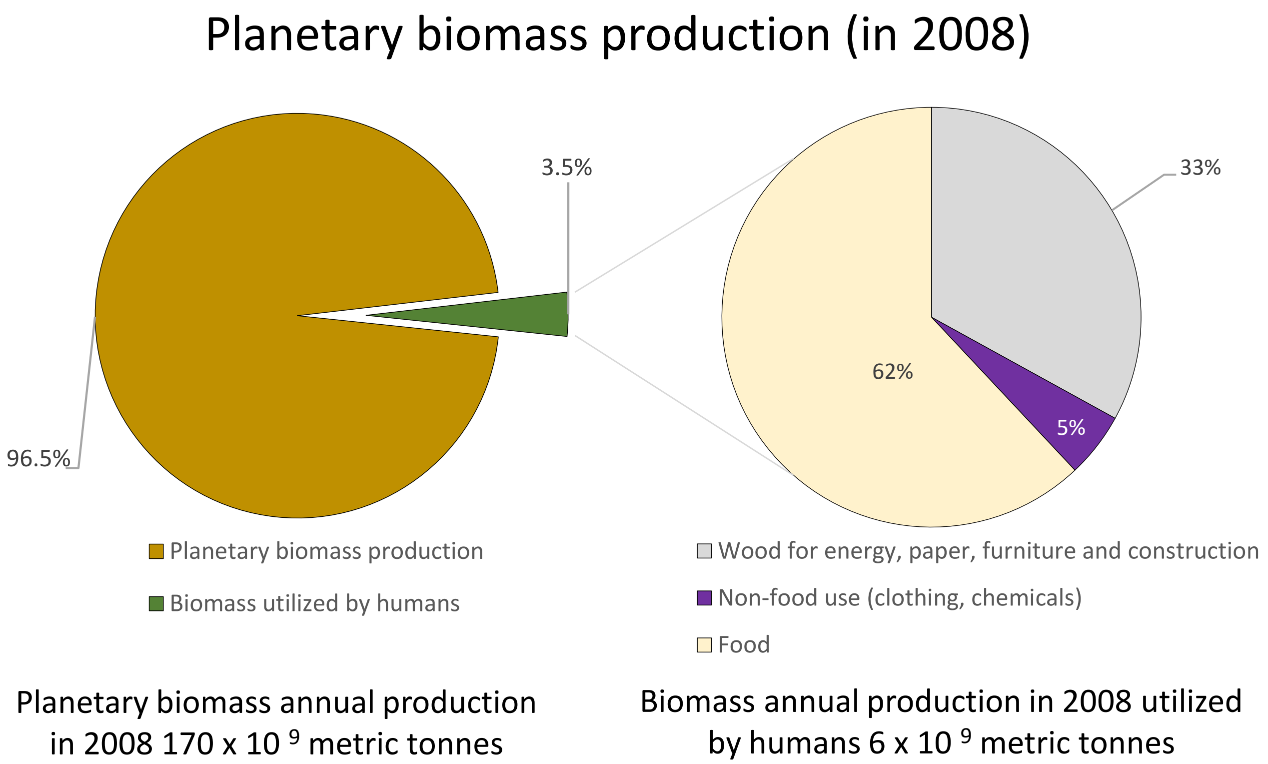


Figure 21.2. Biomass produced annually by the planetary environment, and the annual biomass harvested and used by humans in 2008 (Source: Shen *et al* 2009)

Table 21.1. Domestic supply of biomass in 2017 (Source: WBA 2019)

	Biomass (EJ)	Municipal Waste (EJ)	Industrial Waste (EJ)	Primary Solids Biofuels (EJ)	Biogases (EJ)	Liquid Biofuels (EJ)	Total (EJ)
Africa	15.4	0.00	0.00	15.40	0.00	0.00	30.8
Americas	10.8	0.30	0.05	7.70	0.19	2.57	21.61
Asia	21.6	0.20	0.61	20.10	0.41	0.35	43.27
Europe	7.52	0.95	0.40	4.73	0.71	0.73	15.04
Oceania	0.28	0.00	0.00	0.25	0.02	0.00	0.55
World	55.6	1.45	1.07	48.18	1.33	3.65	111.28

21.1 Biowaste to energy

Bioenergy in its most narrow sense it is a synonym to biofuel, which is fuel derived from biological sources. In its broader, more inclusive sense it includes biomass, the biological material used as a biofuel, as well as the social, economic, scientific, and technical fields associated with using biological sources for energy. Biomass is converted to energy through various processes, including:

- Direct combustion (burning) to produce heat in CHP plants
- Thermochemical conversion to produce solid, gaseous, and liquid fuels
- Chemical conversion to produce liquid fuels
- Biological conversion to produce liquid and gaseous fuels

Renewable natural gas (also biogas or biomethane) is produced in anaerobic digesters at sewage treatment plants and at dairy and livestock operations, where anaerobic digestion is used to produce renewable natural gas. It also forms in and may be captured from solid waste landfills. Properly treated renewable natural gas has the same uses as fossil fuel natural gas.

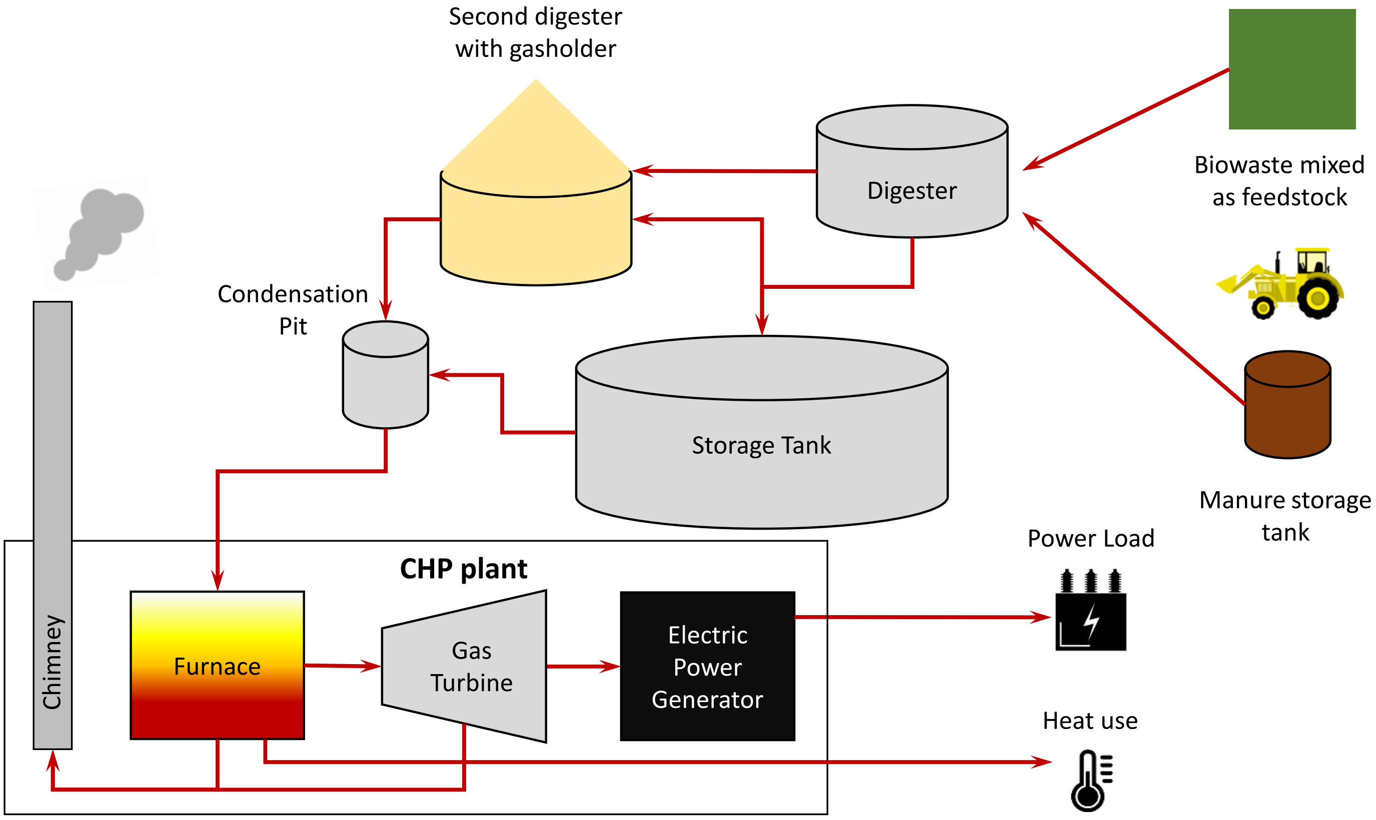


Figure 21.3. Biowaste to energy power CHP plant schematic
(Image: Simon Michaux, using some copyright free clipart)

Waste-to-energy (WtE) or energy-from-waste (EfW) is the process of generating energy in the form of electricity and/or heat from the primary treatment of waste, or the processing of waste into a fuel source. WtE is a form of energy recovery. Most WtE processes generate electricity and/or heat directly through combustion, or produce a combustible fuel commodity, such as methane, methanol, ethanol or synthetic fuels biomass, in fired Combined Heat and Power (CHP) plants and utility scale power generation, or in dedicated biomass power plants (EUBIA 2018 and IEA Bioenergy News 2018). Cogeneration or combined heat and power (CHP) is the use of a heat engine or power station to generate electricity and useful heat at the same time. Cogeneration is a more efficient use of fuel or heat, because otherwise-wasted heat from electricity generation is put to some productive use. Combined heat and power (CHP) plants recover otherwise wasted thermal energy for heating. This is also called combined heat and power district heating. Heat from CHP can be used also for industrial processes if the district heating load is too small. A CHP plant will combust biomass directly, or uses methane gas generated from biomass, and then use the resulting gas to drive a turbine, which in turn generates electricity (Figure 21.3). In 2018, there were an estimated 3 800 biomass power plants with an electric power generation capacity of over 60 GW (ecoprog 2019) (Table 8.3 in Section 8). These plants operated at an overall efficiency in electricity generation of 13% (Di Maria *et al* 2016). In the year 2018, 60 TWh of electricity (or 0.23% of the 2018 total) was generated with biowaste power stations (Table 8.3 in Section 8).

All forms of biomass can be burned directly for heating buildings and water, for industrial process heat, and for generating electricity in steam turbines. The most common method for converting biomass to useful energy is a process called Direct Combustion. Thermochemical conversion of biomass includes pyrolysis and gasification. Both are thermal decomposition processes in which biomass feedstock materials are heated in closed, pressurized vessels called gasifiers at high temperatures. There are other liquefaction techniques, for example hydrothermal liquefaction. For the purpose of this report, only a few of the more common methods of production are examined.

1. **Pyrolysis** is the heating organic materials to temperatures between 400 and 500°C in the near complete absence of free oxygen. Biomass pyrolysis produces fuels such as charcoal, bio-oil, renewable diesel, methane, and hydrogen. Hydrotreating is used to process bio-oil (produced by fast pyrolysis) with hydrogen under elevated temperatures and pressures in the presence of a catalyst to produce renewable diesel, renewable gasoline, and renewable jet fuel. The gas produced by a simialr process to what is shown in Figure 21.4 has been used refine pyrolysis oil for maritime shipping bunker fuel oil and heating applications. All proposals for this application to be used to refine pyrolysis bio-oil upgrading to high quality transportation fuel has not been fully commercialized. Transportation fuels are not obtained directly by fast pyrolysis. Upgrading of the liquid with some form of hydrotreatment is always needed.

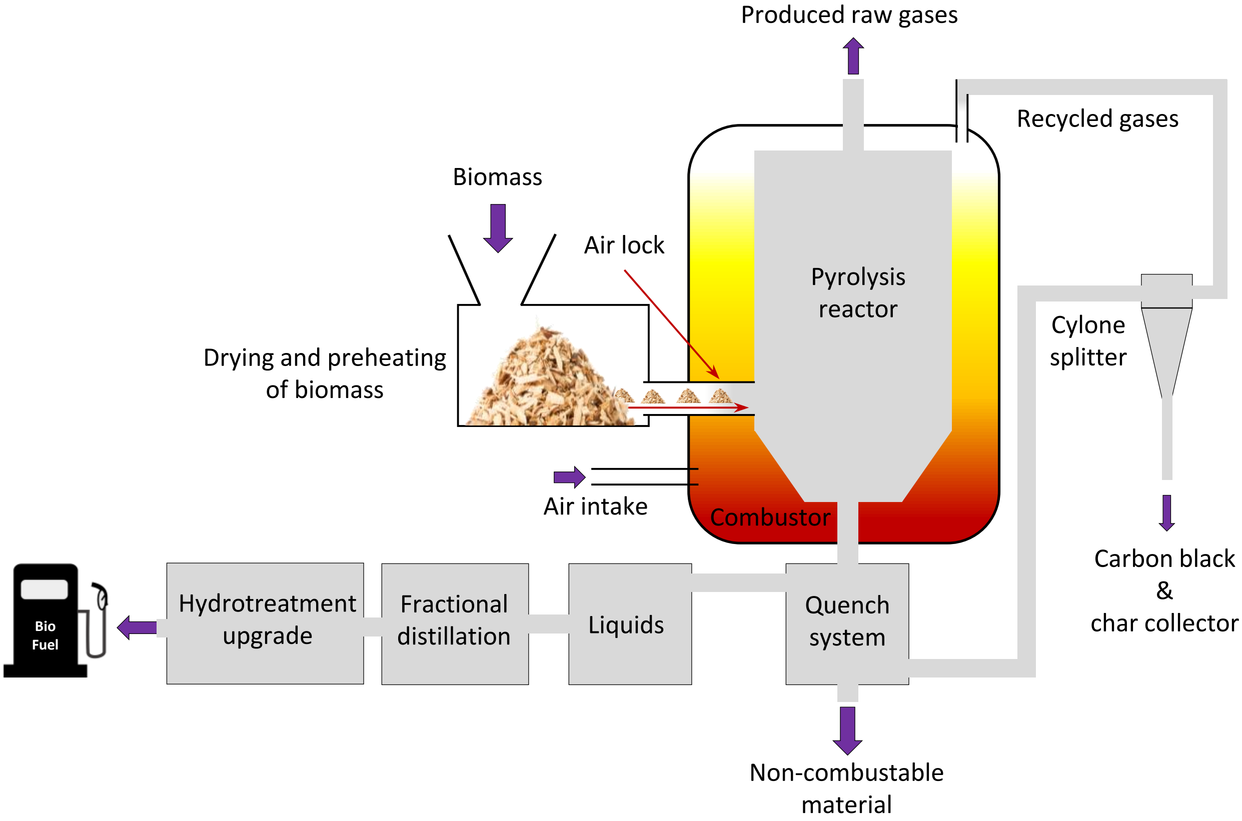


Figure 21.4. Pyrolysis (Image: Simon Michaux)

2. **Gasification** is the heating organic materials to temperatures between 800 and 900°C with injections of controlled amounts of free oxygen and/or steam into the vessel to produce a carbon monoxide (CO) and hydrogen (H_2) rich gas termed syngas (also spelt synthesis gas). Syngas can be used directly as a fuel for diesel engines, for heating, and for generating electricity in gas turbines. It can also be treated to separate the hydrogen from the gas previously produced. The syngas can be further processed to produce liquid fuels or gaseous fuels (methane, methanol, Fischer-Tropsch hydrocarbons). Some purification/conditioning of product gas is needed for almost all applications.

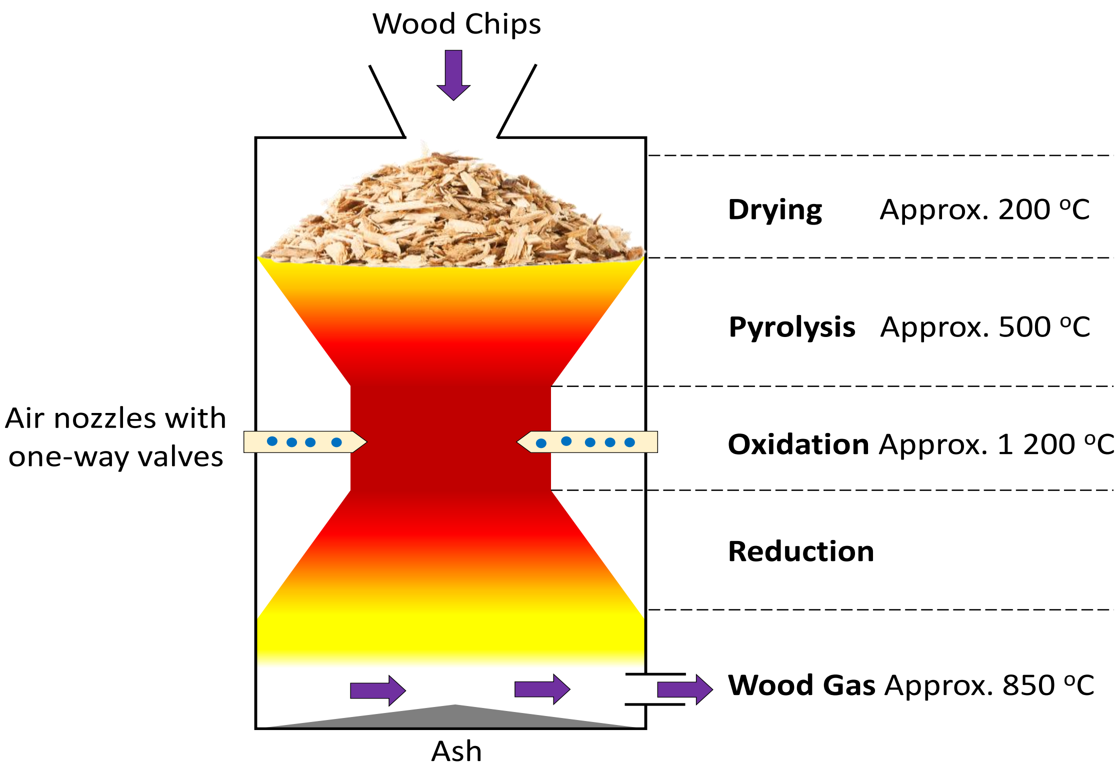


Figure 21.5. Wood gasification
(Image: Simon Michaux)

21.2 Biofuel

A biofuel is a fuel that is produced through contemporary processes from biomass, rather than a fuel produced by the very slow geological processes involved in the formation of fossil fuels, such as oil. Since biomass technically can be used as a fuel directly (e.g. wood logs), alternatively the terms biomass and biofuel are often used interchangeably. Usually, the word biomass simply denotes the biological raw material the fuel is made of, or some form of thermally/chemically altered solid end product, like pellets or briquettes.

The word biofuel is usually reserved for liquid or gaseous fuels, used for transportation (U.S. Energy Information Administration). If the biomass used in the production of biofuel can regrow quickly, the fuel is generally considered to be a form of renewable energy. Biofuels can be produced from plants (i.e. energy crops like corn), or from agricultural, commercial, domestic, and/or industrial wastes (if the waste has a biological origin). Biofuels are generally classified into four categories. They are:

1. First generation biofuels - First-generation biofuels are made from sugar, starch, vegetable oil, or animal fats using conventional technology. Common first-generation biofuels include Bioalcohols, Biodiesel (fatty acid esters), Vegetable oil, Bioethers, Biogas. HVO (Hydrotreated Vegetable Oil) renewable diesel would locate somewhere in between first and second generation (made from fats and oils using advanced technology)

2. Second generation biofuels - These are produced from non-food crops, such as cellulosic biofuels and waste biomass (stalks of wheat and corn, and wood). Examples include advanced biofuels like biohydrogen, biomethanol.

3. Third generation biofuels - These are produced from micro-organisms like algae.

4. Fourth-generation biofuels are made using non-arable land biomass products. This class of biofuels includes electrofuels and photobiological solar fuels (Moravvej *et al* 2019). Electrofuels are not necessarily biofuels. They might be classified to biofuel if CO_2 comes from biogenic source.

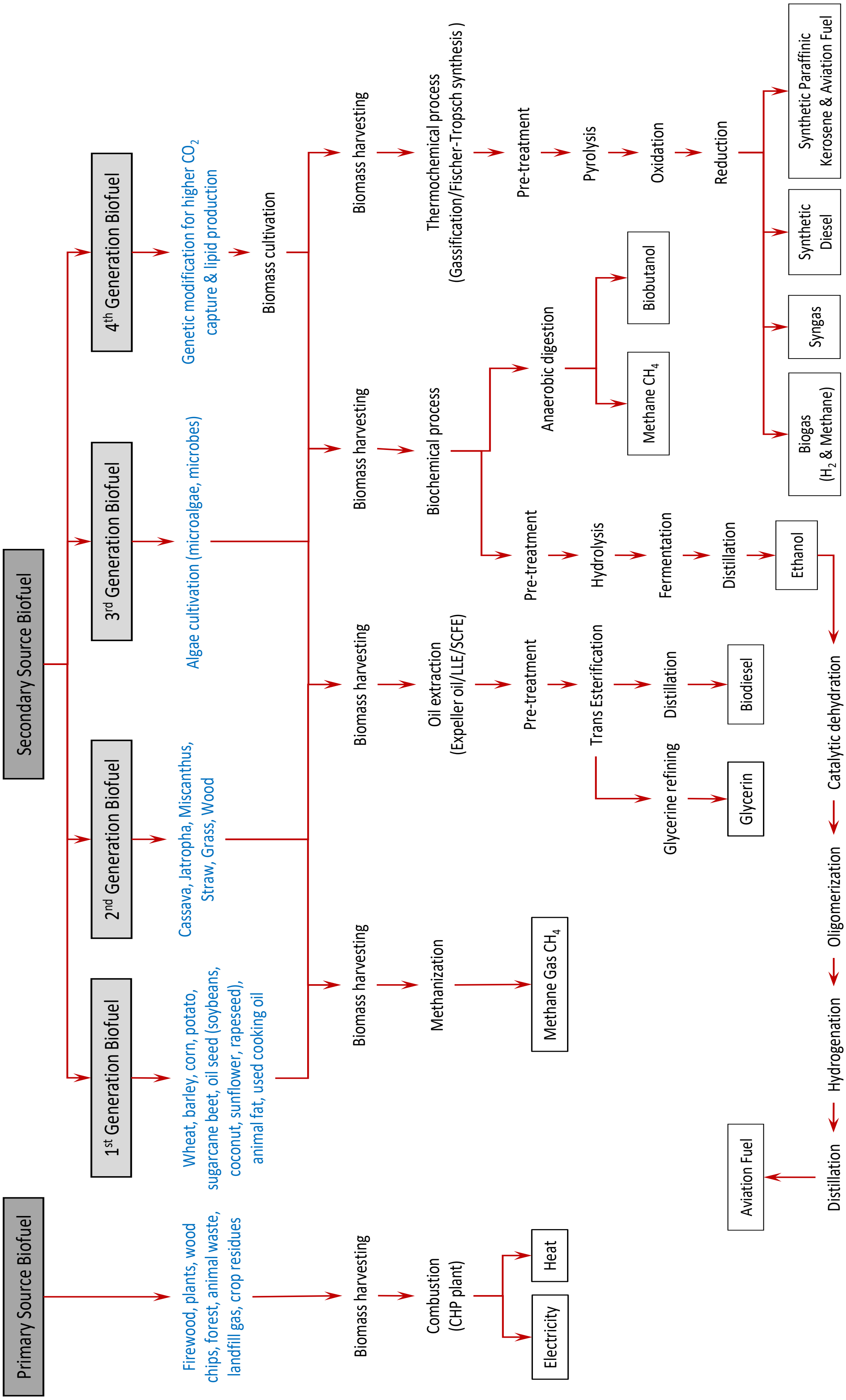
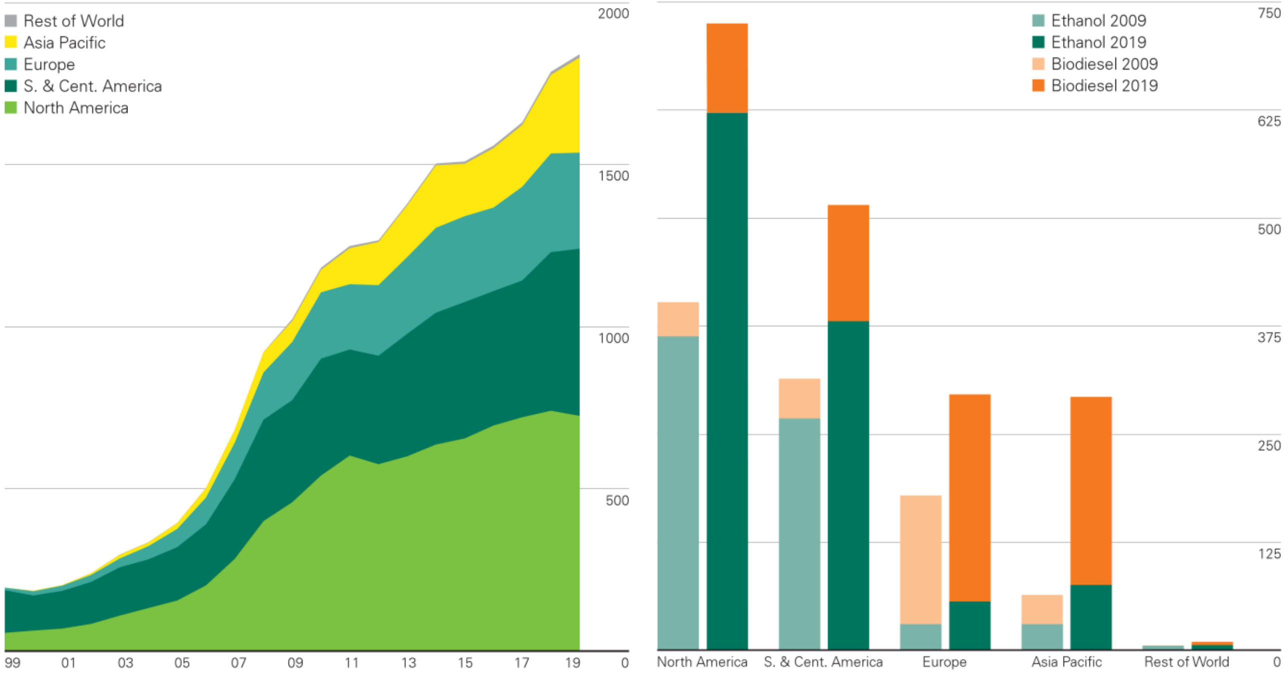


Figure 21.6. Process paths for 1st, 2nd, 3rd and 4th Generation of biofuels
(Image: Simon Michaux)

World biofuels production

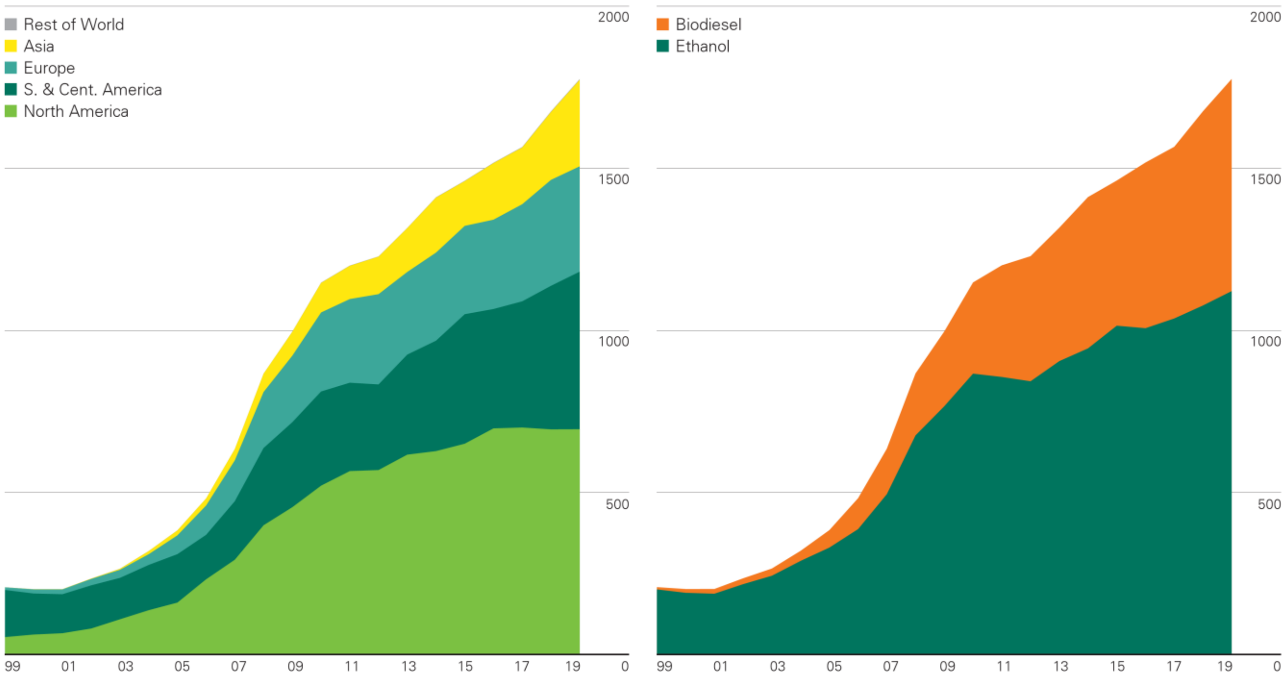
Thousand barrels of oil equivalent per day



Biofuels production growth averaged 3% (54,000 barrels of oil equivalent per day or boe/d, less than half the 10-year average. Growth was led by Brazil (31,000 boe/d) and Indonesia (32,000 boe/d) but US output declined by 19,000 boe/d. Growth was weighted towards biodiesel, which grew by 34,000 boe/d driven largely by Indonesia. Biodiesel is the dominant fuel in Europe and Asia Pacific (making up 81% and 74% of biofuels respectively in 2019), while ethanol is the main fuel in North America (86% of total) and S&C America (74%).

World biofuels consumption

Thousand barrels of oil equivalent per day



Biofuels consumption rose by 6% (100,000 boe/d). As with production, growth was driven mainly by Brazil (42,000 boe/d), most of which was ethanol and Indonesia (56,000 boe/d), which was largely biodiesel. At the global level, ethanol made up 63% of biofuels in 2019, but the share of biodiesel has risen continually. For example, biodiesel's share was 23% in 2009 but rose to 37% last year.

Figure 21.7. Global biofuels production and consumption – data shown in Appendix I (Source: BP Statistical Review of World Energy 2020)

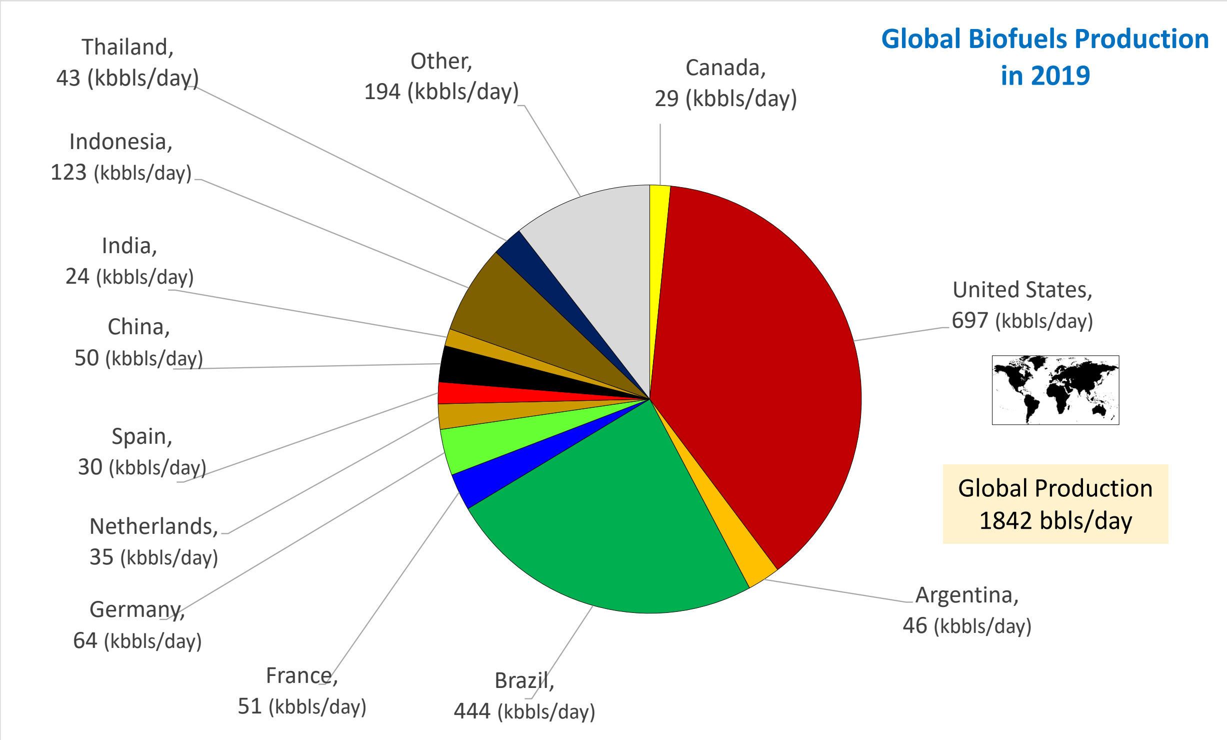


Figure 21.8. Global biofuels production in 2019 (Source: BP Statistical Review of World Energy 2020) (World Map Image by Clker-Free-Vector-Images from Pixabay)

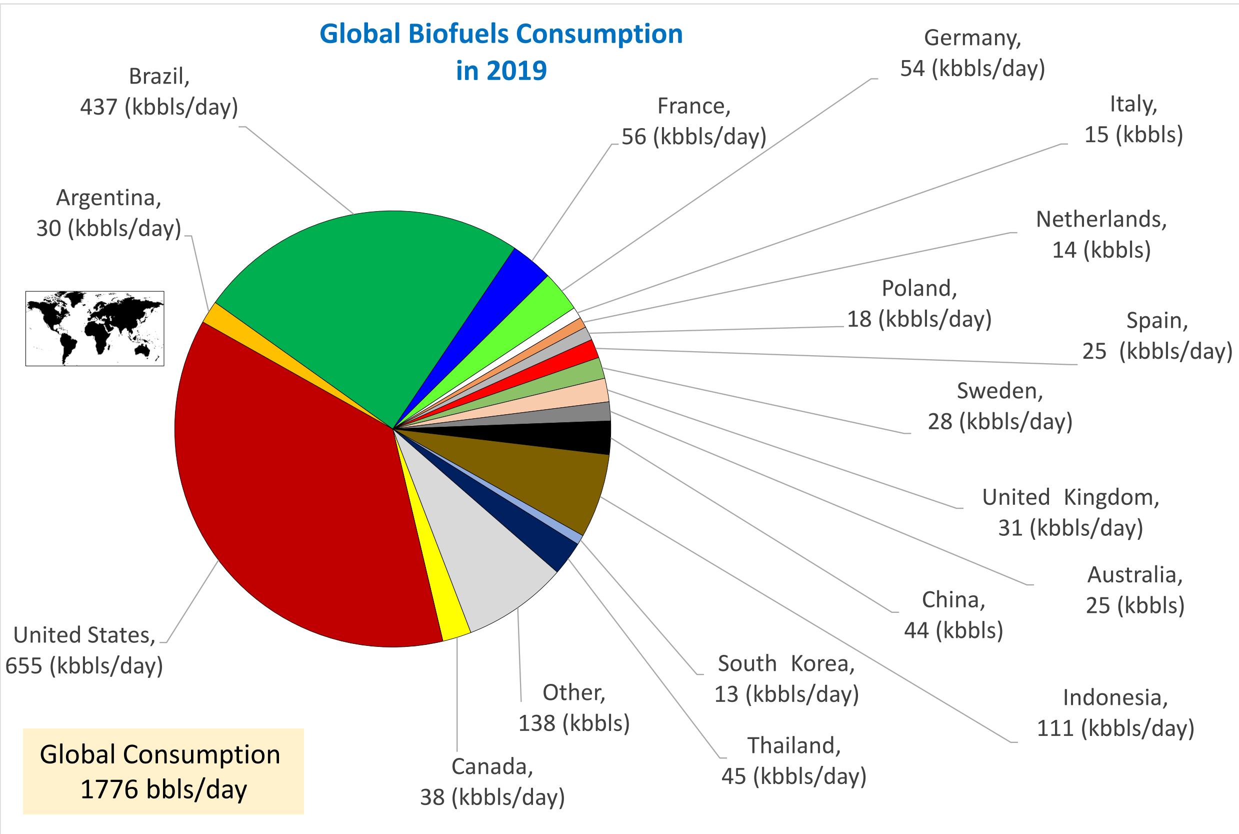


Figure 21.9. Global biofuels consumption in 2019 (Source: BP Statistical Review of World Energy 2020) (World Map Image by Clker-Free-Vector-Images from Pixabay)

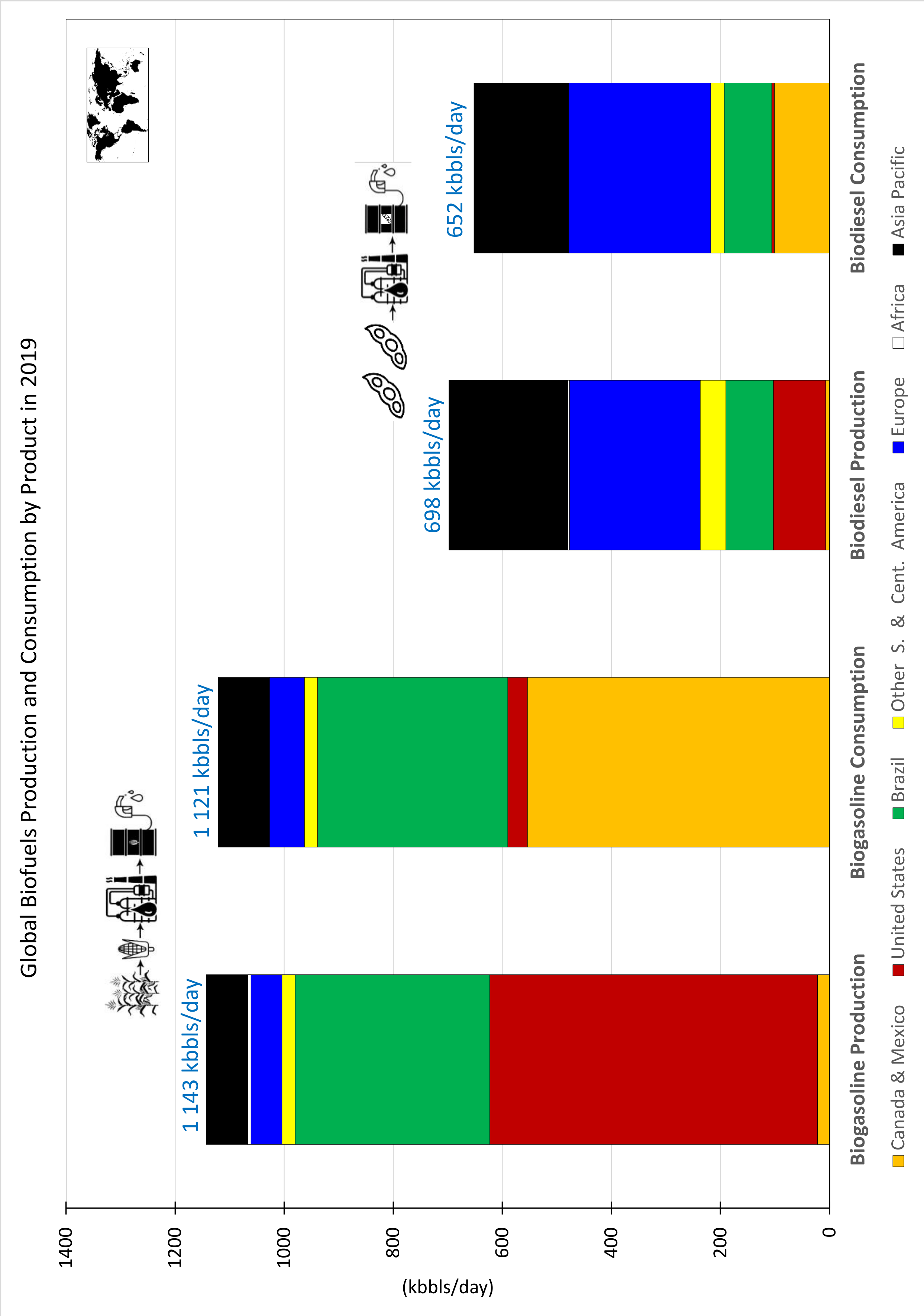


Figure 21.10. Global biofuels production and consumption in 2019, by product
(Source: BP Statistical Review of World Energy 2020) (World Map Image by Clker-Free-Vector-Images from Pixabay)

Biofuel production from the first generation is known to be made from agricultural products such as corn or sugarcane. The second-generation biofuels use all forms of cellulosic biomass. The third and fourth generations of biofuel production involve “algae-to-biofuels” technology. Metabolic engineering of microorganisms for biofuel production forms the basis for fourth-generation biofuel production which can meet this need. The two most common types of biofuel are bioethanol and two different biodiesels. products: fatty acid esters and HVO (Hydrotreated Vegetable Oil). Esters are typically called biodiesel and HVO are often called renewable diesel. HVO of these is the product with growing volumes and market.

In 2018, global biofuel production was 95 371 thousand tonnes of oil equivalent (ktoe) (Appendix I and BP Statistical Review of World Energy 2019).

21.3 Biodiesel

Biofuel is fuel derived from biological sources such as soybean oil or animal fats and is produced by a chemical process that removes the glycerin from the oil. The majority of biodiesel is produced from soybean feedstock (FAO 2008a). Limited amounts of biodiesel can be used in any diesel vehicle without modification (Sadaka 2013). Vehicles that are able to use biodiesel include buses, delivery trucks, waste disposal and recycling trucks, construction equipment, heavy-duty freight-hauling trucks, boats, passenger vehicles and tractors. Biodiesel can be blended at any ratio with petroleum diesel to achieve cost efficiency and improve cold weather performance.

The United States produces more than a billion gallons a year of biodiesel (Friedemann 2021). This biodiesel is made from 95 % vegetable oils (68 % soybean, 16 % corn, 11.4 % canola) and 4.6 % animal fats and grease (EIA 2019).

Soy is a much more productive feedstock to produce biodiesel compared to corn. Corn can yield 18 gallons of biodiesel per acre, where soybeans can yield 57 gallons of biodiesel per acre (NRC 2014). Corn yields 177 bushels per acre and soy just 39 bushels. This difference is related to the fat content of each plant feedstock. Corn is 4% fat whereas soy is 20% fat (Troeh & Thompson 2005, Friedemann 2021). Biobased fat is required to produce biodiesel. Despite its low-fat content (4%) and because of its high yield, corn contributes 16% of annual United States biodiesel production in 2019 (EIA 2019).

A chemical conversion process known as transesterification is used for converting vegetable oils, animal fats, and greases into fatty acid methyl esters (FAME), which are used to produce biodiesel. This process is the reaction of oil or fat with an alcohol (methanol) to form biodiesel and glycerol (Sadaka 2013). A catalyst such as sodium or potassium hydroxide is required. Glycerol is produced as a byproduct. Biodiesel has a higher flash point than fossil diesel and so is safer for storage or in the event of an accident.

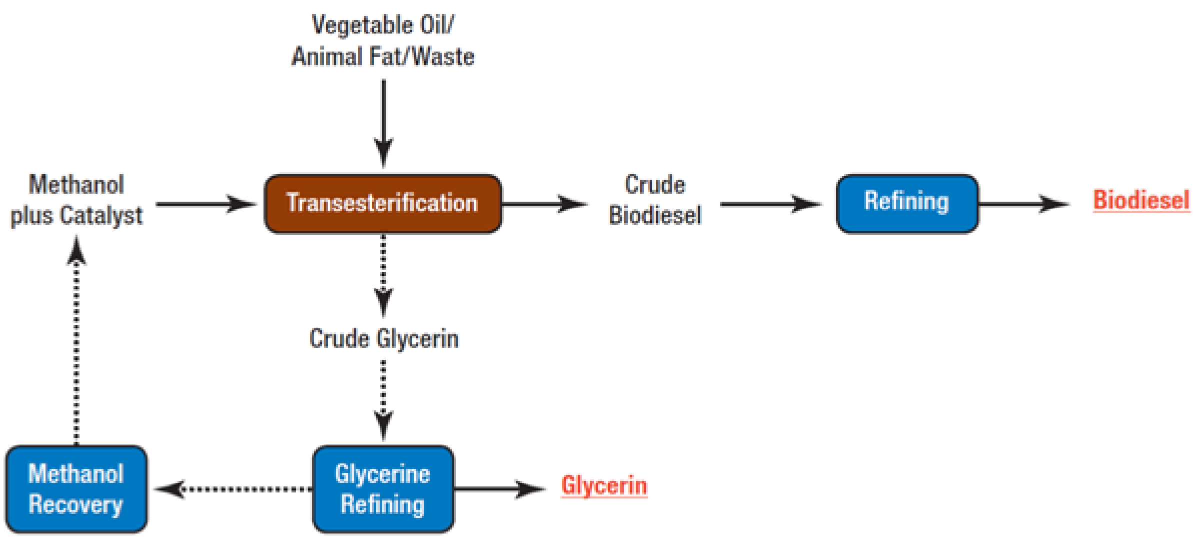


Figure 21.11. Schematic production path for Biodiesel
(Source: U.S. Department of Energy, https://afdc.energy.gov/fuels/biodiesel_production.html)
(Copyright License: https://www.energy.gov/about-us/web-policies)

From Sadaka 2013 (orginal units in acres, pounds, and gallons):

- 1 km^2 of soybean land produces about 9 637 bushels (1 acre produces 39 bushels)
- 1 bushel of soybeans weighs 27.2 kg
- 1 km^2 of soybean land can produce about 262 279 kg (or 262.3 tonne) of soybeans
- 1 bushel of soybeans produces 4.99 kg of oil
- 1 km^2 of soybean land produces 48 084 kg (or 48 tonne) of oil
- 1 kg of soybean oil produces about 0.973 kg of biodiesel
- 1 km^2 of soybean land produces 46 851.6 kg (or 46.9 tonne) of biodiesel
- 1 liter of biodiesel weighs 0.875 kg
- 1 km^2 of soybean land produces about 53 317.6 liters (57 gallons per acre) of biodiesel

Given that:

- 1 US gallon = 3.79 liters
- 1 acre = 0.0041 km^2
- 1 btu = 0.000293 kilowatt hours

To produce 1 liter of soy based biodiesel, 4.91 kg of soybean seed is required. The land use to grow soybeans can be quantified, where 53 317 liters of biodiesel could be produced on 1km^2 of arable land used to grow soybeans (data taken from Sadaka 2013, then converted from imperial units to standard SI units).

It takes approximately 14 000 liters of water to produce enough soybeans to make a 1 liter of biodiesel (Gerbens-Leenes *et al* 2009).

Corn and soy are high maintenance crops because they need a lot of pesticides to produce a good yield. Of global pesticide use on crops, corn's share is 39.5% and soybeans 22% (Mclaughlin and Walsh 1998; Padgitt *et al* 2000; Pimentel 2003; Patzek 2004; Fernandez-Cornejo et al 2014).

21.4 Renewable diesel (HVO)

High quality renewable diesel (also known as HVO or Hydrotreated Vegetable Oil) is made from renewable raw materials and can be used to fuel all diesel ICE engines. HVO diesel and conventional biodiesel (also termed as FAME or Fatty Acid Methyl Ester) are often blended. However, they are different products, although both are made from organic biomass. They differ in the manufacturing process and in purity and quality of the final product (Lehtonen 2021, Rimkus *et al* 2020).

The high-quality, HVO renewable diesel is made mainly from organic waste and residues. In the manufacturing process, the raw materials are cleaned of impurities and hydrotreated at a high temperature. The end result is a homogeneous, colorless, odorless, and fossil diesel with a chemical composition similar to fossil diesel, often also referred to as "advanced biofuel" or "second generation biofuel".

The conventional first-generation FAME-type biodiesel is produced by esterifying vegetable oils or fats (see Section 21.3). The esterification process is limited with the use of low quality or impure raw materials such as waste and residues. The quality of conventional biofuels also varies according to the raw material used.

HVO renewable diesel is produced in the process of hydrogenation (treatment with hydrogen atmosphere) and uses hydrogen and not methanol as the “catalyst.” A by-product of this process is propane, where conventional transesterification processes have glycerin as a by-product. Another important difference between the two processes is the fact that hydrogenation removes all oxygen from the vegetable oils while esterification does not. It gives an advantage to the HVO production as it helps to avoid oxidation (Athanasios *et al* 2018, Bohl *et al* 2018).

The main product of the HVO process is the, so called, Green Diesel. It has to be noted, though, that the HVO plant is a type of biorefinery and thus allows for production of a wide range of products from biofuels to biochemicals. Except for Green Diesel, the HVO installation can be used to produce Green Jet Fuel while Green Naptha and Green GPL, together with propane, are the by-products of the production process.

The feedstock used in the process can be of the same or much lower quality than while producing the regular biodiesel, but the final product is better quality. The main strength points of the HVO diesel are: high cetane number, high energy density and lack of oxygen content. The key advantage of Green Diesel, however, is its CFPP level which can go down to -20°C or even -50°C irrespective of the feedstock used. This, in turn, makes HVO suitable for use during cold winters even in Nordic countries as well as for use as jet fuel (Greenea 2014). The HVO diesel has the potential to be blended without limits. Thus, it is a type of drop-in fuel.

In the recent past, the FAME process was the most economical process requiring only low temperatures and pressures and producing a 98 % conversion yield. Current developments in HVO renewable biodiesel are improving these performance metrics. This report has used the FAME process path as it was possible to collect data on the material inputs to calculate what is required to process 1 liter of diesel fuel.

21.5 Bioethanol

Bioethanol is an alcohol made by fermentation, mostly from carbohydrates produced in sugar or starch crops such as corn, sugarcane, or sweet sorghum, where most bioethanol is produced using corn feedstock (FAO 2008a). Ethanol is an alcohol product produced from corn, wheat, sugar cane, and biomass and used as an additive in gasoline to increase its octane level. Cellulosic biomass, derived from non-food sources, such as trees and grasses, is also being developed as a feedstock for ethanol production (Neupane 2017). To date, commercialization of cellulosic ethanol production has been very challenging. Ethanol can be used as a fuel for vehicles in its pure form (E100), but it is usually used as a gasoline additive to increase octane and improve vehicle emissions. Bioethanol is widely used in the United States and in Brazil (Biswas 2019). Biodiesel is not the same thing as raw vegetable oil or unaltered used frying grease (Figure 21.12).

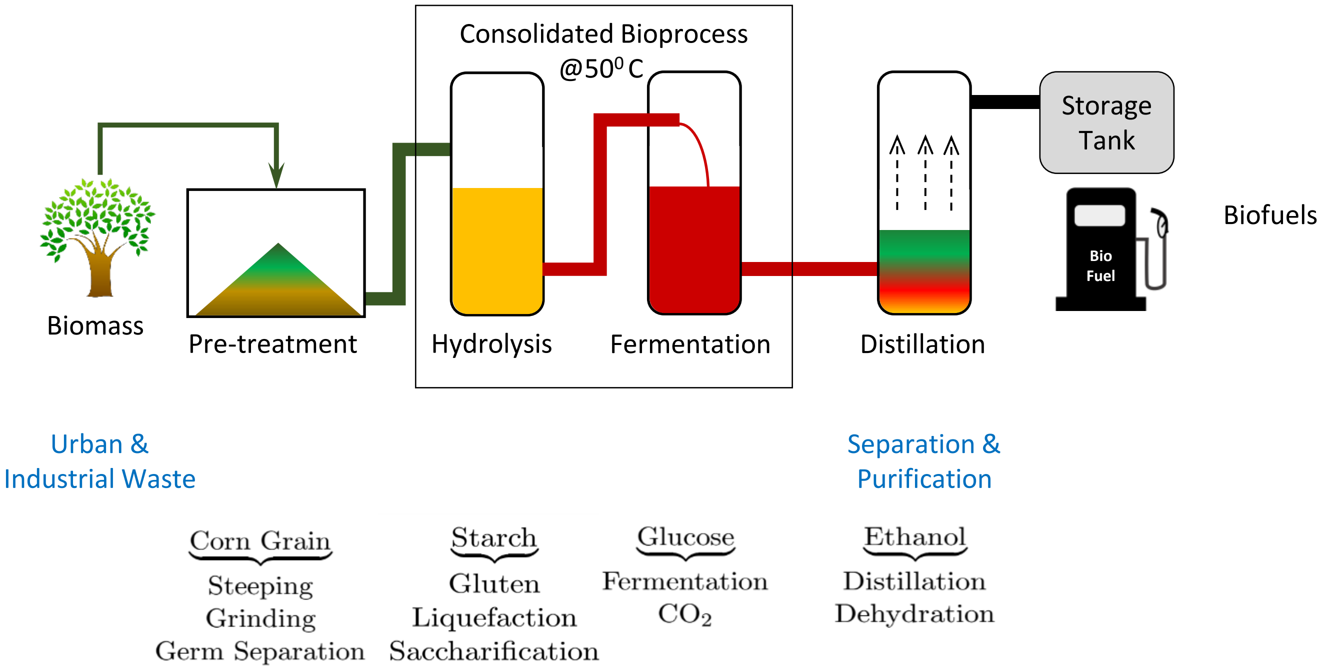


Figure 21.12. Biofuel generation
(Source: https://paulvandecruys.files.wordpress.com/2014/03/blog-8.jpg)
(Image: Simon Michaux, using some copyright free clipart)

In the United States in 2015, an average of 2.8 gallons of ethanol was produced per bushel of corn (IEA 2020b). The average corn yield in the Unites States was 167.5 bushels per acre in 2015, with a yield of 462 gallons per acre of bio ethanol produced (EIA Monthly Biodiesel Production Report, https://www.eia.gov/biofuels/biodiesel/production/).

Given that:

- 1 bushel of corn = 0.022 metric tons of corn
- 1 US gallon = 3.79 liters
- 1 acre = 0.0041 km^2
- 1 btu = 0.000293 kilowatt hours

Converting the imperial units into standard S.I. units, resulting in:

- 1 km^2 of corn growing land produces about 41 372 bushels (1 acre produces 167.5 bushels)
- 1 km^2 of corn growing land can produce about 901 127 kg (or 901.13 tonne) of corn
- 1 km^2 of corn growing land produces 432 142 liters of bio-ethanol
- 2.08 kg of corn oil produces about 1 liters of ethanol

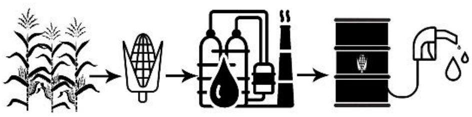
The average yield of anhydrous ethanol from corn is estimated to be 0.480 Liters of ethanol (EtOH) per kg of corn grain, or 2.085 kg of corn was consumed per liter of bioethanol produced. As part of the waste plume from producing ethanol from corn, for every liter of ethanol produced, 12 liters of noxious liquid sewage effluent are released which need to be treated (Schulz 2007, orginal units in gallons).

An acre of sugar cane can produce approximate 35 ton yield or about 560 gallons of ethanol (Hofstrand, 2009).

A large proportion of he the global corn, soy and sugar crop is already consumed to meet biofuel production demand. In the United States, 40% of the corn crop is used to make ethanol biofuel (EIA Monthly Biodiesel Production Report, https://www.eia.gov/biofuels/biodiesel/production/).

The water consumption footprint for food crop production is already quite high. In the United States, 70 % of groundwater withdrawals is used to grow irrigated crops (Friedemann 2021), where the remaining 30 % is used by livestock, aquaculture, industry, mining, and thermoelectric power plants (USGS 2018).

The water consumption footprint to grow corn is 2570 liters (680 gallons) of rainfall or irrigation water to produce enough corn to make just one liter of ethanol (Gerbens-Leenes *et al* 2009). In some irrigated corn acreage in the United States Western regions, groundwater is being mined at a rate 25% faster than the natural recharge of its aquifer (Pimentel 2003, NRC 2011, Friedemann 2021).



Corn and soy are 50 or more times more prone to soil erosion than sod crops like wheat, barley, rye, and oats. After harvest, the corn fields are often left bare, where the unprotected soil is highly susceptible to erosion from wind and heavy rain. Large volumes of sediment, pesticides, and fertilizer are washed away into water ways. For each liter of ethanol produced, an estimated 2.40 to 4.79 kg of soil is lost to erosion (NRC 2014, J. Schnoor, Friedemann 2021)

Global production of corn and soy, erode more topsoil, cause more pollution, global warming, acidification, eutrophication of water, water treatment costs, fish kills, and biodiversity loss than most other crops (Powers

2005, Troeh & Thompson 2005, Zattara & Aizen 2019). The cultivation of corn consumes more nitrogen based fertilizer than most other crops (Padgitt et al. 2000; Pimentel, NRC 2003), and significant quantities of phosphorus based fertilizers. Corn requires a lot of fertilizer because corn plants are natural adept at absorbing nitrogen and storing it in the corn grain. But unfortunately, much of the nitrogen fertilizer applied does not go into the grain but instead washes away into lakes, rivers, and the ocean (NRC 2014).

The Energy Returned on Energy Invested (ERoEI) ratio for corn based ethanol is 0.8 to 1.6:1 (Pimental *et al* 2005, Farrell *et al* 2006). From a calorie count audit perspective, several studies have shown that it takes about one calorie of fossil fuel to make a calorie of ethanol (Pimentel 2003, Murphy *et al* 2011).

21.5.1 Bioethanol fuel use in Aircraft

It is possible to produce jet fuel from biomass, in a fashion where jet aircraft can perform to specification. Conventional jet fuel is produced by refining petroleum crude. Its composition depends on the raw crude oil, but is typically around 20% paraffins, 40% isoparaffins, 20% naphthenes and 20% aromatics (Blakey, Rye & Wilson, 2011). Each of these components plays a critical role in providing specific fuel characteristics.

For example, the high hydrogen-to-carbon ratio of paraffins and isoparaffins enhances the heat density per unit mass of fuel; naphthenes help to reduce the freeze point, which is critical at high altitudes; and aromatics contribute to material compatibility and prevent leaks in the seals of some aircraft (Liu, Yan & Chen 2013, Blakey, Rye & Wilson 2011, Bauen *et al* 2009). For biofuel to be viable as jet fuel, all of these material specifications would be required to be met (Mawhood *et al* 2014).

The biomass to liquids (BTL) process involves the gasification of biomass feedstocks (after pre-treatment), followed by Fischer-Tropsch synthesis of the resulting syngas (also termed as gasification/Fischer-Tropsch synthesis or GFT). The ASTM-certified fuel produced by this pathway is called Fischer-Tropsch synthetic paraffinic kerosene (FT-SPK).

The pretreated feedstock is gasified at high temperatures and pressures with a controlled volume of oxygen to generate synthesis gas (syngas), a mixture mostly composed of carbon monoxide and hydrogen. The syngas is then conditioned to remove CO_2 and impurities such as tar, H_2S, COS, HCN, NH_3 and HCl. This can involve a combination of physical and chemical process such as thermal or catalytic cracking, scrubbing, filters, and cyclones (Liu, Yan & Chen 2013, Güell *et al* 2012).

The clean syngas is subjected to Fischer-Tropsch synthesis, during which it reacts with hydrogen in the presence of a metallic catalyst (commonly iron, cobalt, or nickel). The reactions are usually conducted at temperatures of 150°C to 300°C and pressures of 10 to 40 bars (Maniatis, Weitz & Zschocke, 2013, Bauen et al., 2009). The resulting product is a mix of saturated hydrocarbons, ranging from gases to waxes. The mixture is upgraded to liquid fuels using methods common in conventional petroleum refineries, for example hydrocracking and distillation, or oligomerisation (Blakey, Rye & Wilson 2011).

Alcohol to jet (ATJ) refers to the conversion pathway that produces jet fuel from biomass via an alcohol intermediate (ethanol). A wide range of processes can be used to synthesise alcohols, depending on the characteristics of the feedstock. Sugars can be directly converted to alcohols though fermentation with yeasts or microbe, whilst starches are converted via acidic or enzymatic hydrolyzation (to release sugars), followed by fermentation. Conversion of lignocellulosic feedstocks is more complex, involving either aggressive hydrolyzation followed by fermentation, or thermochemical conversion (gasification to produce a syngas) followed by fermentation or catalytic hydrogenation to synthesize alcohols (Teelucksingh 2013, Güell *et al* 2012, Rosillo-Calle *et al* 2012).

The alcohols produced undergo a four-step upgrading process to create hydrocarbons in the jet fuel range (Teelucksingh 2013, Güell *et al* 2012):

1. Alcohols are catalytically dehydrated to generate olefins,
2. Olefins are oligomerised, typically in the presence of catalysts, to produce a middle distillate containing diesel and kerosene fractions.
3. The middle distillates are hydrogenated
4. Distillation

A wide range of biomass feedstocks are suitable for ATJ, including forestry and agricultural residues, corn starches and sugars, as well as municipal solid waste (Güell et al., 2012). Ideal biomass feedstocks are highly porous, contain low levels of highly soluble lignin and have low ash and acetyl content (as this can inhibit fermentation).

Jet fuel has a calorific density of 43.0 MJ/kg. This high value allows heavy aircraft like the A350-900 Airbus to fly 15 000 km by carrying only 141 000 liters of fuel. If this power system was phased out, then its replacement would have to do something similar (ideally). An electric powered system that could make such a large aircraft fly any practically useful distance would require a very heavy battery bank. A hydrogen fuel cell would require the storage of hydrogen fuel under pressure. The size and geometry (a reinforced cylinder) of this tank and the amount of hydrogen that could be stored would also mean the aircraft would have a short range or could not carry very much cargo.

A viable technology solution to phase out jet fuel was not able to be found in a useful from for this report. That is, clearly presented data in the widespread application at an industrial scale, at a cheap enough cost for society to access and use the outcome. The closest possible technology that could do this is the use of biofuels as an aviation tool (to be discussed in Section 22, Scenario D). More work needs to be done before this solution can be directly implemented though.

Since 2008, more than 150,000 flights have used biofuels. Only five airports have regular biofuel distribution in 2019 (Bergen, Brisbane, Los Angeles, Oslo, and Stockholm), with others offering occasional supply (Le Feuvre 2019). Trials of using algae as biofuel were carried out by Lufthansa, and Virgin Atlantic as early as 2008, although there is little evidence that using algae is a reasonable source for jet biofuels (Reddy & O'Neil 2015). By 2015, cultivation of fatty acid methyl esters and alkenones from the algae, isochrysis, was under research as a possible jet biofuel feedstock.

As of 2017, there was little progress in producing jet fuel from algae, with a forecast that only 3 to 5% of fuel needs could be provided from algae by 2050. Further, algae companies that formed in the early 21st century as a base for an algae biofuel industry have either closed or changed their business development toward other commodities, such as cosmetics, animal feed, or specialty oil products.

Current biojet volumes are on practice based on HVO product derived from fats. This is considered as the easiest and most potentially viable route to industrial scale biojet production in the short run. By 2030, it may be possible for biojet volumes to be produced by a gasification- Fischer-Tropsch pathway (J. Lehtonen personal communication).

This biofuel technology solution could make jet aviation viable after fossil fuels are phased out. However, in its current state of readiness, it is not viable to consider this as a full replacement of petroleum based aviation jet fuel as a fuel. Global consumption of jet fuel in 2018 by volume was 2 260 million barrels. To produce this volume of fuel that is viable for aviation from biofuels at the required rate is not practical at this time.

The ERoEI ratio for biofuels is between 0.8:1 to 1.6:1, with rare examples of 10:1 (as discussed in Section 4.5). This implies that this process will be difficult to apply on a large scale. Also, biofuels are in direct competition with the production of food, at a time when food shortages are observed around the world (as discussed in Section 11).

Batteries are too heavy in mass to be practical in developing a commercial sized Electric Vehicle jet aircraft. Biofuel could be a technology that is possible in a small scale conceptual fashion, where biofuel is blended with petroleum derived jet fuel. Aviation biofuel is a biofuel used for aircraft. Sustainable Alternative Jet Fuel (SAJF): a general term used to describe the class of non-petroleum-based jet fuels (or blended components) that are being pursued by the aviation industry. It is considered by some to be the primary Figure 21.13 shows a summary of the biofuel to jet fuel applications conversion pathways.

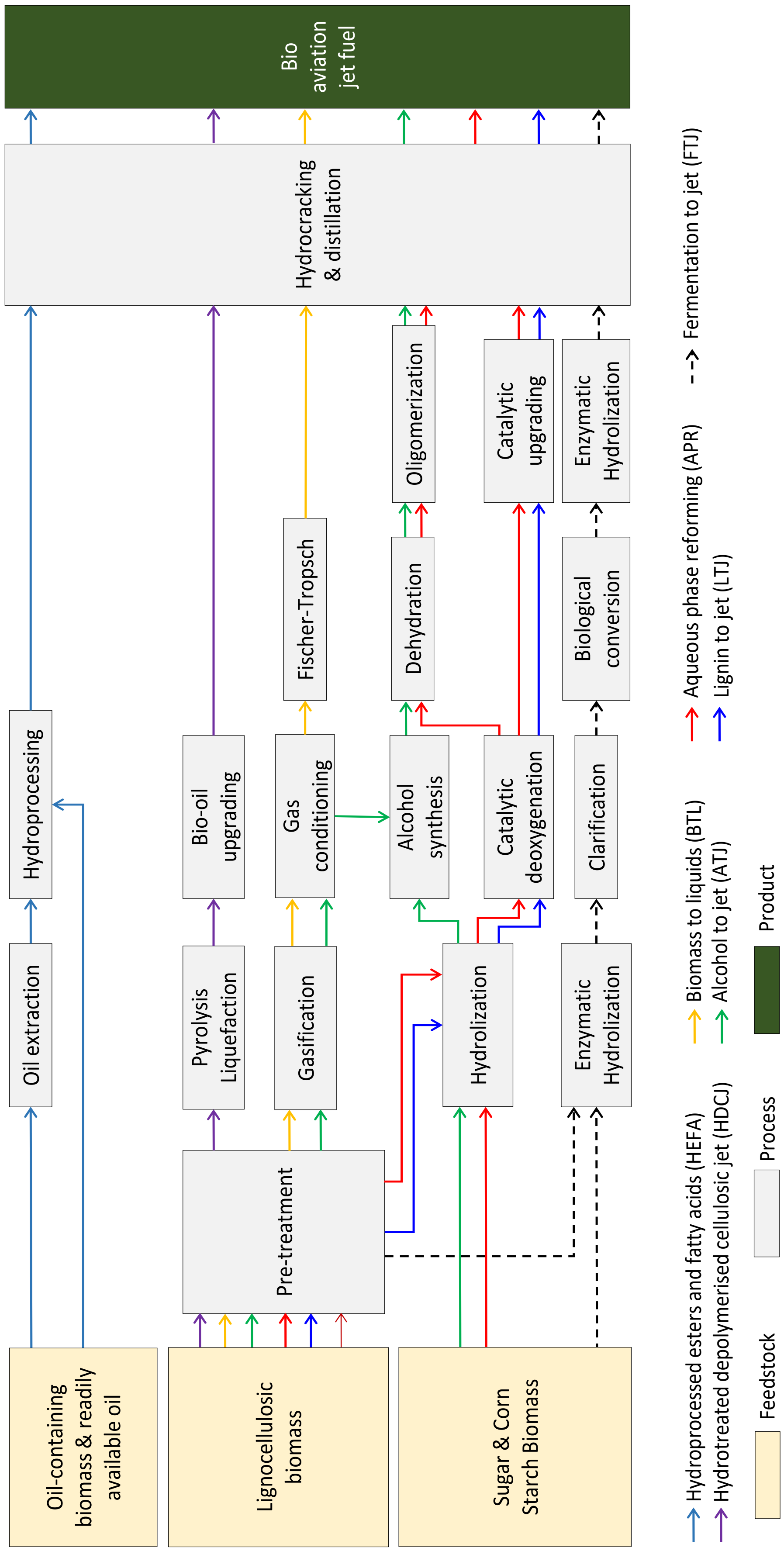


Figure 21.13. Biojet conversion pathways: feedstocks and processes
(Source: Redrawn from Mawhood *et al* 2014)

means by which the aviation industry can replace conventional petroleum derived jet fuel (General Aviation Manufacturers Association *et al* 2018). The first flight using blended biofuel took place in 2008 (Downing 2011).

Since then, aircraft makers, engine manufacturers and oil companies have developed this technology in sophistication and reliability. Biofuels were approved for commercial use to be blended with jet fuel in July 2011 (General Aviation Manufacturers Association *et al* 2018). Since then, some airlines have experimented with using biofuels on commercial flights. The focus of the industry has now turned to second generation sustainable biofuels (sustainable aviation fuels) that do not compete with food supplies nor are major consumers of prime agricultural land or fresh water. NASA has determined that 50% aviation biofuel mixture can cut air pollution caused by air traffic by 50–70% (Elliot 2017). The relevant industry standards for fuel classification are ASTM D1655 and ASTM D7566 (General Aviation Manufacturers Association *et al* 2018)

ASTM D1655 (Standard Specification for Aviation Turbine Fuel)

Defines specific types of aviation turbine fuel for civil use in the operation and certification of aircraft, and describes fuel found satisfactory by the Original Equipment Manufacturers (OEMs) and regulatory authorities for the operation of aircraft and engines. The specification can be used as a standard in describing the quality of aviation turbine fuel from the refinery to the aircraft and covers the use of purchasing agencies in formulating specifications for purchases of aviation turbine fuel under contract. The specification covers two types (or grades) of commonly used jet fuel that differ in freeze point:

- Jet A: commercial jet fuel grade commonly used in North America (-40ºC freeze point).
- Jet A-1: jet fuel grade commonly used outside of North America (-47ºC freeze point).

ASTM D7566 (Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons)

Defines aviation turbine fuel (jet fuel) produced with synthesized components derived from non-petroleum, non-shale, and non-oil sand origin. This can include jet fuel produced from coal, natural gas, landfill recovery gas, biomass (lignocellulose, sugars, fats, oils, and greases), waste streams, syngas, etc.

21.6 Biofuel from algae

Algae fuel, algal biofuel, or algal oil is an alternative to liquid fossil fuels that uses algae as its source of energy-rich oils, which can be used to make biodiesel and bio jet fuel. Algae is a broad classification term for a large and diverse group of photosynthetic eukaryotic organisms, which are grown in various grades of saline water, in open system ponds, or in closed system tanks. Algae contain three essential ingredients: carbohydrates, proteins, natural oils, where algae may contain in their total mass, about 55% of oil (Bošnjaković 2013). These are the key ingredients to obtain biodiesel, bioethanol, hydrogen, and methane (National Algal Biofuels Technology Roadmap, National Algal Biofuels Workshop, College Park, 2008). Heterotrophic and mixotrophic cultivation of microalgae is an alternative to photoautotrophic cultivation with the potential of improving the economic feasibility of algal lipid-based products (Avagyan & Singh 2019).

Algae species can grow much faster than food crops (in the right conditions) and has the potential to produce hundreds of times more oil per unit area than conventional crops such as rapeseed, palms, soybeans, or jatropha (Atabani 2012). Algae cultivation farms can have several harvests in a very short time-frame, as some species have a harvesting cycle of 1–10 days (Chisti 2007). This means that a algae farm has a different production cycle compared to conventional sources like corn or soy, which have annual planting seasons.

Several advantageous characteristics of biofuel sourced from algae, are that they have a high flash point (Microalgae as a Feedstock for Biofuel Production, www.ext.vt.edu), and are biodegradable and relatively harmless to the environment if spilled (Quinn 2011).

In the United States, 15 000 metric tons a year of algae are produced (U.S. DOE 2016). Compared to current biofuels, algae are tremendously expensive to produce, ranging from $719 to $3000 per dry ton, versus switchgrass, corn stover, and other land biomass costing $30–$60 per dry ton (U.S. Department of Energy 2016).

Microalgae biomass production accounts for 65 to 85% of the overall cost of biofuel manufacturing. The phototrophic microalgae pathway is not effective in terms of cost and environmental impacts. This algae feedstock source can be used only for high-value purposes other than biofuel production unless significant technological interventions are put in place (Avagyan & Singh 2019). A number of innovations such as nitrogen, phosphate or potassium starvation/depletion, genetic modification, polyculture cultivation, and a biorefinery for cost reduction have been assessed in various forms, but many uncertainties remain.

Compared to open pond photobioreactor closed systems have 13 times better yield and collecting is a cheaper. This happens because the concentration of biomass is 30 times higher (Microalgae as a Feedstock for Biofuel Production, www.ext.vt.edu). Advantages over open systems are in achieving higher densities of algae, higher productivity can reduce pollution and capture direct and diffuse light and are not subject to contamination by air. However, closed systems have higher capital and operating costs. Quantity of CO_2 should be carefully managed; otherwise it leads to starvation of algae and increasing of pH. Photobioreactor has several limiting factors (Bošnjaković 2013):

- Cooling
- Mixing
- Controlling of the accumulation of oxygen.

The production of bioethanol is so performed that the separated biomass is decomposed, and then undergo the process of fermentation with the addition of yeast, after which bioethanol is extracted. Hydrogen and methane are produced in bioreactors (Bošnjaković 2013). The remains of algae cells after the production of biofuels can be used as animal feed, and as they contain a balanced amount of nitrogen and phosphorus, are used as organic fertilizer.

The basis of natural oil derived from microalgae is in TAG (Tri-Acyl-glycols) form, which is a real form of oil for biodiesel production. In the production of biodiesel, oil is converted into methyl esters of fatty acids and this process is called transesterification or alcoholysis.

From the literature:

- Algae technology is unique in its ability to produce a useful product from waste CO_2 (Bošnjaković 2013). Production of microalgae biomass can fix carbon dioxide (1 kg of algal biomass fixes roughly 1.83 kg of CO_2) (Chisti 2007).

- Microalgae have an energy content of 18 to 28.8 MJ/kg (5 to 8 kWh/kg) of dry weight depending on the species and lipid content (Lardon *et al* 2009).

- An open pond system is achieved growth 12-40 g/m^2/day, depending on whether the size of the pool using 720 hectares or 220 hectares (Bošnjaković 2013).

- Algae generate methane production from 200 000 to 400 000 m^3/km^2 per year (Bošnjaković 2013).

- 1kg of dry biomass can be produced from 2 kg of algae (Bošnjaković 2013).

- 1 kg of oil is produced from 2.5 kg of dry biomass (Bošnjaković 2013).

- The intensity of light that is necessary for the growth of microalgae is about 200 µE/m^{-2}/s^{-1} (Bošnjaković 2013).

- To produce 45 kg of biodiesel, 45 kg of oil to reacts with 4.5 kg of a short chain alcohol (methanol or ethanol), in the presence of catalyst (acidic, alkaline, or enzymatic catalysis) (Bošnjaković 2013). 1 kg of glycerine remains as a by-product of the process of creating biodiesel.

- During the production of 220 billion liters of algal biofuels, the evaporative loss from ponds would be 312 trillion liters per year (Wigmosta *et al* 2011, Friedemann 2021).

Given:

- The density of biodiesel is equal to 874.7 kg/m³ at 15.5 °C at standard atmospheric pressure.
- 1 ha = 0.01 square kilometers
- 1 square kilometer = 1,000,000 square meters
- 1 cubic meter = 1000 liters
- 1 liter = 1.0 × 10^{-12} cubic kilometers

Then:

- Open pond system is achieved algae growth of 40 tonne/km^2/day, or 14 600 tonne/km^2/year, assuming the use of 7.2 km^2 ponds

- For each liter of biodiesel produced in an open pond, 1418.2 liters of water would evaporate into the atmosphere, requiring replacement into the pond from another source.

- To produce 1 liter of biodiesel, 0.87 kg of oil is needed, which reacts with 110.5 ml of a short chain alcohol (methanol or ethanol), in the presence of catalyst (acidic, alkaline, or enzymatic catalysis. 22.2 g of glycerine remains as a by-product of the process of creating biodiesel.

- To produce 0.87 kg of oil, 2.19 kg of biomass is required.
- To produce 2.19 kg of biomass, 4.37 kg of algae is required.

However, algae as a fuel feedstock cost more per unit mass than other second-generation biofuel crops due to high capital and operating costs (D'Elia *et al* 2010) but are claimed to yield between 10 and 100 times more fuel per unit area (Salim *et al* 2010).

Managing algae species populations can require constant monitoring and optimization. The high fat species (for algal biofuels, the goal is to use obese algae with at least 60% fat) require specific conditions with very little variation if they are to survive. They can easily be killed off or have their growth stunted by too much heat, cold, evaporation, pH level, saline level, UV, lack of nutrients, or too much of a nutrient (U.S. Department of Energy 2010).

Algae production farms that use open ponds have a serious challenge to navigate. Ponds can be contaminated with wild species of invading algae predators via wind, rain, snow, insects, waterfowl, and animals. Among the predators are zooplanktons, where each one can eat 200 algae a minute and crash a pond in as little as 2 days (SNL 2017). In practice, about a third of the time all of a pond's algae die within 3 months (Park *et al* 2011). This is often termed 'Pond Crash'.

Large-scale algal biofuel production is likely to require large volumes of water, comparable to large-scale agriculture (U.S. Department of Energy 2010). Wigmosta *et al* (2011) estimated during the production of 220 billion liters of algal biofuels, the evaporative loss from ponds would be 312 trillion liters per year.

An advantage of algae over land plants is that the water can be saline, brackish, wastewater, and low quality. The problem is that the water being evaporated is fresh and continuing to use low-quality water to refresh the pond can introduce and concentrate killer microbes, heavy metals, chemicals, salts, toxins, and other harmful materials (U.S. Department of Energy 2010), causing pond crash events.

Microalgae have an energy content of 18 000 to 28 800 kJ/kg (5 to 8 kWh/kg) of dry weight depending on the species and lipid content (Lardon *et al* 2009). Photobioreactors are currently very energy-intensive. Major energy consumption (60–70%) occurring in harvesting, drying, and extraction steps is unavoidable to prepare lipids suitable for the transesterification reaction. Table 21.2 shows a summary of the energy consumption requirements for each basic step of the production of biofuel from algae, with a calculation of the Energy Returned on Energy Invested (see Figure 6.1 in Section 6). The largest energy intensive step is the drying of the algae. To address this directly Table 21.2 examines dry algae feedstock and wet algae feedstock, from the same algae pond. As can be seen, operating costs of processing wet algae is higher than dry algae. There are a number of logistical and practical issues in handling large volumes of wet algae.

Table 21.2. Energy requirements for different steps in algal biodiesel production
(Source: Martinez-Guerra & Gnaneswar Gude 2016, Liu et al 2013)

Biodiesel production step (basis: 1 kg of algal biodiesel)	Dry algal biomass (MJ)	Wet algal biomass (MJ)
Microalgae culture and harvesting	7.5	10.6
Drying	90.3	0
Extraction	8.6	30.8
Oil transesterification	0.9	0.9
Total	107.3	42.3

	ERoEI Ratio	ERoEI Ratio
Microalgae energy content 18 MJ/kg	0.17	0.43
Microalgae energy content 28.8 MJ/kg	0.27	0.68

As can be seen in Table 21.2, producing biofuel from algae requires more energy per unit mass than the energy content in the algae. The calculated ERoEI ratios range between 0.17 and 0.68. As these ratios less than one, the ERoEI is considered negative. While this is the case, biodiesel from algae feedstock is not viable.

21.7 Biofuel from seaweed

Biofuel can also be produced from seaweed and seagrass, often termed macroalgae. Macroalgae can be converted into bio-oil, and its lipids can then be separated for biodiesel production. This is not commonly done as some species of microalgae (60 to 65%) have a much higher content of lipids compared to macroalgae seaweed (0.2 to 4%) (Avagyan & Singh 2019).

Macroalgae cultivation can be done in a variety of coastal environments, classed as off-shore, near-shore, or on-shore sites. Harvesting of wild seaweed and seagrass has the potential for degradation of the local environmental, if done on an industrial scale (Avagyan & Singh 2019). Growing seaweed artificially takes so much fossil energy to produce that several studies have found the EROI to be negative (Milledge & Harvey 2016, Friedemann 2021)

The harvesting of macroalgae has a high cost, with an estimated at $USD 1/kg (Avagyan & Singh 2019). It will be difficult to harvest sufficient seaweed to provide significant quantities of biofuel of the scale of demand to service the transport sector (Avagyan & Singh 2019).

21.8 Food versus fuel land use dilemma in the production of biofuels

The production of bioenergy and biofuels is in competition with the production of food in a global context (FAO 2015a, United Nations 2019). The food versus fuel is the dilemma regarding the risk of diverting farmland or crops for biofuels production to the detriment of the food supply. The biofuel and food price debate involves wide-ranging views, and is a long-standing, controversial one in the literature. There is disagreement about the significance of the issue in the literature, in what is causing it, and what can or should be done to remedy the situation. This complexity and uncertainty are due to the large number of impacts and feedback loops that can positively or negatively affect the price system. Moreover, the relative strengths of these positive and negative impacts vary in the short and long terms and involve delayed effects. The academic side of the debate seems to be blurred by the use of different economic models and competing forms of statistical analysis.

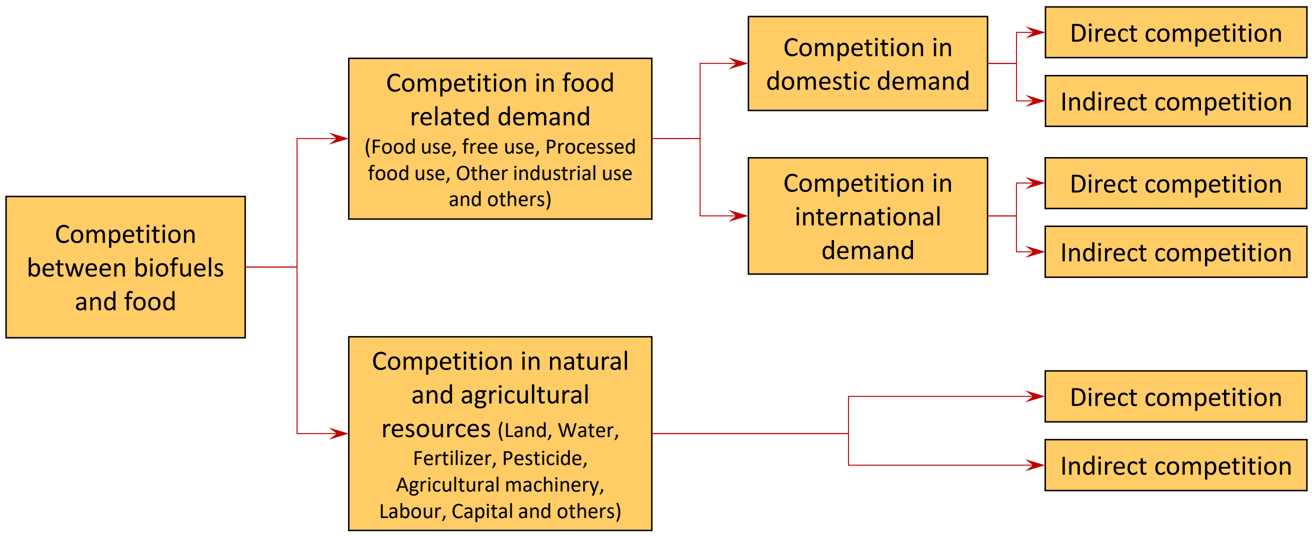


Figure 21.14. Competition between biofuels and food for arable land use
(Image: Simon Michaux)

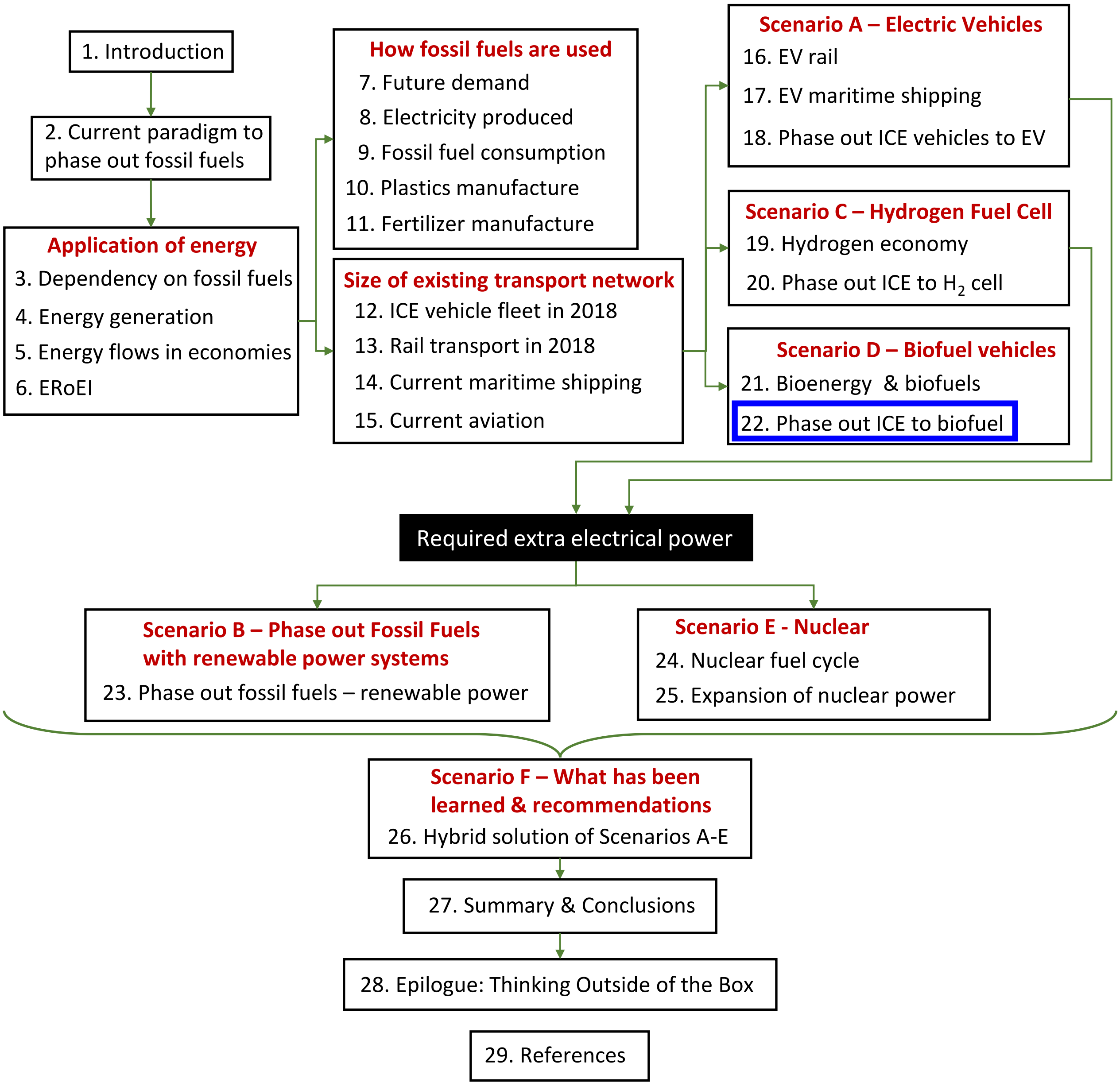
Biofuel production has increased in recent years. Some commodities like maize (corn), sugar cane or vegetable oil can be used either as food, feed, or to make biofuels. For example, since 2006, a portion of land that was also formerly used to grow other crops in the United States is now used to grow corn for biofuels, and a larger share of corn is destined to ethanol production, reaching 25% in 2007 (USDA 2019). Second generation biofuels could potentially combine farming for food and fuel and moreover, electricity could be generated simultaneously, which could be beneficial for developing countries and rural areas in developed countries.

With global demand for biofuels on the increase, there is also fear of the potential destruction of natural habitats by being converted into farmland. Environmental groups have raised concerns about this trade-off for several years, but now the debate became high profile due to the 2007–2008 world food price crisis (Lagi *et al* 2011). Alternatively, several studies do show that biofuel production can be significantly increased without increased acreage (Shen *et al* 2009). Whichever of these studies is more correct, this is an issue that needs to be examined and understood.

Scenario D in Section 22 will examine the size and scope of the biofuels production sector if all petroleum fueled ICE vehicles are fueled with biofuel instead.

22 SCENARIO D – PHASE OUT FOSSIL FUELS AND SUBSTITUTE WITH BIO-FUELS & BIO-WASTE

Scenario D is to examine the global footprint of the biofuels production sector, if all petroleum products (gasoline petrol, diesel, marine bunker oil fuel, and jet fuel) were phased out and substituted with biofuels. Using the outcomes of Section 21, calculations were made if biofuel was sourced from soy, corn on land, and algae in water. The resulting footprint was compared against global capacity to expand into this additional requirement.



Assessment of the Extra Capacity Required of Alternative Energy Electrical Power Systems to Completely Replace Fossil Fuels

Most of biofuel currently produced is sourced from oil seed crops soy and corn. Soy feedstock has shown to be the most effective to produce biodiesel, and corn has been shown to be most effective in producing ethanol. Ethanol has been used to blend into gasoline, and it has the capacity to fuel Internal Combustion Engine (ICE) technology directly if required. Cellulosic ethanol is not commercial (Friedemann 2021). Biofuel is considered a drop in fuel, that can be used with existing infrastructure and existing ICE vehicles. Algae from aquaculture has also been a proposed feedstock for biofuels, with work done to produce bio diesel and jet fuel.

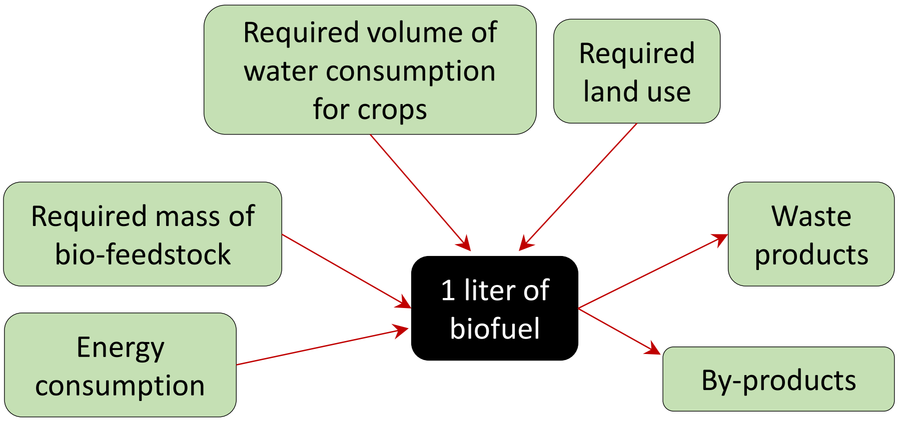


Figure 22.1. Calculation inputs and outputs for biofuels in Scenario D (Image: Simon Michaux)

Using a form like Figure 22.1, calculations will be made to estimate the scale of production of corn and soy as feedstock to produce biodiesel and ethanol to meet 2018 global demand for gasoline, diesel, marine bunker fuel and jet fuel. The mass of feedstock will be used to estimate the area of needed arable land, water consumption in production. These numbers will be compared to a relevant global parameter like global scale of crop lands.

22.1 Petroleum products consumed for transport

Table 22.1 shows the fossil fuel petroleum product consumption. It is these fuel volumes that global annual biofuel production will be required to replace.

Table 22.1. Petroleum product consumption in the year 2018
(Source: from Table 9.2 in Section 9, OECD Data Statistics Database)

Fossil Fuel	Fuel consumed globally in 2018	
	(bbls)	(Liters)
Petrol	9,307,500,000	1.48E+12
Diesel	10,439,000,000	1.66E+12
Marine fuel *	194 499 000 (tonne)	2.63E+11
Jet fuel	2,260,000,000	3.59E+11
	Annual total	3.76E+12

* Units of tonnes were converted to liters where:
1 tonne = 8.5 barrels
1 Barrel volume unit is equal to 158.98 Liters
Thus, scalar to convert tonne to liters = 1351.39

22.2 Production of biodiesel biofuel from soy

In Scenario D, soy is used as a feedstock to produce biodiesel as a substitute biofuel for diesel fuel and marine bunker fuel oil. Numbers assembled in Section 21.3 are adjusted to estimate the mass flows required to produce 1 liter of ethanol. Where:

- 4.91 kg of soybean seed produces 1 liter of biodiesel
- To produce 1 liter of biodiesel, 14 000 liters of water will be used to irrigate the soy crop

Figure 22.2 shows these numbers in a material flow sheet to produce 1 liter of biodiesel from a soybean feedstock. This flowsheet is a composite from several sources of data (often in units of gallons and pounds, converted to liters and kg) that are discussed in Section 21.3.

This flowsheet was applied to the 2018 global annual demand for diesel (1.66 x 10^{12} liters) and marine bunker fuel oil (2.63 x 10^{11} liters) combined to a production target of 1.92 x 10^{12} liters of bio ethanol produced from soy feedstock. This was then adjusted to estimate the area of arable land required to grow soybeans, assuming for every 1 km^2 of soy growing land produces 53 317 liters/km^2 of bio-ethanol. This resulted in a needed 36.0 million km^2 needed in the global system to produce soy for biofuels. This data is shown in Table 22.2 and shown graphically in Figure 22.4.

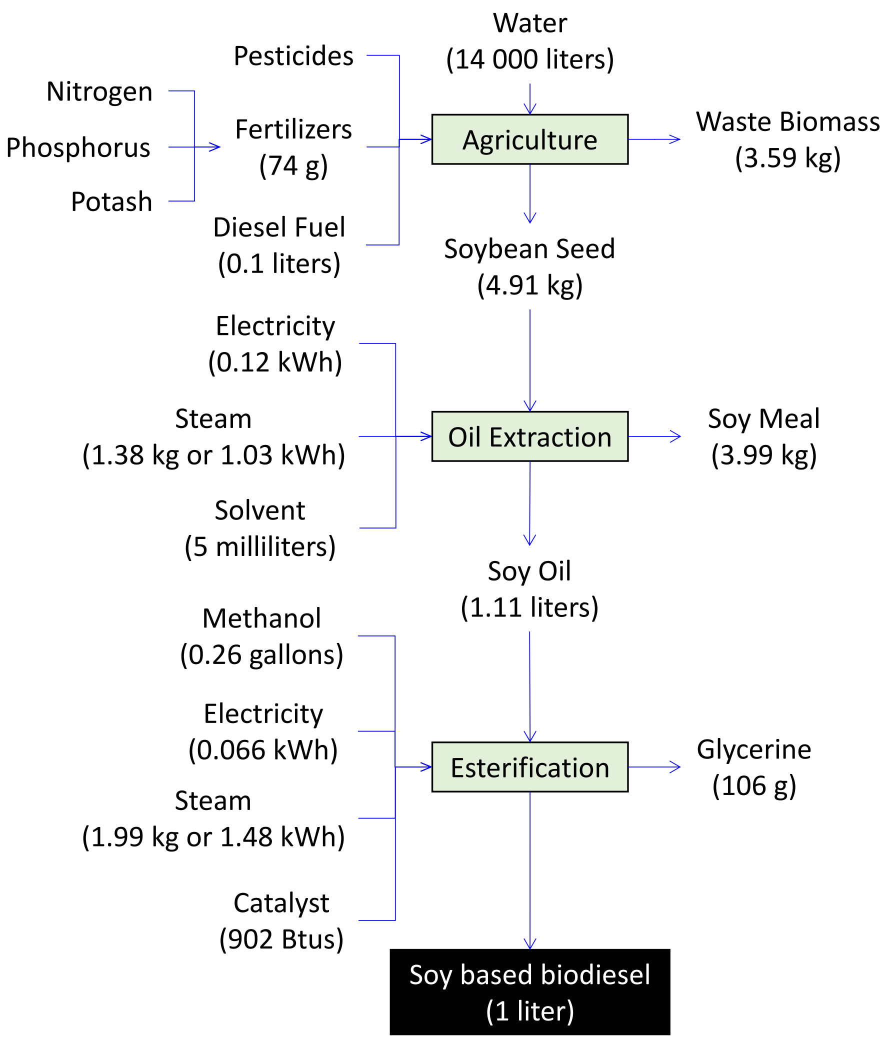


Figure 21.2. Inputs and material flows to produce 1 liter of soy based biodiesel
(Source: based on data from Sadaka 2013, Gerbens-Leenes *et al* 2009) (Image: Simon Michaux)

22.3 Production of ethanol biofuel from corn

In Scenario D, corn is used as a feedstock to produce ethanol as a substitute biofuel for gasoline petrol. It can also be used as a substitute for jet fuel (with some extra distillation steps). Algae feedstock has been more effective to produce biofuel, which is discussed in Section 21.4. Numbers assembled in Section 21.4 are adjusted to estimate the mass flows required to produce 1 liter of ethanol. Where:

- 2.08 kg of corn grain produces 1 liter of ethanol
- To produce 1 liter of ethanol, 2 575 liters of water will be used to irrigate the corn
- To produce 1 liter of ethanol, 12 liters of noxious sewerage effluent are produced

Figure 22.3 shows these numbers in a material flow sheet to produce 1 liter of ethanol from a corn feedstock. This flowsheet is a composite from several sources of data (often in units of gallons and pounds, converted to liters and kg) that are discussed in Section 21.4.

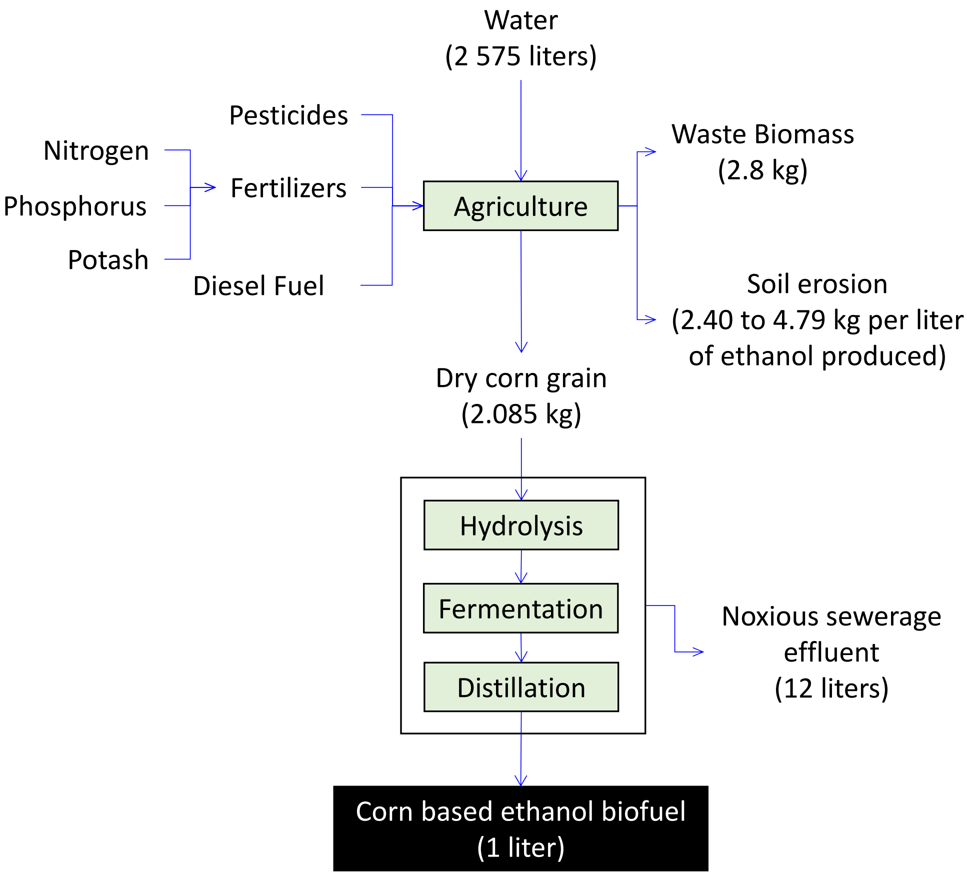


Figure 22.3. Inputs and material flows to produce 1 liter of corn based ethanol
(Source: based on data from IEA 2020b, EIA Monthly Biodiesel Production Report,
https://www.eia.gov/biofuels/biodiesel/production/ Schulz 2007, Gerbens-Leenes *et al* 2009, NRC 2014)
(Image: Simon Michaux)

This flowsheet was applied to the 2018 global annual demand for gasoline (1.48 x 10^{12} liters) and jet fuel (3.59 x 10^{11} liters) combined to a production target of 1.84 x 10^{12} liters of bio ethanol produced from corn feedstock. This was then adjusted to estimate the area of arable land required to grow corn, assuming for every 1 km^2 of corn growing land produces 432 142 liters/km^2 of bio-ethanol. This resulted in a needed 4.26 million km^2 needed in the global system to produce corn for biofuels. This data is shown in Table 22.2 and graphically in Figure 22.4.

22.4 Estimation of required arable land area to grow corn and soy for biofuel

The outcomes of applying the flowsheets in Figures 22.2 and 22.3 to the fossil fuel consumptions. Given 1 km^2 of corn growing land produces 432 142 liters of bio-ethanol and 1 km^2 of soybean land produces about 53 317.6 liters of biodiesel, the area of arable land was estimated and shown in Table 22.2. It was assumed that ethanol sourced from corn feedstock would substitute for pterol gasoline and jet fuel, and that biodiesel sourced from soybean feedstock would substitute for diesel and marine bunker fuel oil.

Table 22.2. Estimated arable land required to grow corn and soy to produce enough biofuels to subsitute 2018 annual petroleum product consumption

Fossil Fuel	Fuel consumed in 2018 (Liters)	Bioethanol to be produced (Liters)	Biodiesel to be produced (Liters)	Arable land needed to produce the same quantity of biofuel	
				Corn (km^2)	Soybeans (km^2)
Petrol	1.48E+12	1.48E+12		3,424,277.7	
Diesel	1.66E+12		1.66E+12		31,129,195.9
Marine fuel	2.63E+11		2.63E+11		4,929,981.7
Jet fuel	3.59E+11	3.59E+11		831,465.8	
Total	3.76E+12 (liters)	1.84E+12 (liters)	1.92E+12 (liters)	4.26 (million km^2)	36.06 (million km^2)

As shown in Table 22.2, the area of arable land to produce enerough biomass to susbitute for pertoeulm product fuels would be 40.31 million km^2 (4.26 million + 36.06 million = 40.31 million). This requried additional area is comaprable to the 2017 forest land proportion of the whole planet (Figure 22.4). To grow corn and soy, arabale land is required, where much of area currently used for liverstock grazing, forestry and shrub land is not suitable (FAO 2015a). This means that it is not a simple matter to expand the current crop land use proportion. Ideally, the additional arable land to grow corn and soy will involve the expansion of the existing crop land proportion (11 million km^2, coloured red in Figure 22.4).

This implies the following:

- The required arable land to grow feedstock for biofuels is 3.66 times the existing land use to grow crops.
- Even if it was possible to do so, the expansion of crop land to accommodate biofuel feedstock, could result in the near complete deforestation of the remaining forest regions on the planet Earth.
- The growing of food would be in direct competition to growing feedstock for biofuels.
- Land degradation is a current problem to address, the addition of growing biofuel feedstock with existing indsutrial agricultural methods, would acclerate land degradtion.

Figure 22.4 does not inlcude the land use to generate the biomass to produce bioplastics, as discussed in Section 10.2.

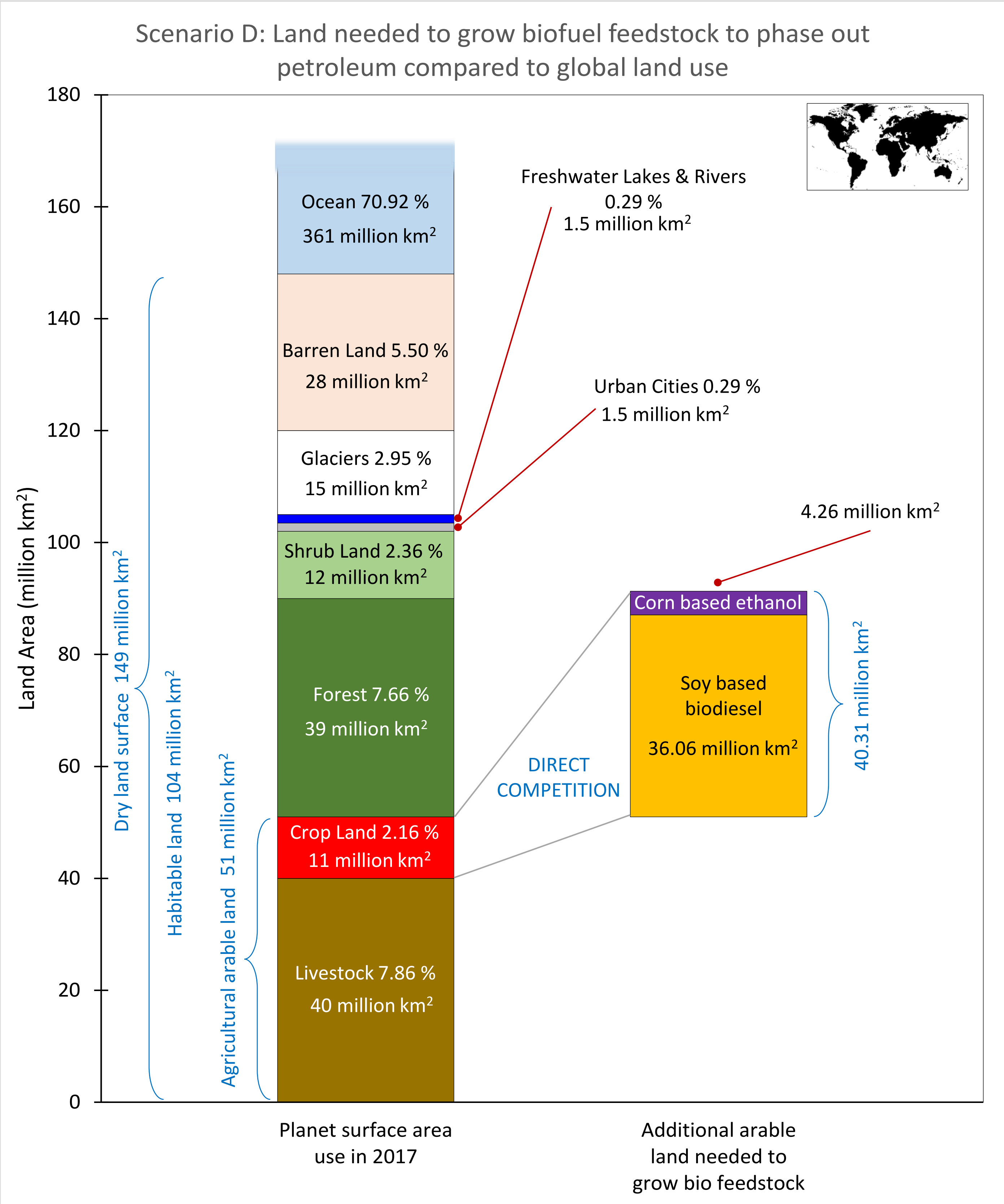


Figure 22.4. Comparison of additional requried arable crop land to grow enough biofuels to substitute global 2018 annual demand of petroleum products (Image: Simon Michaux) (World Map Image by Clker-Free-Vector-Images from Pixabay) (Planet surface area source: United Nations 2019)

22.4.1 Global capacity of arable land

To harvest biomass for bioenergy applications, crops have to be harvested from arable land used for either food production, or directly from arable land tasked for biofuel feedstock production. Arable land is defined as land that can be ploughed and used to grow crops or graze livestock. The term land broadly includes aspects of climate, topography, vegetation, soils, and other natural resources, and is the foundation for agricultural production. Arable land could also be seen as the most fertile and productive parts of the planetary natural environment (FAO 2015a, United Nations 2019).

According to the Food and Agriculture Organization of the United Nations, in the year 2017, the world's arable land amounted to 11.07 million km^2, out of a total of 50.8 million km^2 of land used for agriculture (FAOSTAT Land Use module. Food and Agriculture Organization). About one-third of agricultural land is used as cropland, while the remaining two-thirds consist of meadows and pastures) for grazing livestock. Land allocated to grazing of livestock is used in this fashion because this terrain is unsuitable for food or biofuel crops, which is why it is used mainly for livestock (Ritchie 2017).

Within cropland, about 10 % of the area is used for permanent crops, such as fruit trees, oil palm plantations and cocoa plantations. A further 21 % is equipped for irrigation, which is an important land management practice in agriculture.

Land conversion from natural ecosystem environments to agricultural productions historically has been the largest cause of loss of biomass and carbon in biomass above and below ground. Today, land conversion to agriculture continues to be a major driver of biodiversity loss, habitat destruction, and land degradation (FAO 2015a, United Nations 2019). The business goal of efficient land, land management plans and strategies that used needed to maximize crop productivity, have not allowed the effective minimizing of potential environmental impact due to excessive loss of habitats and overuse of natural resources such as soils and water.

Figure 22.4 in the LHS column shows a data summary from the Global Land Cover Share database (Latham *et al* 2014), which was developed to quantify the proportions of the major land cover classes defined by the Food and Agriculture Organization of the United Nations (Weber 2010). Also, 29 % of the ice free land on the planet is not suitable for biomass farming (FAO 2015a, United Nations 2019, Friedemann 2021). These geographic regions are too frozen, too wet, too dry, too rocky, too salinated, too compacted, too acidic, too steep, the topsoil layer is too thin, or have been polluted with some kind of toxic element, or deficient in one or more of the required 16 crop nutrients.

The land most suitable for agricultural production were the first to be historically settled by human communities and are now heavily urbanized with cities, suburbs, roads, and buildings. The best land for growing food, happens to be where most major cities are sited today. Another quarter of the earth's land is degraded from erosion (see Section 11.5). Historically, the expansion of the human civilization footprint accelerated the change of the natural environment through migration and population increase as food, shelter, and materials were sought and harvested. It is estimated that humans have directly modified at least 70 million km^2, or greater than 50 percent of Earth's ice-free land area (Hooke, Martín-Duque, and Pedraza 2012).

Figure 22.5 shows how the global land used to grow crops has expanded historically. The land used to grow crops in 2016, was more than any other time historically. Figure 22.5 was presented in this section to put the extra arable land required to grow biofuels in context.

It should also be noted that current demand for food production, and industrial agricultural production methods are resulting in an annual arable land loss at a rate of 0.5% each year (Cameron & Osborne 2015) (see Section 11).

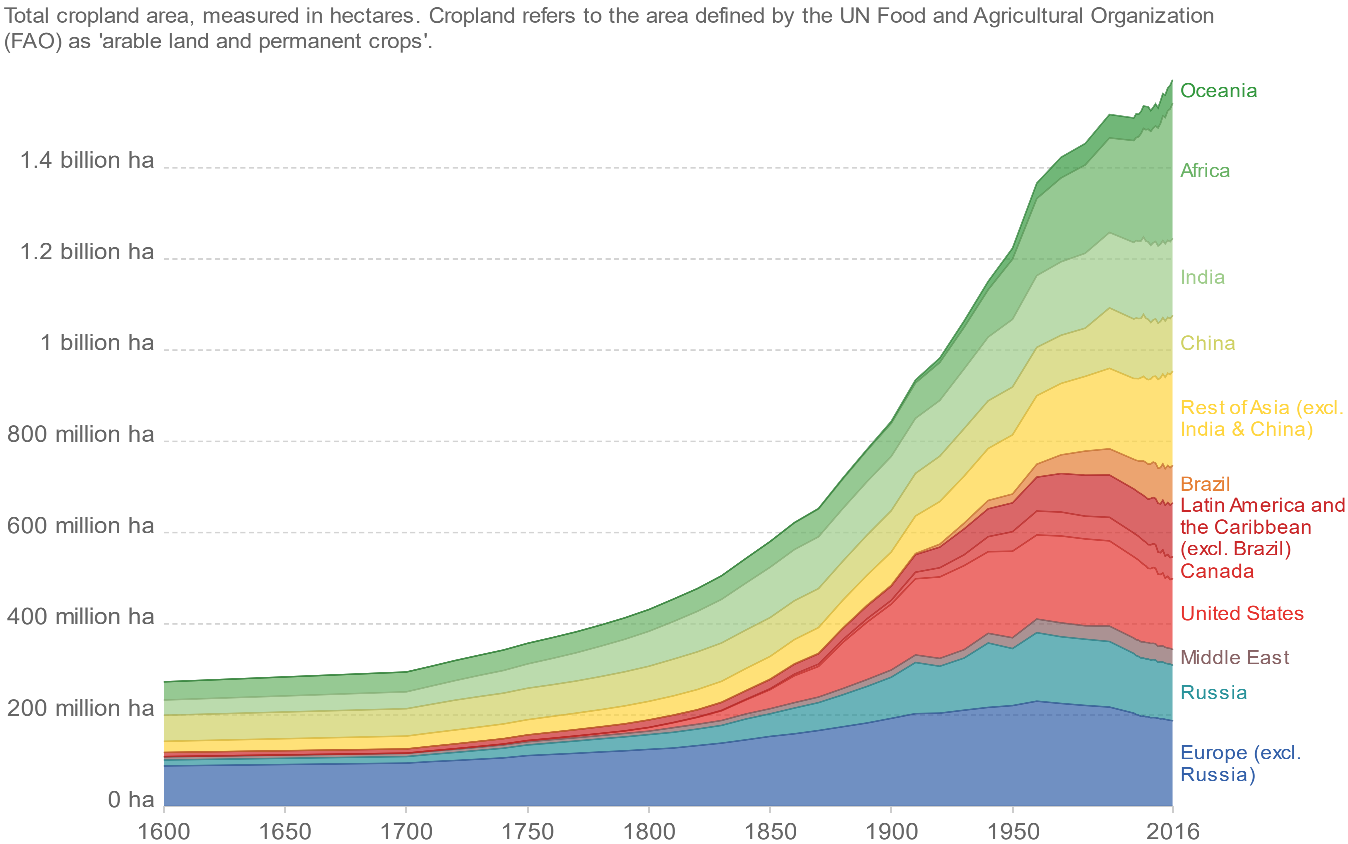


Figure 22.5. Cropland use over the long term 1600 to 2016 (Source: Hannah Ritchie and Max Roser (2013) - "Land Use". Published online at OurWorldInData.org. Retrieved from: 'https://ourworldindata.org/land-use' [Online Resource])

In the United States, 60.5 billion liters of ethanol are produced as an annual rate in 2019 (EIA Monthly Biodiesel Production Report, https://www.eia.gov/biofuels/biodiesel/production/). Given that an estimated 2.40 to 3.79 kg of soil is lost to soil erosion for each liter of ethanol produced from corn (NRC 2014, J. Schnoor, Friedemann 2021), then an estimated 145.1 million tonnes to 229.2 million tonnes of topsoil was lost in the United States from just corn production in 2019. Table 22.3 shows an estimate of the topsoil lost to erosion in 2019 for just the United States, assuming that topsoil had an average depth of 150mm, and soil had a density of 1330 kg/m^3 (FAO 2015a).

Table 22.3. Estimated soil erosion loss in 1 year (2019) in the United States

Soil lost to erosion per litre of ethanol produced (kg)	Soil lost to erosion as a result of producing 60.5 billion liters of ethanol in 2019 (million tonnes)	Area of land assuming 150mm depth of topsoil and a soil density of 1330 kg/m^3 (km^2)
2.40	145.1	727.3
3.79	229.2	1148.9

So, for 1 year's production of corn production in the United States, topsoil was eroded to completely degrade the equivalent of between 727.3 km^2 and 1148.9 km^2 of land. This thought experiment would not happen all in one place and would be spread over the whole crop growing area. This also does show that soil erosion will have to be part of the calculus if biofuels are scaled up to industrial scale production in a global context.

22.5 Estimation of required fresh water needed to irragate cropland to grow corn and soy for biofuel

Soy and corn crops are very water intensive. Much more so than many other food crops (FAO 2015a). The water consumption footprint to grow corn is 2 570 liters of rainfall or irrigation water to produce enough corn to make just one liter of ethanol (Gerbens-Leenes *et al* 2009). In the same fashion, it takes approximately 14 000 liters of water to produce enough soybeans to make a 1 liter of biodiesel (Gerbens-Leenes *et al* 2009).

The outcomes of applying the water footprint data in flowsheets in Figures 22.2 and 22.3 to the fossil fuel consumptions. Given 1 liter of biodiesel requires 14 000 liters of fresh water (rainwater or irragtion) to irrigate the soy crop, and that 1 liter of etahnol requires 2 575 liters of fresh water to irrgate the corn crop, the volume of fresh water required to be drawn from the global hydrological cycle, to produce the needed biomass, was estimated and shown in Table 22.4. It was assumed that ethanol sourced from corn feedstock would substitute for pterol gasoline and jet fuel, and that biodiesel sourced from soybean feedstock would substitute for diesel and marine bunker fuel oil. The volumes of ethanol and soy biodiesel to be produced was taken from Table 22.2.

Table 22.4. Estimated water consumption footprint for 1 years production of corn and soy feedstock to produce biofuel to substitute petroleum products (based on 2018 consumption)

	Volume of fresh water (liters)	Volume of fresh water need to produce biomass (liters)	Volume of fresh water need to produce biomass (m^3)	Volume of fresh water need to produce biomass (km^3)
Soy biodiesel liters to be produced annually	1.92E+12	2.69E+16	2.69E+13	26,915.2
Water needed per liter of fuel	1.40E+04			
Corn ethanol liters to be produced annually	1.84E+12	4.74E+15	4.74E+12	4,735.6
Water needed per liter of fuel	2.58E+03			

Total annual volume of fresh water required to produce corn and soy biomass: 31 650.8 km^3

The fresh water required to irrigate corn and soy crops to produce biofuels for one year's consumption of petroleum products (based on 2018 numbers) was estimated to be 31 650.8 km^3. This additional annual freshwater requirement for biomass production is graphically compared to the 2018 global water withdrawal for the global human society, from the planetary hydrological freshwater cycle in Figure 22.6. The data in the LHS of Figure 22.6 was taken from a United Nations study (UNESCO 2019 and WWAP 2019).

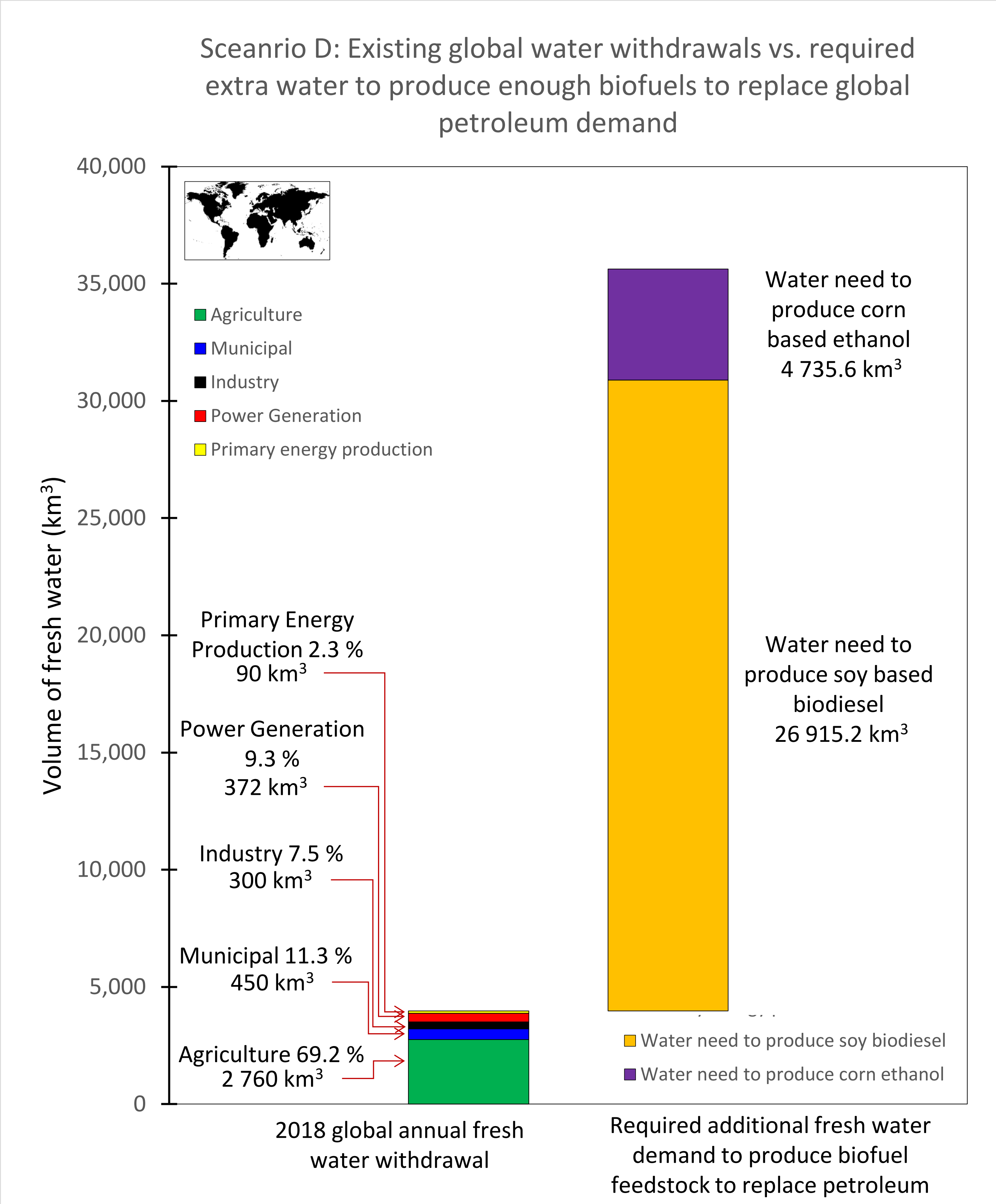


Figure 22.6. Existing global freshwater withdrawal for the global human society (LHS), compared to estimated annual freshwater required to produce enough biofuels using corn and soy biomass feedstock to substitute for annual petroleum product demand (based on 2018 consumption rates). (Source data: UNESCO 2019 and WWAP 2019, and OECD Data Statistics Database) (World Map Image by Clker-Free-Vector-Images from Pixabay)

As can be seen in Figure 22.6, the required additional fresh water for biofuels is approximately 9 times the existing global freshwater withdrawals. To put this in historical context the global annual water withdrawals from the planetary freshwater hydrological cycle over the last 113 years. As can be seen in Figure 22.7, freshwater consumption by the human species in the last few years has been at an unprecedented high.

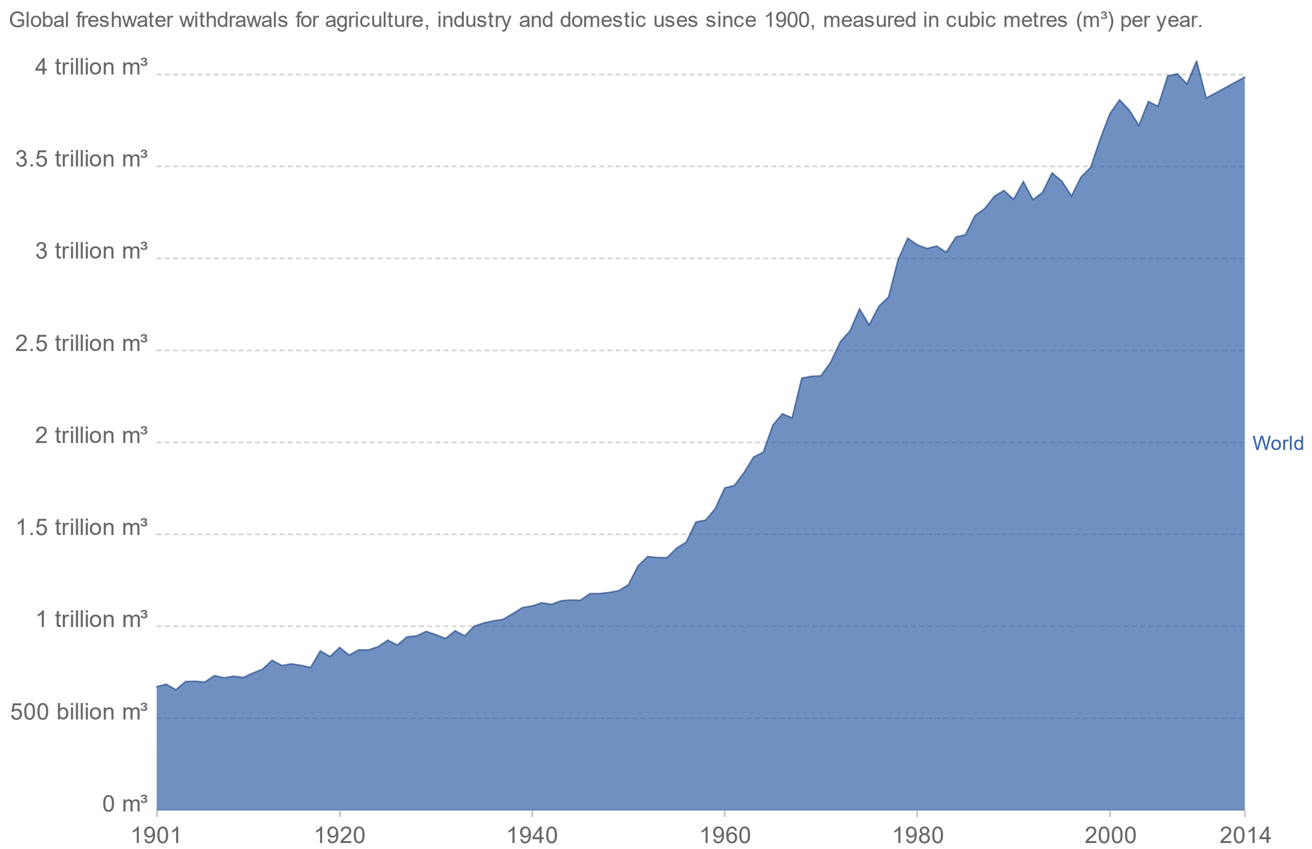


Figure 22.7. Global freshwater use between 1900 and 2014
(Source: Hannah Ritchie and Max Roser (2017) - "Water Use and Stress". Published online at OurWorldInData.org. Retrieved from: 'https://ourworldindata.org/water-use-stress' [Online Resource])

To put the required additional 4 trillion m^3 (3 990 km^3) freshwater to produce biofuels in context, consider how much of the existing human population that are already experiencing water supply stress. According to a United Nations study on global water demand (United Nations 2019 and WWAP 2019), over 2 billion people live in countries experiencing high water stress.

Water stress is defined in its simplest terms as occurring when water demand or withdrawal substantiates a large share of renewable water resources. The World Resources Institute (WRI) define baseline water stress based on the ratio of annual water withdrawals to renewable resources (Gassert *et al* 2013). Water stress categories are based on this percentage (% of withdrawals to renewable resources):

- <10% = low stress
- 10-20% = low-to-medium stress
- 20-40% = medium-to-high stress
- 40-80% = high stress
- >80% = extremely high stress

Water scarcity is more extreme than water stress and occurs when water demand exceeds internal water resources. Figure 22.8 shows water stress as a function of nation state internal freshwater resources. In 2017, there were 31 countries experience water stress between 25% (which is defined as the minimum threshold of water stress) and 70%, and 22 countries which were above 70% and are therefore under serious water stress (UNESCO 2019, Ritchie & Roser 2017 and WWAP 2019). Growing water stress indicates substantial use of water resources, with greater impacts on resource sustainability, and a rising potential for conflicts among users.

In 2015, three out of ten people (2.1 billion people, or 29% of the global population) did not have access to a safely managed drinking water service, whereas 844 million people did not have access to a basic drinking water service. Of all the people using safely managed drinking water services, only one out of three (1.9 billion) lived in rural areas (WHO/UNICEF 2017).

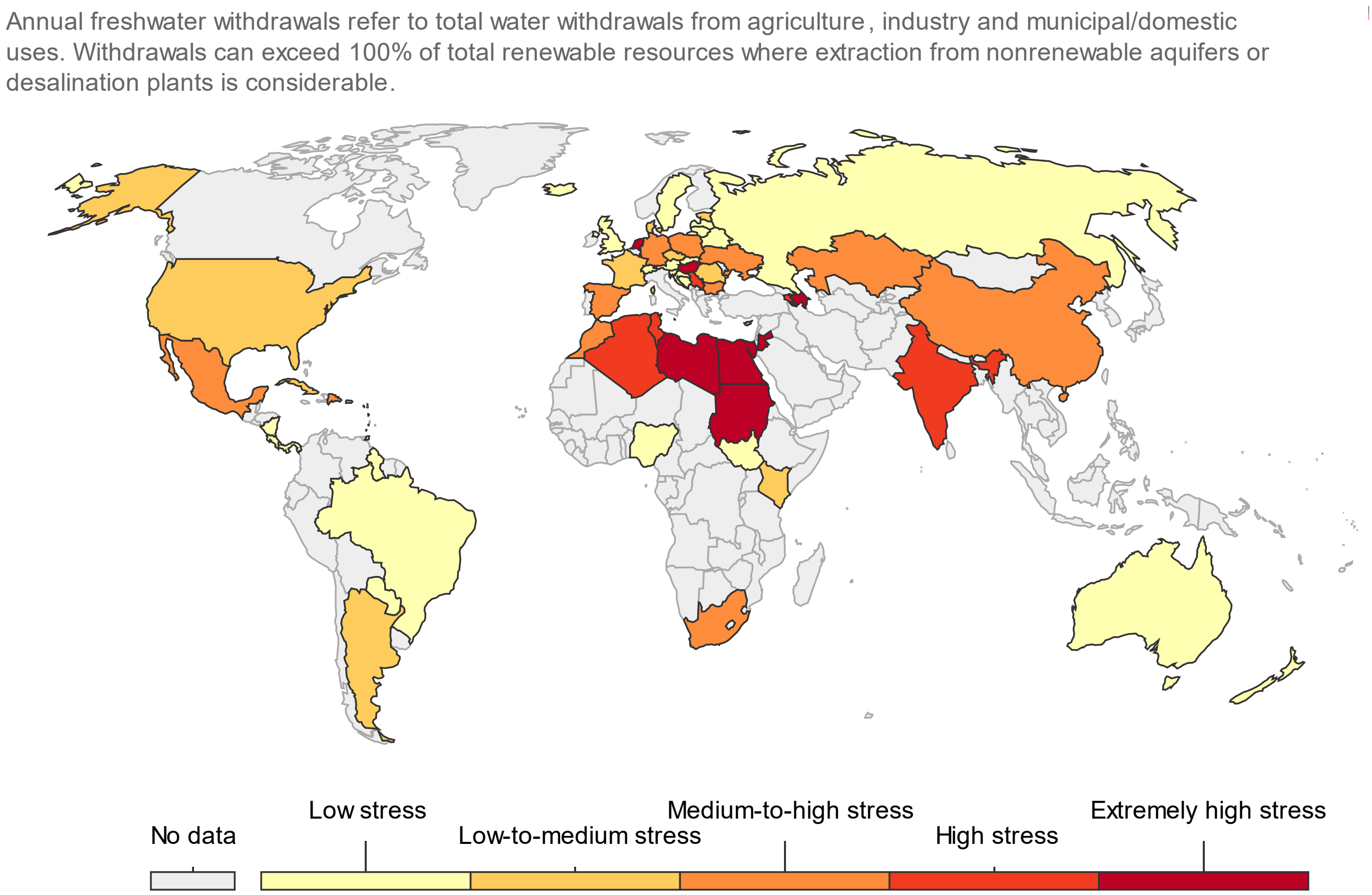


Figure 22.8. Nation state water stress as a ratio of domestic freshwater withdrawals as a proportion of domestic freshwater resources. (Source: Hannah Ritchie and Max Roser (2017) - "Water Use and Stress". Published online at OurWorldInData.org. Retrieved from: 'https://ourworldindata.org/water-use-stress' [Online Resource])

This highlights that currently there are water stress issues to be resolved with the existing level of freshwater demand and the existing human population. The extra annual freshwater demand suggested in Figure 22.6 is probably impractical.

22.6 Global footprint for Biofuel produced from algae feedstock

A school of thought proposes that biofuels sourced from algae feedstock is the best way to phase out petroleum fueled ICE vehicles. So, in addition to examining biofuels from corn and soy from land crops, Scenario D will have a parallel simulation where all biofuel is sourced from algae grown in open ponds positioned in coastal areas sea water, river estuaries and lakes.

In Scenario D, algae are used as a feedstock to produce biodiesel as a substitute biofuel for diesel fuel and marine bunker fuel oil. Numbers assembled in Section 21.5 are adjusted to estimate the mass flows required to produce 1 liter of biofuel.

Figure 22.9 shows these numbers in a material flow sheet to produce 1 liter of biodiesel from a algae feedstock. This flowsheet is a composite from several sources of data (often in units of gallons and pounds, converted to liters and kg) that are discussed in Section 21.5.

This flowsheet was then applied to the 2018 global annual demand for petroleum products (Table 22.2) where an annual production of 3.76 x 10^{12} liters of biofuels are required to be produced from algae feedstock. Table 22.5 shows the estimated mass of algae required to meet this annual demand would be 1.64 x 10^{10} tonne. Given that open pond farms have an estimated productivity of 14 600 tonnes of algae produced annually from each square kilometer, the total pond area required to grow 1.64 x 10^{10} tonne of algae a year 1.126 million km^2 (Table 22.5).

Table 22.5. Mass of algae biomass feedstock and open pond area required to annually produce enough biofuels to substitute petroleum products (using 2018 consumption numbers)

Fossil Fuel	Fuel consumed in 2018 (Liters)	Mass of feedstock algae (assuming 4.37kg of algae produces 1 liter of biofuel) (kg)	Mass of feedstock algae (assuming 4.37kg of algae produces 1 liter of biofuel) (tonne)	Area of algae open ponds needed (assuming a productivity of 14 600 tonne/km^2) (km^2)
Petrol	1.48E+12	6.47E+12	6.47E+09	442,918.7
Diesel	1.66E+12	7.25E+12	7.25E+09	496,763.8
Marine fuel	2.63E+11	1.15E+12	1.15E+09	78,673.3
Jet fuel	3.59E+11	1.57E+12	1.57E+09	107,547.3
Total	3.76E+12 (liters)		1.64E+10 (tonne)	1,125,903.1 (km^2)

This was compared to the freshwater area taken up by rivers and lakes over the entire planet Earth in Figure 22.10. As can be seen, the required area of open ponds is equivalent to 75.1% of global freshwater areas. Clearly this would have an enormous environmental impact and be a challenge to implement.

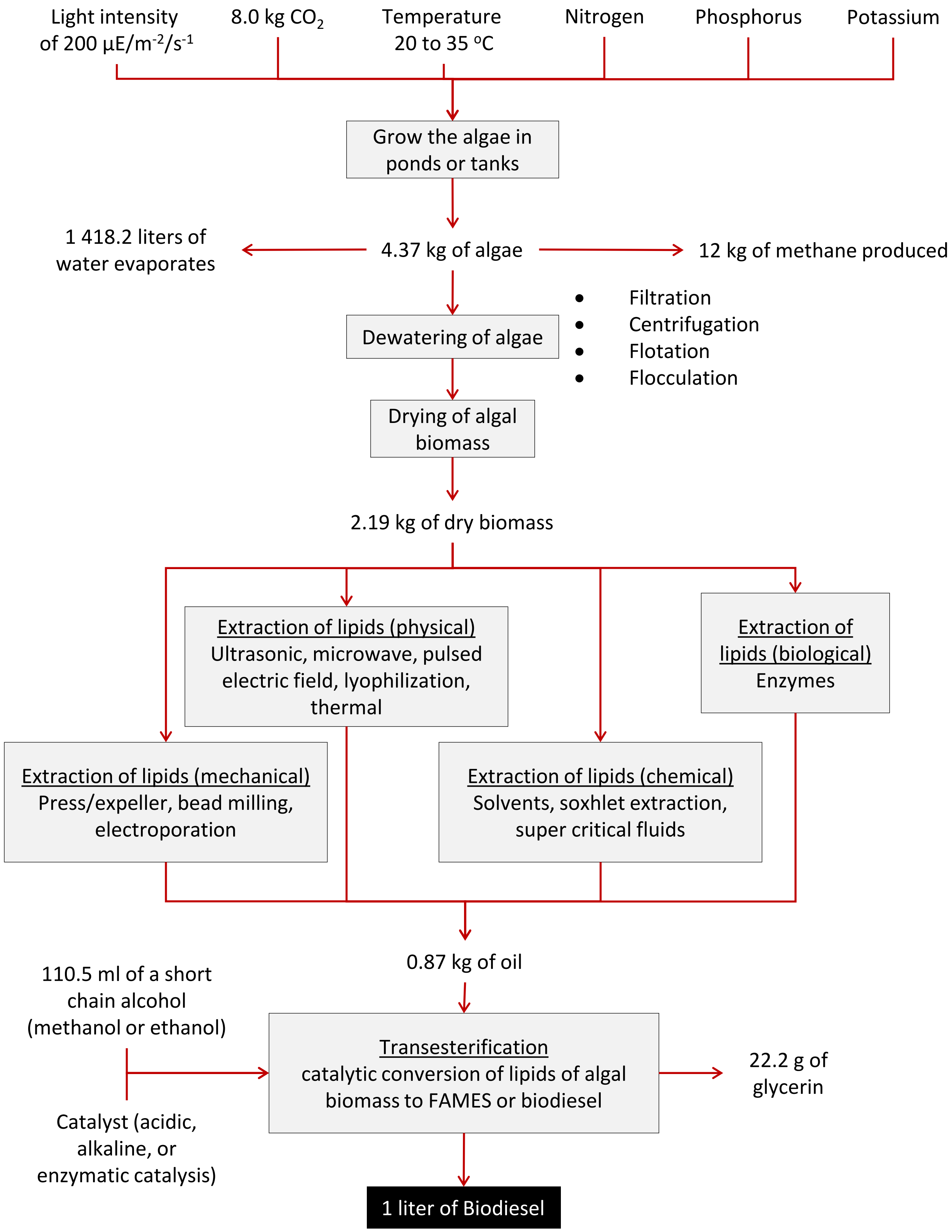


Figure 22.9. Inputs and material flows to produce 1 liter of algae based biodiesel
(Source: data drawn from Bošnjaković 2013, Chisti 2007, Wigmosta *et al* 2011) (Image: Simon Michaux)

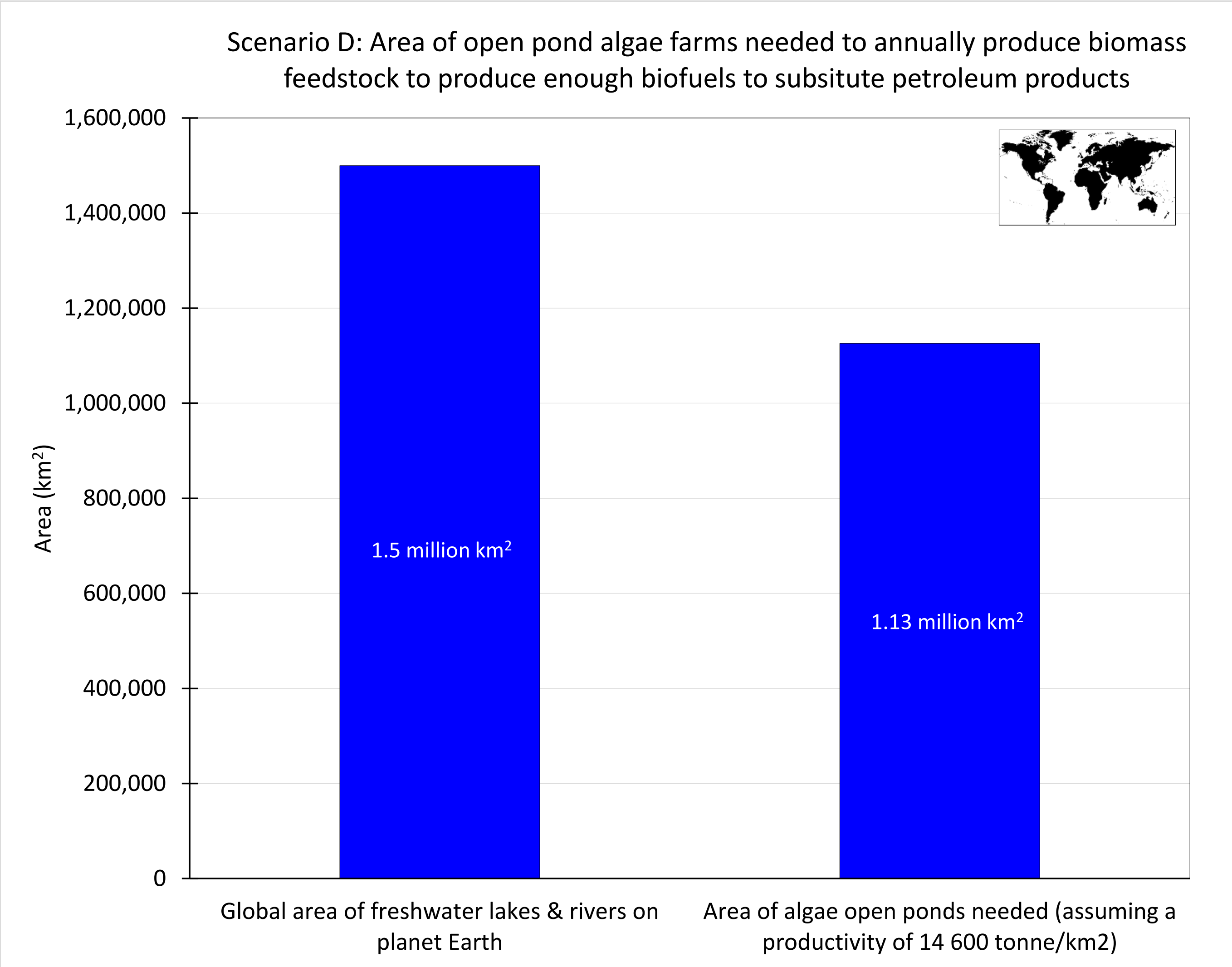


Figure 22.10. Estimated area of open pond algae farms needed to annually produce enough biomass to produce biofuels to substitute annual petroleum product demand. (Source for freshwater proportion of planet surface, United Nations 2019) (World Map Image by Clker-Free-Vector-Images from Pixabay)

Table 22.6. Water evaporated from open ponds during annual production of enough algae biomass sourced biofuels to substitute petroleum products (using 2018 consumption numbers)

Fossil Fuel Substituted	Biofuel produced from algae open ponds in 2018 (Liters)	Water evaporated, assuming 1418.2 liters evaporated out of open pond farms per liter of biofuel produced (liters)	Water evaporated, assuming 1418.2 liters evaporated out of open pond farms per liter of biofuel produced (km^3)
Petrol	1.48E+12	2.10E+15	2.10E+03
Diesel	1.66E+12	2.35E+15	2.35E+03
Marine fuel	2.63E+11	3.73E+14	3.73E+02
Jet fuel	3.59E+11	5.10E+14	5.10E+02
Total	3.76E+12 (liters)		5334.70 (km^3)

Given that for each liter of biofuel produced, 1 418.2 liters of water would evaporate out of the open pond systems, the total annual water loss from algae open pond farms was estimated at 5 334.7 km^3 (Table 22.6). This estimated annual evaporation rate was graphically compared to the annual freshwater demand withdrawal from the planetary hydrological water cycle by the global human society in Figure 22.11. As can be seen, if biofuel sourced from algae feedstock was implemented as a direct substitution for petroleum, then an extra volume of water, 134.3 % the size of existing total water withdrawal would need to be sourced somehow. This extra water could be brackish or saline water, but it must be carefully managed as to not introduce predatory zooplanktons and wild algae that could cause a pond crash. In practical terms with current operations, introduced water is usually filtered freshwater (SNL 2017 and Park *et al* 2011). This volume of water recharge would be needed to maintain stability of algae populations in the open ponds.

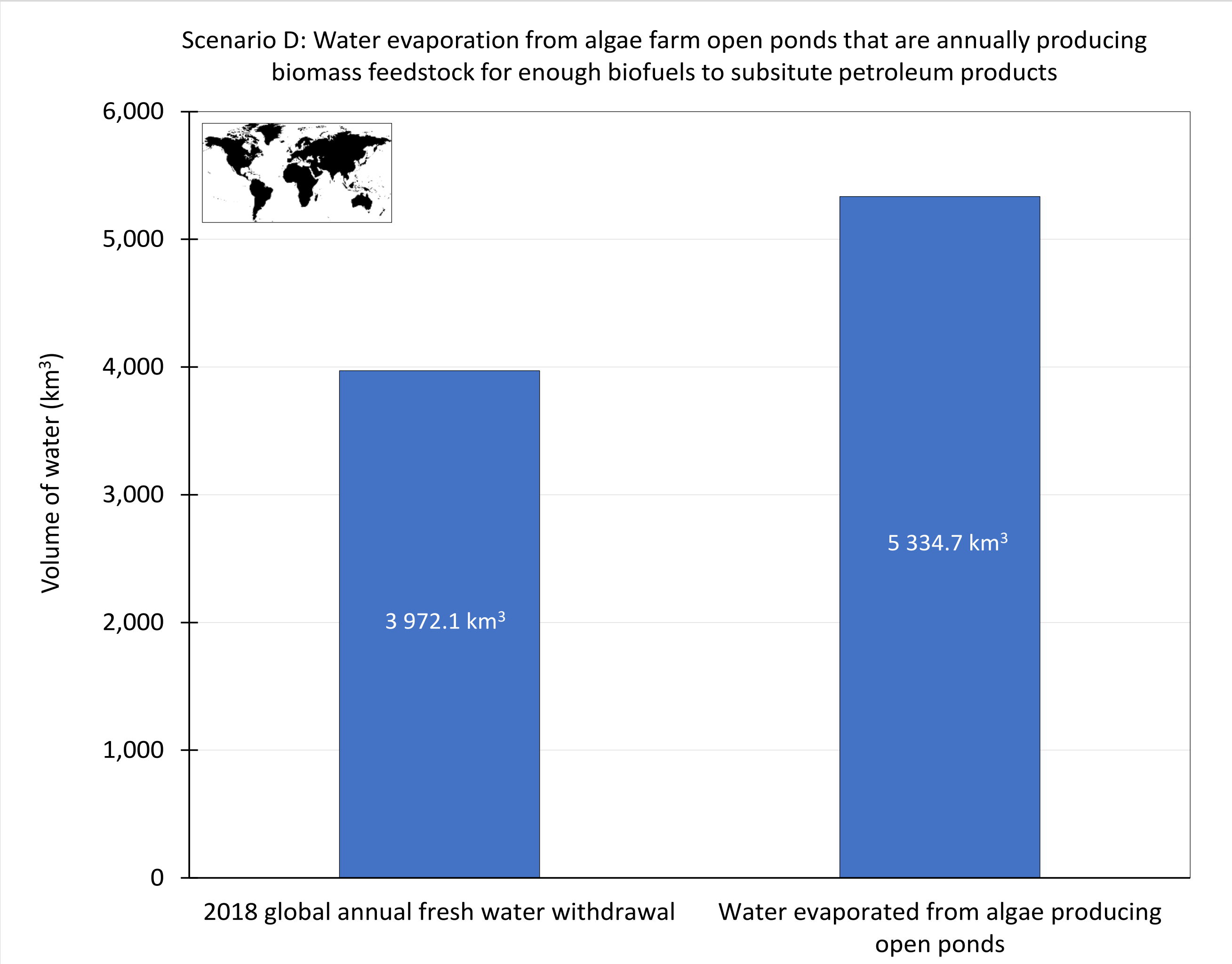


Figure 22.11. Estimated annual water evaporation from open pond algae farms if they produced enough biomass to produce biofuels to substitute for petroleum products (2018 global consumption)
(World Map Image by Clker-Free-Vector-Images from Pixabay)

If algae sourced biofuel is to become viable, one of the greatest challenges that is required to be addressed is the energy consumption of production. As shown in Table 21.2, the energy required to produce biofuel from 1 kg of algae was 12 kWh for wet algae feedstock and 30 kWh for dry feedstock. Even though the use of wet feedstock is not currently practical (Martinez-Guerra & Gnaneswar Gude 2016, Liu *et al* 2013), it was assumed that these logistical issues could be resolved (resulting in a more conservative estimate of energy consumption) and the energy consumption to process 1 kg of algae was 12 kWh. Microalgae have a potential energy content of 5 to 8 kWh/kg of dry weight depending on the species and lipid content (Lardon *et al* 2009). For this thought experiment, an assumed 6.5 kWh/kg of energy content was assumed. Thus, 12 kWh was required to produce a quantity of biofuel, which had a theoretical 6.5 kWh of energy. This was how algae biofuel had a negative ERoEI ratio.

Table 22.7 shows the outcome of this thought experiment. To annually produce the needed 3.76 x 10^{12} liters of biofuel, 193 148 TWh of energy was consumed to process the 1.64 x 10^{13} kg (Table 22.1) of algae feedstock. The energy contained in the produced biofuel had a theoretical energy content of 106 848.2 TWh. This was shown graphically in Figure 22.12.

Table 22.7. Energy consumed to annually produce enough algae biomass biofuels to substitute petroleum products (using 2018 consumption numbers)

Fossil Fuel Substituted	Biofuel produced from algae open ponds in 2018 (Liters)	Energy use to produce algae biofuel (assuming 12 kWh to process 1 kg of algae) (MJ)	Energy use to produce algae biofuel (assuming 12 kWh to process 1 kg of algae) (kWh)	Energy use to produce algae biofuel (assuming 12 kWh to process 1 kg of algae) (TWh)
Petrol	1.48E+12	2.74E+14	7.60E+13	75982.7
Diesel	1.66E+12	3.07E+14	8.52E+13	85219.8
Marine fuel	2.63E+11	4.86E+13	1.35E+13	13496.4
Jet fuel	3.59E+11	6.64E+13	1.84E+13	18449.7
Total	3.76E+12 (liters)	6.95E+14 (MJ)	1.93E+14 (kWh)	193,148.7 (TWh)

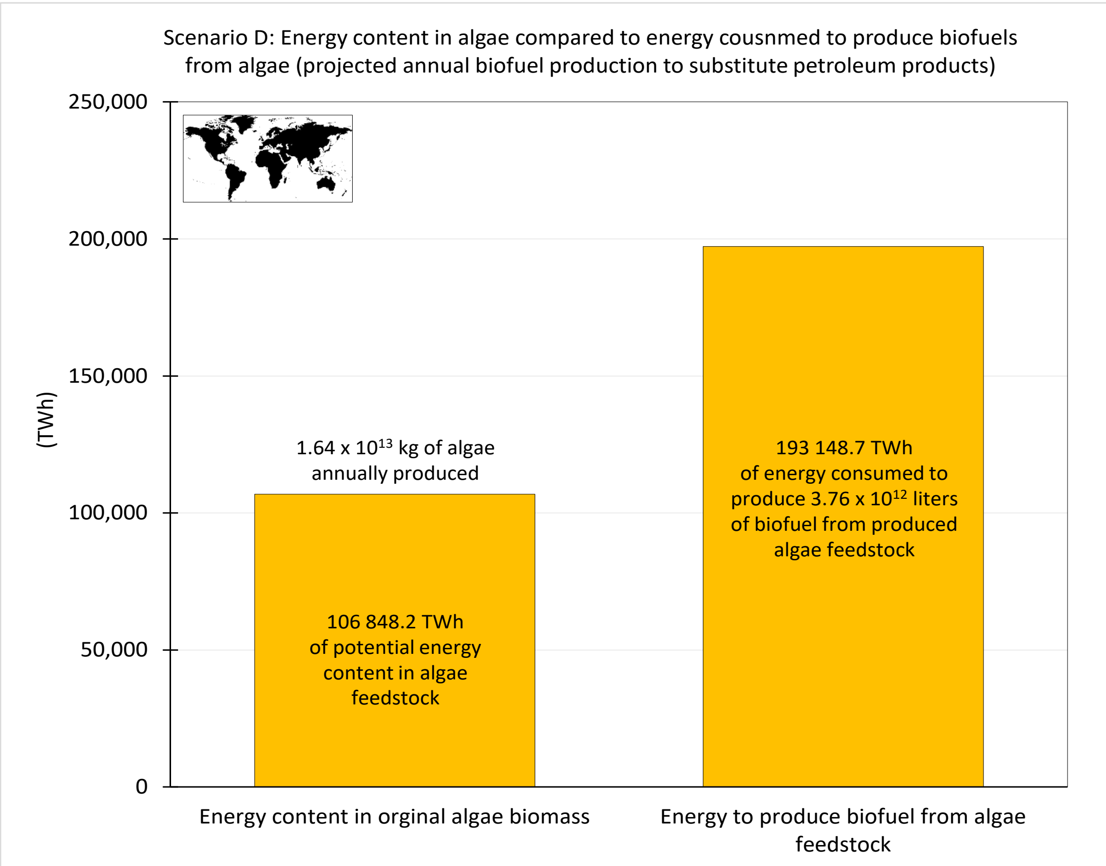


Figure 22.12. Energy content of produced biofuel compared to energy consumed to process algae feedstock (World Map Image by Clker-Free-Vector-Images from Pixabay)

22.7 Outcomes of Scenario D

The outcomes of Scenario D show clearly that the footprint of the proposed biofuel production done at a scale large enough to substitute petroleum product consumption far exceeds the planetary environmental capability and is also logistically impractical. The problem is the required volume of biofuel needed vs. the global arable land availability, and the global freshwater availability. Biofuel production technologies work quite well on a small scale. The issues raised only become unmanageable when examining what is required to scale up production to replace petroleum.

If all biofuel was sourced from soybean or corn feedstock, the arable land required to grow enough biomass would far exceed the current global land used for food production (crops). That arable land used for food production has been subject to persistent degradation and deterioration, which is projected to continue while current industrial agricultural production methods remain standard practice. The expansion of crop land into other land use sectors like livestock grazing is often not possible as the land is not suitable to grow crops, where all of the best arable land is already used to grow food. The additional area required for biofuel feedstock is comparable to the remaining planetary forested area. Proposing the complete deforestation of the entire planet, just to keep the existing transport fleet operating would be environmentally irresponsible. This means that the extra capacity to grow biofuel feedstock is in direct competition with existing food production.

Then there is the water consumption footprint of growing the needed feedstock of corn and soy. These two crops in particualr are very water intensive. The Scenario D thought experiment showed that the required additional fresh water for biofuels is approximately 9 times the existing global freshwater withdrawals. The existing freshwater withdrawals by the global human society is at a historical high. Simultaneously, there are multiple regions around the world that are subject to fresh water supply stress. The extra water suggested here probably is unlikely to be considered. Biofuel produced form algae feedstock is often discussed in the literature. Once again, this process path does work on a small scale and is supported externally by fossil fuel systems, but once scaled up, very serious practical challenges make this fuel source unviable. The major setback for algae biofuel is the negative ERoEI ratio. Far more energy is used to produce the biofuel than the energy contained in the final biofuel product. The ERoEI ratio of biodiesel is low, approximately 1.3 to 1.9 (Pimentel and Patzek 2005; Hill *et al* 2006), which is far lower than the needed ratio of 10 to14:1 needed to economic growth in its current form (Lambert *et al* 2014, see Section 6). Bio ethanol has a similar ERoEI ratio.

That being stated, biofuels do have their place. Biofuels are a drop in fuel and can be directly applied to existing ICE technologies with minor modifications. Biofuels have the capacity to keep the aviation industry operational, where electric propulsions systems (and their batteries) cannot due to their weight. Hydrogen fuel aircraft also face many technological barriers due to engineering constraints of how the hydrogen gas can be stored on the aircraft during flight. Due tot the high internal pressure of the H_2 tank, it's geometry and size require it to be stored inside the fuselage, thus limiting carrying capacity. Biomass sources aviation fuel has none of these limitations and can be used in place of jet fuel (with minor modifications). Biofuels also are the most promising technology vector to replace many plastic applications (see Section 10.2). Figure 22.13 shows a comparison of Scenario A, C and D energy footprints to replace petroleum fueled IVE vehicles.

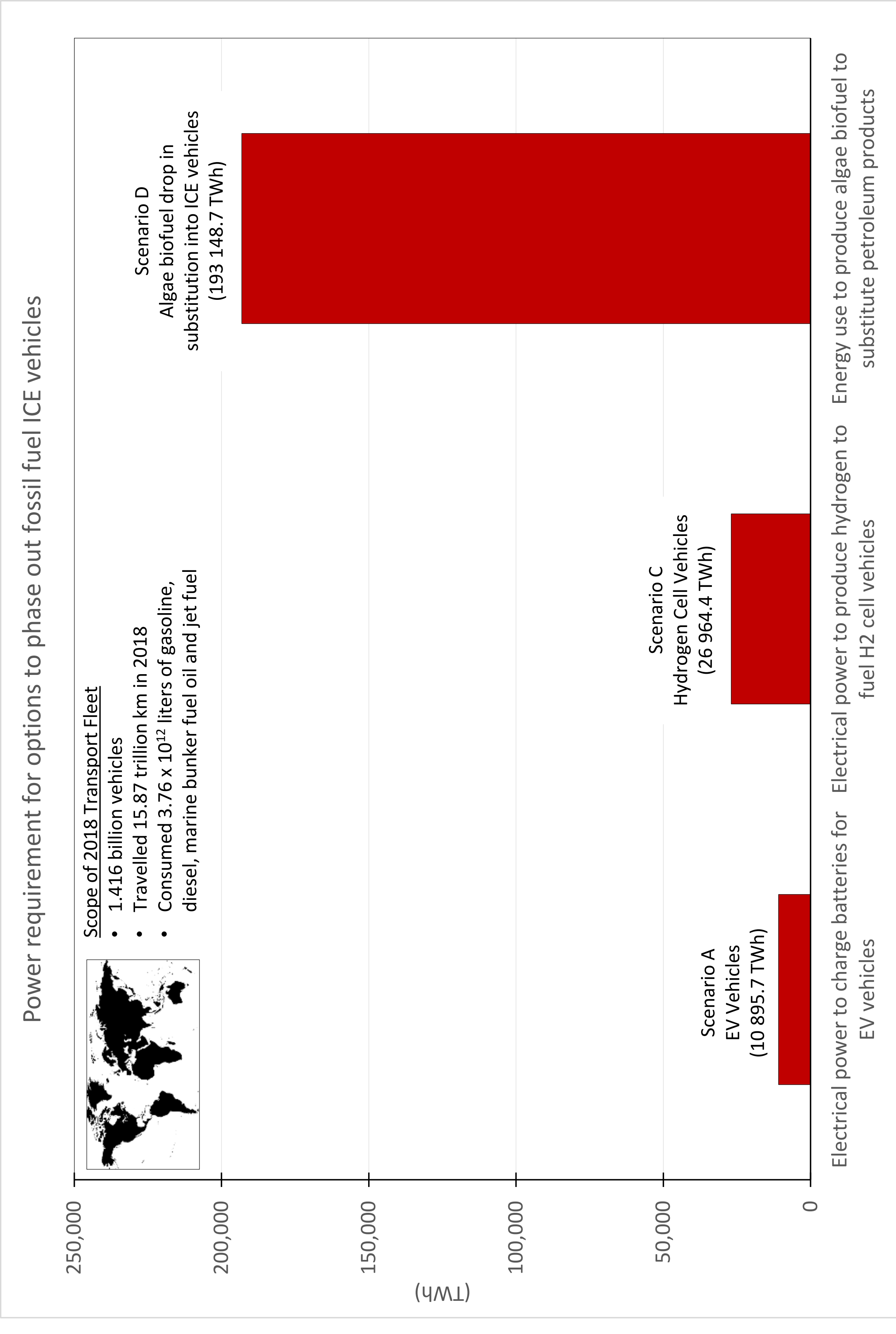
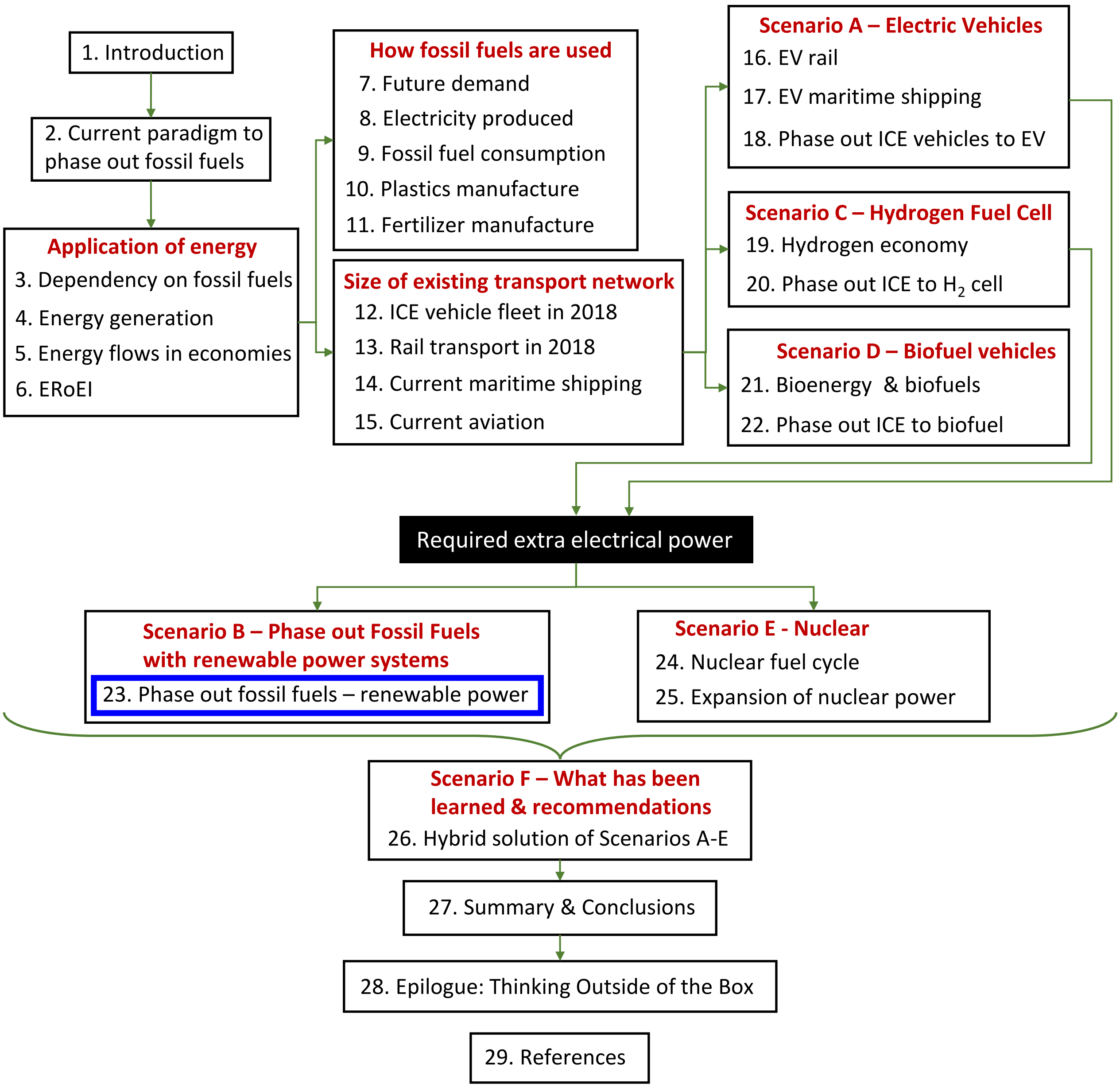


Figure 22.13. Power requirements of Scenario's A, C and D options to phase out petroleum fueled ICE vehicles (World Map Image by Clker-Free-Vector-Images from Pixabay)

23 SCENARIO B – PHASE OUT FOSSIL FUELS COMPLETELY AND SUBSTITUTE WITH RENEWABLE POWER SOURCES

The purpose of Section B is to examine what will be necessary to phase out fossil fuels entirely. Oil, gas, and coal for all applications would be all phased out. Petroleum product fueled ICE vehicles would be phased out and substituted with EV vehicles, where all supporting electrical power will be sourced from non-fossil fuel systems like wind, solar, hydro, biomass and nuclear.



Assessment of the Extra Capacity Required of Alternative Energy Electrical Power Systems to Completely Replace Fossil Fuels

The current paradigm amongst strategic planners all over the world is to phase out fossil fuels. The European Commission has stated as a goal to become less reliant on fossil fuels and use more sustainable power sources (European Commission 2019). The EU has agreed a comprehensive update of its energy policy framework to facilitate the transition away from fossil fuels towards cleaner energy and to deliver on the EU's Paris Agreement commitments for reducing greenhouse gas emissions. The completion of this new energy rulebook – called the Clean Energy for all Europeans package - marks a significant step towards the implementation of the energy union strategy, adopted in 2015. All other nations are considering a similar transition.

These good intentions are all good and well, but the current industrial paradigm shows something else entirely. Figure 23.1 shows the projected demand for petroleum and other liquids between 2018 and 2050. There is not only a persistent increase in demand, but not even a discernable reduction anywhere in this prediction.

Most of the future production is predicted to be in non-OPEC countries, where non-OPEC countries produce slightly more than half of crude oil output through the projection period, accounting for 55% of global production in 2050. This predicted production of crude oil, lease condensate, natural gas plant liquids (NGPLs) and other liquid fuels from 2018 to 2050, reaching 127 million barrels per day (b/d) in 2050, or about 30% more than 2018 levels.

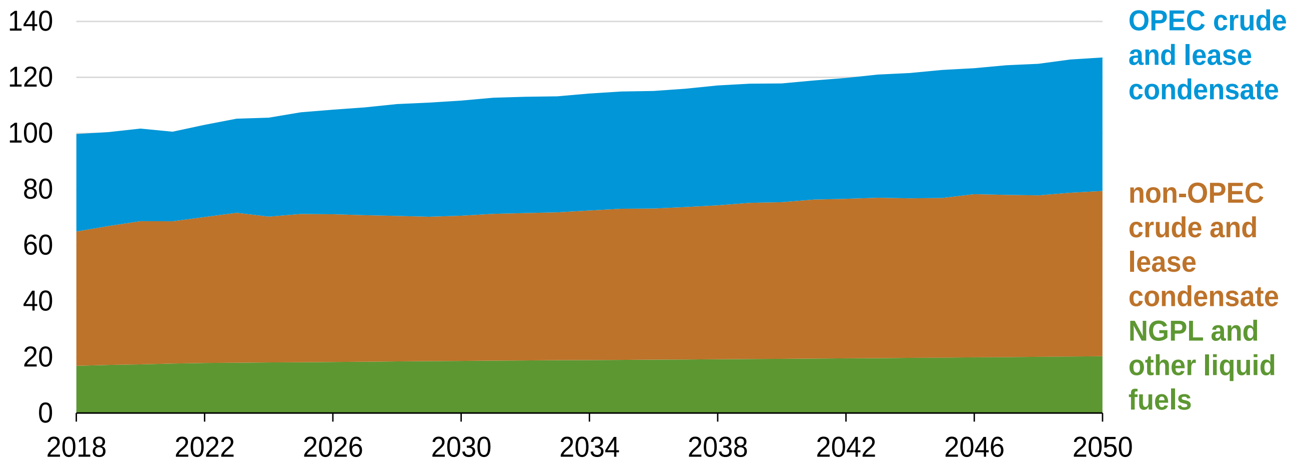


Figure 23.1. World petroleum and other liquid fuels production million barrels per day (Source: EIA International Energy Outlook 2019 with projections to 2050)

One of the objectives of this report is to examine the requirements of the phase out of fossil fuels, oil, gas, and coal. This report does not consider the timing or mechanism of the transition. It is to examine what would be required if the entire current system was using sustainable renewable power systems. For example, if all cars in the global fleet become electric vehicles and are charged off the global power grid, how much extra capacity is required for that global electrical power grid? If all electric power generation was to become renewable, how much extra capacity is needed from renewable systems after the phasing out of gas and coal electric power generation? Nuclear power is considered as an option as one of the remaining systems.

Figure 23.2 below shows the major uses of oil, gas and coal, which account for the bulk of fossil fuel consumption. Each fossil fuel would be examined separately.

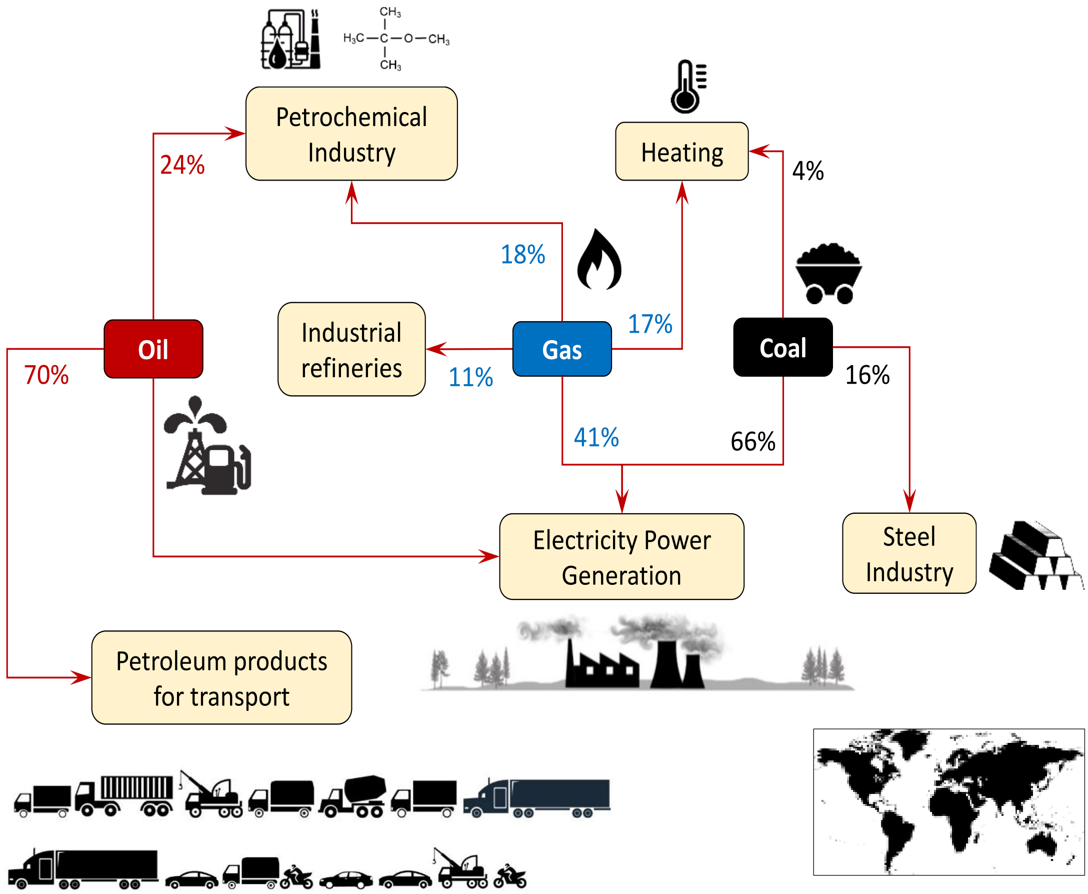


Figure 23.2. Fossil fuels used and their main applications
(Source: data assembled from BP Statistical review of World Energy 2019, World Steel Association, IEA 2018, OECD)
(World Map Image by Clker-Free-Vector-Images from Pixabay, royalty free clipart, some clipart purchased)

Scenario B - Phase out Fossil Fuels Completely and Substitute with Renewable Power Sources

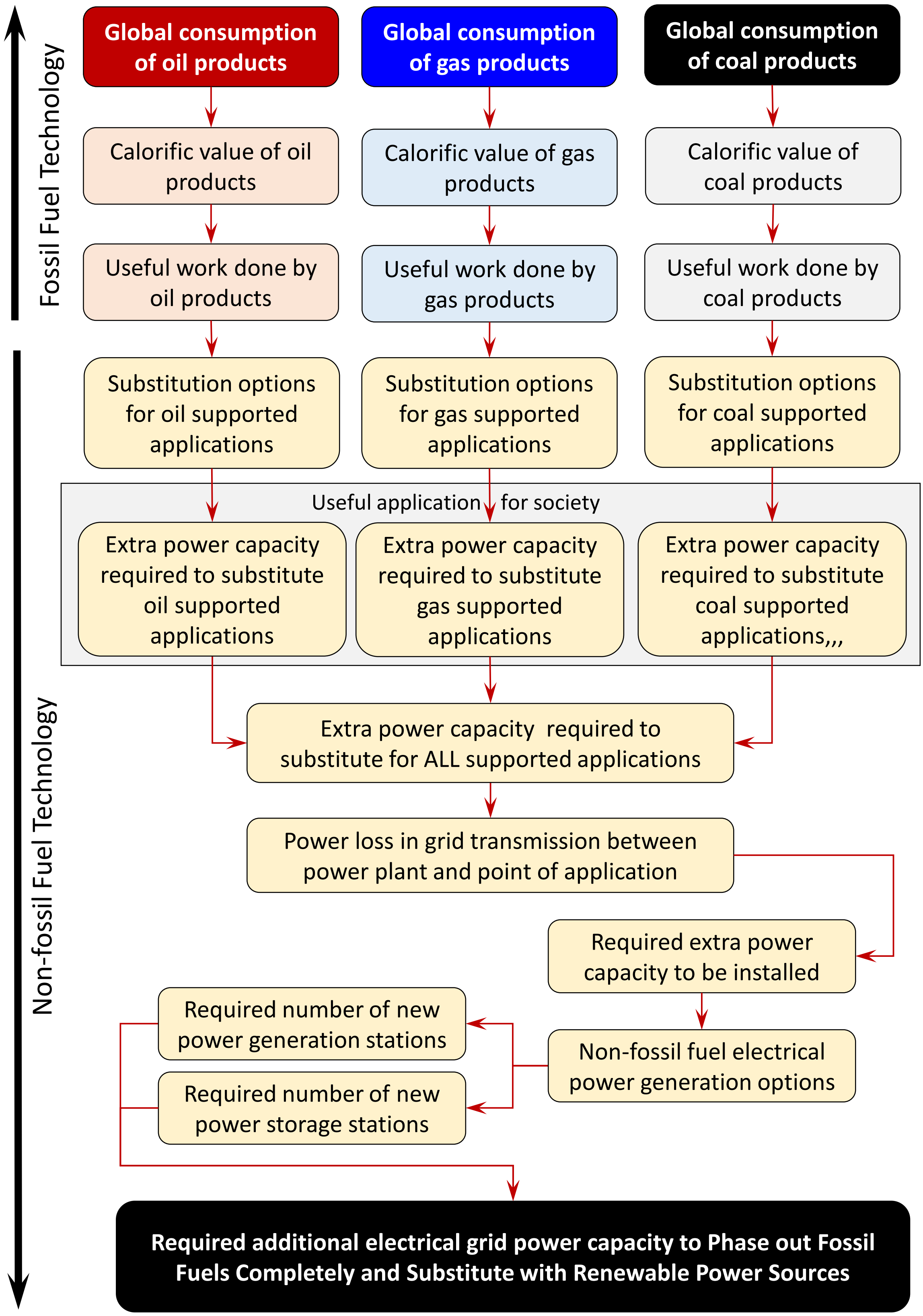


Figure 23.3. Required calculations for the steps to phase out petroleum products – Scenario B (Image: Simon Michaux)

23.1 Phasing out of Oil as an Energy Source

The logistics of phasing out petroleum products is examined in Section 21, Scenario A. To phase out ICE technology vehicles and fully substitute with EV technology vehicles, an extra 10 895.7 TWh of extra capacity of power generation is required.

In addition to this, 14% of primary oil consumption is to supply the petrochemical industry (Source: IEA 2018. In 2018, this was an estimated 652.7 Mtoe. This includes plastics and fertilizer manufacture. At the time of writing this report, there was no viable substitution technology that is able to supply the required volumes of plastics and petrochemical fertilizers.

23.2 Phasing out of Gas as an Energy Source

The use of gas and gas derivatives has been growing for decades (Figure 9.19, Section 9). In 2018, 41% of gas was globally consumed to generate **6 182.8 TWh** of electrical power. This power generation capacity will have to come from non-fossil fuel supported sources (See Section 8, Table 8.4 and Appendix B).

In 2018, 17% of gas was used for heating applications. This application will have to be done with electric heaters and be charged off the electric power grid. If that fraction of gas (562.6 Mtoe of the 2018 global consumption of 3309.4 Mtoe) was converted to electricity, it would produce an estimated 2 560 TWh.

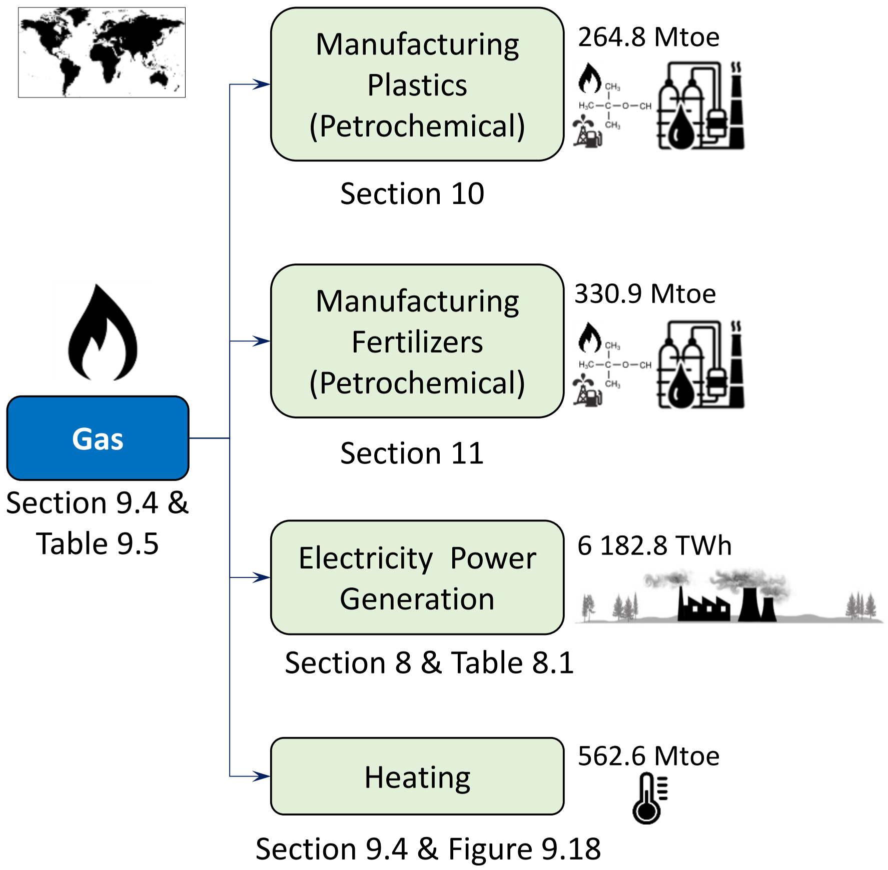


Figure 23.4. Applications of gas by report section, 2018 values
(Source: Appendix E, BP Statistical review of World Energy 2019, Plastics Europe 2018, IEA 2019)
(World Map Image by Clker-Free-Vector-Images from Pixabay, royalty free clipart, some clipart purchased)

If that electricity was converted to a heating application, the conversion from electric power to heating application is approximately 92%, because almost all purchased energy is converted to building heat (Source: U.S. Dept. of Energy). The extra power draw this will require is to be an estimated 2 780 TWh in extra capacity. Assuming 10 % of grid transmission loss, **2 816 TWh** would be required to be delivered annually. This is assuming solar and geothermal cannot directly replace heating applications. There are low-enthalpy domestic heating technologies using heat exchange pumps. The scale up potential of these technologies is not clear. Nevertheless, they would not be able to substitute all industrial scale heating applications. As previously stated, there is no viable substitute for the petrochemical industry for the use of gas in the manufacture of plastics, fertilizers, herbicides, or pesticides (Section 10).

23.3 Phasing out of coal as an Energy Source

The use of coal has been growing for decades (Figure 9.26, Section 9). In 2018, 66% of coal was globally consumed to generate **10 100.5 TWh** of electrical power. This power generation capacity will have to come from non-fossil fuel supported sources (See Section 8, Table 8.4, and Appendix B).

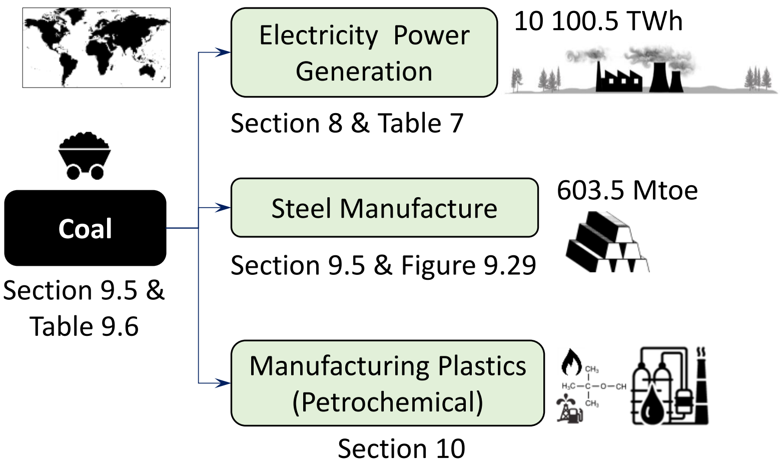


Figure 23.5. Applications of coal by report section, 2018 values
(Source: Appendix F, BP Statistical review of World Energy 2019, World Steel Association)
(World Map Image by Clker-Free-Vector-Images from Pixabay, royalty free clipart, some clipart purchased)

A further 16% of coal was consumed by the steel industry in 2018, where 71% of steel was made using coal (Figure 9.29 and 9.35 in Section 9). About one-quarter of the world's steel is produced by the Electric-Arc Furnace method (EAF), which uses high-current electric arcs to melt steel scrap and convert it into liquid steel of a specified chemical composition and temperature.

The electric power used in EAF operation, however, is high, at 360 to 600 kilowatt-hours per ton of steel, and the installed power system is substantial, where a 100-ton EAF facility often has a 70-megavolt-ampere transformer.

Global crude steel production reached 1808.6 million tonnes (Mt) for the year 2018 (World Steel Association 2018). If all steel in 2018 was manufactured using an electric arc furnace, then 71% of 1808.6 Mt would have to be transferred away from using coal to refine crude steel to using an electric arc. So, 71% of 1808.6 Mt is 1284.1 Mt. This means that 51.4 TWh (5.14 x 10^{11}kWh) of extra electricity would need to be generated, where an average of 400 kWh is needed to produce one tonne of steel. Accounting for 10 % power grid transmission loss, **56.54 TWh** of power would need to be delivered annually.

In Sweden, an initiative that endeavors to revolutionize steel-making is being developed called HYBRIT, a collaboration between SSAB, LKAB and Vattenfall (HYBRIT 2019). HYBRIT aims to replace coking coal, traditionally needed for ore-based steel making, with hydrogen. The result will be the world's first fossil-free steel-making technology, with virtually no carbon footprint. During 2018, work started on the construction of a pilot plant for fossil-free steel production in Luleå, Sweden. The goal is to have a solution for fossil-free steel by 2035. While still in feasibility, this potentially could provide a way to manufacture steel without coal.

23.4 Electrical power required to phase out fossil fuels

To quantify what is needed in context of extra electrical power generation capacity to phase out fossil fuels, the following needs to be assembled:

- Estimated needed electrical power to charge an entirely Electric Vehicle transport fleet
- Estimated needed electrical power to directly substitute for fossil fuel power generation
- Estimated needed electrical power to directly substitute for gas heating of buildings
- Estimated needed electrical power to directly substitute for steel manufacture using coal
- Accounting for 10% grid transmission power loss between power generation station and point of application
- Scale up proportions estimated to spread the extra required power across existing non-fossil fuel power generation systems, in the same fashion as Figure 21.9 in Section 21
- Estimated number of new power stations in each of the non-fossil fuel generation systems, assuming the same capacities as developed in Section 21, Table 21.7
- Estimated number of power storage stations to manage intermittent supply from variable power sources like wind and solar as developed in Section 21, Table 21.28. A practical approach for Scenario B could be an optimized and networked storage capacity of the scale of the kWh delivered to the power grid by all wind and solar power sources only, **over a 4 week cycle**. The numbers used were based on the Australian Hornsdale Power Reserve (100 MWh capacity), adjacent to the Hornsdale wind farm, built by Tesla (Parkinson 2017a).
- Estimated quantity of lithium ion batteries needed

Each of these tasks was done for the following system scopes in separate calculations:

- United States
- Europe EU-28
- China
- Global

Summarizing all of the different aspects of this report is shown in Figure 23.17 in flow sheet form. If each of the fossil fuels were phased out, and a renewable sustainable substitution was applied (almost always EV and alternative power), what extra power draw capacity on the electricity grid would be required?

23.4.1 Extra electrical power required in the United States to completely phase out fossil fuels

Table 23.1. Estimated kilowatt hours needed to phase out fossil fuels entirely in the United States with the same scope of activity as in 2018

Fossil Fuel Supported Task	Fossil Fuel	Sustainable Solution	Extra capacity required from the electric power grid at the point of application (TWh)	Extra annual capacity required to be generated at power station, accounting for 10% grid transmission loss (TWh)
ICE Car & Truck Transport (Sections 9.1 & 12)	Oil, Petroleum, Gasoline	EV vehicles charged by non-fossil fuel generated electricity power (Section 21)	2,958.4	3,254.3
Electrical Power Generation (Section 8)	Oil	Non-fossil fuel electrical power generation (Sections 3 & 22)	26,4 (direct substitution)	26.4
Electrical Power Generation (Section 8)	Gas	Non-fossil fuel electrical power generation (Sections 3 & 22)	1 578,5 (direct substitution)	1,578.5
Building Heating (Sections 9.4 & 8)	Gas	Electric heating used instead	907.6	998.4
Electrical Power Generation (Sections 9.5 & 8)	Coal	Non-fossil fuel electrical power generation (Sections 3 & 22)	1 245,8 (direct substitution)	1,245.8

Sum Total to Phase out Fossil Fuels **7,103.3**

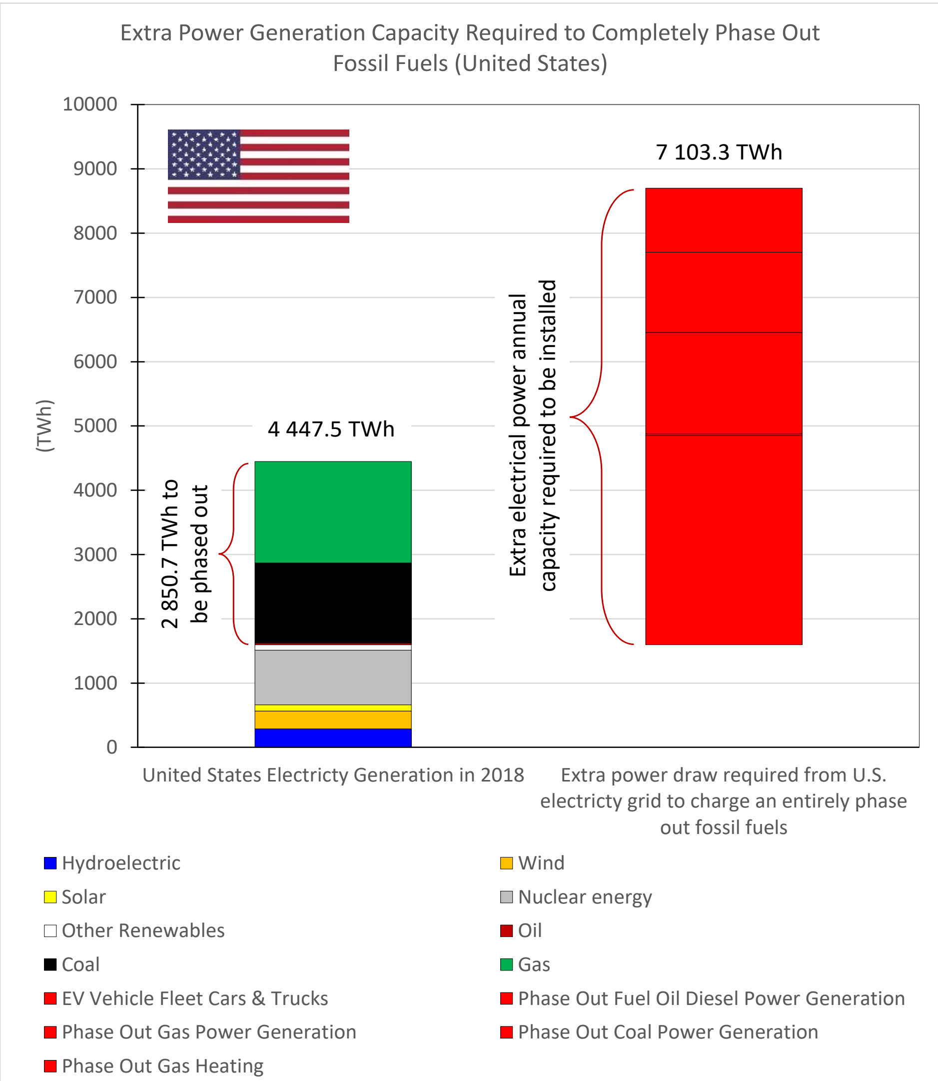


Figure 23.6. Extra capacity in the electrical power system to phase out fossil fuels in the United States – Part 1 (Source. for LHS column of data, BP Statistical Review of World Energy)

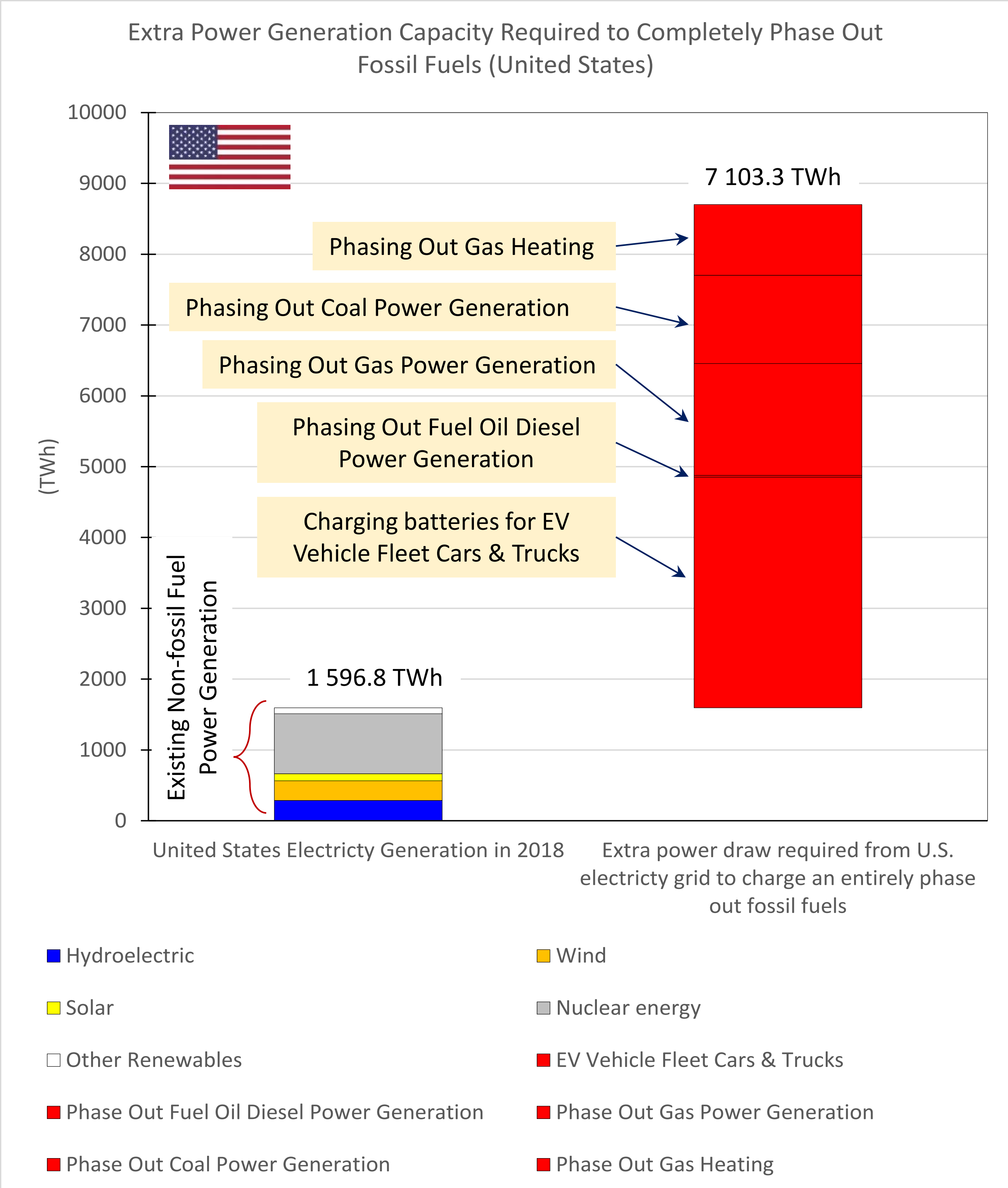


Figure 23.7. Extra capacity in the electrical power system to phase out fossil fuels in the United States – Part 2 (Source. for LHS column of data, BP Statistical Review of World Energy)

Table 23.2. Estimated number of new power stations to be installed in the United States required to phase fossil fuels entirely (Source: Appendix B, BP Statistical Review of World Energy, Global Energy Observatory)

Power Generation System	U.S. electricity production in 2018 (BP Statistical Review of World Energy 2019) (kWh)	2018 ratio percent of all U.S. non-fossil fuel electrical power systems (%)	Expanded extra required annual capacity to phase out fossil fuels (kWh)	Average Plant Capacity (Global Energy Observatory) (MW)	Power Produced by a Single Average Plant in 2018 (kWh)	Estimated number of required additional new power plants of average size to phase out fossil fuels (number)
Nuclear	8.50E+11	52.77%	3.75E+12	2 046.5 MW	1.28E+10	293
Hydroelectric	2.89E+11	17.93%	1.27E+12	225.4 MW	1.33E+09	961
Wind	2.78E+11	17.25%	1.23E+12	37. 2 MW	8.12E+07	15,080
Solar PV	9.71E+10	6.03%	4.28E+11	33.1 MW	3.30E+07	12,965
Other Renewable	9.70E+10	6.02%	4.28E+11	76.97 MW	7.70E+07	5,560
Total (kWh)	1.61E+12		7.10E+12			34,859
Total (TWh)	1,610		7,103			

Table 23.3. Estimated number of 100 MW power storage stations to be built in the United States to address renewable source intermittency of supply (wind and solar) at the scope required to phase out fossil fuels entirely

Power Generation System	Expanded extra required annual United States capacity to phase out fossil fuels (kWh)	Storage capacity required for a 4 week period to manage winter period, with limited sun & wind (kWh)	Number of 100 MWh capacity power storage stations to meet power generation in a 4 week cycle (number)	Mass of Li-Ion batteries @230 Wh/kg (tonnes)
Wind	1,23E+12	9,42E+10	942 413	4,10E+08
Solar PV	4,28E+11	3,30E+10	329 522	1,43E+08
Total Storage Capacity	1,65E+12 1 653.5 TWh	127,2 TWh Summed Battery Capacity	1 271 935 number of storage stations	553 015 383 tonnes of batteries

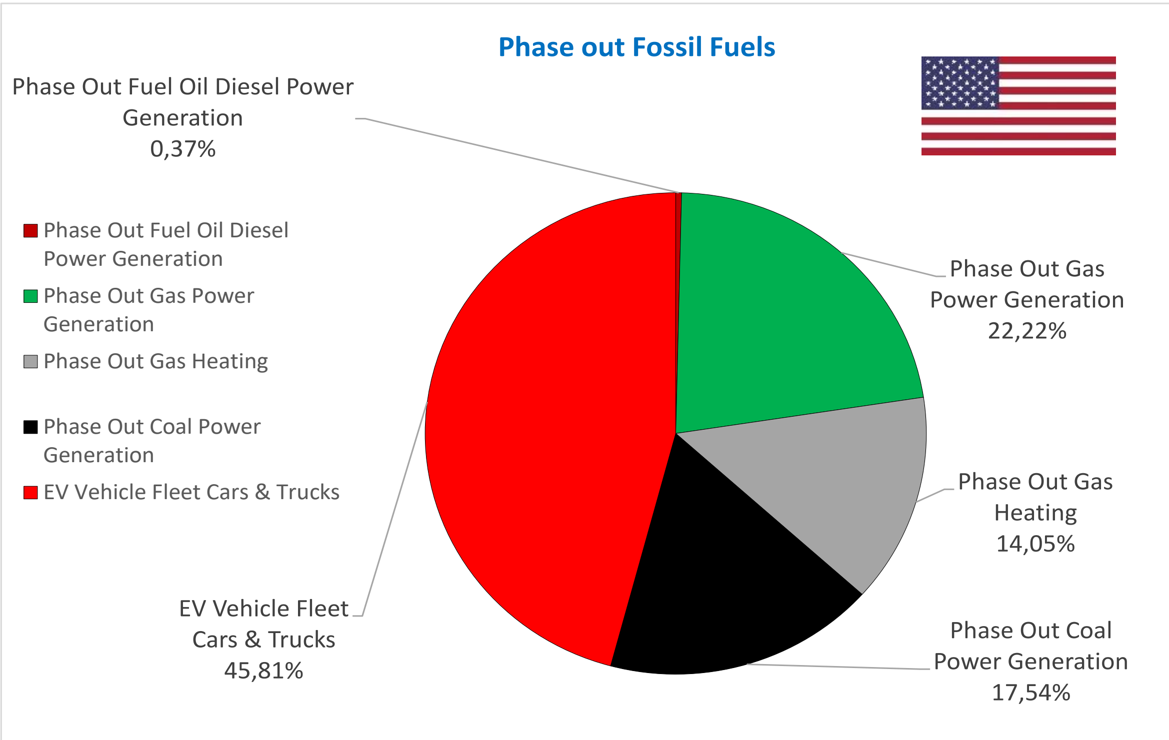


Figure 23.8. Comparison of needed extra electrical power capacity required to phase out all fossil fuels in the United States, by application proportion

23.4.2 Extra electrical power required in Europe EU-28 to completely phase out fossil fuels

Table 23.4. Estimated kilowatt hours needed to phase out fossil fuels entirely in the European Union (EU-28) with the same scope of activity as in 2018

Fossil Fuel Supported Task	Fossil Fuel	Sustainable Solution	Extra capacity required from the electric power grid at the point of application (TWh)	Extra annual capacity required to be generated at power station, accounting for 10% grid transmission loss (TWh)
ICE Car & Truck Transport (Sections 9.1 & 12)	Oil, Petroleum, Gasoline	EV vehicles charged by non-fossil fuel generated electricity power (Section 21)	517.0	571.4
Electrical Power Generation (Section 8)	Oil	Non-fossil fuel electrical power generation (Sections 3 & 22)	56 (direct substitution)	56
Electrical Power Generation (Section 8)	Gas	Non-fossil fuel electrical power generation (Sections 3 & 22)	619,7 (direct substitution)	619.7
Building Heating (Sections 9.4 & 8)	Gas	Electric heating used instead	779.0	856.9
Electrical Power Generation (Sections 9.5 & 8)	Coal	Non-fossil fuel electrical power generation (Sections 3 & 22)	655,2 (direct substitution)	655.2
			Sum Total to Phase out Fossil Fuels	**2,759.2**

Table 23.5. Estimated number of new power stations to be installed in the European Union (EU-28) required to phase fossil fuels entirely (Source: Appendix B, BP Statistical Review of World Energy, Global Energy Observatory)

Power Generation System	EU-28 electricity production in 2018 (BP Statistical Review of World Energy 2019) (kWh)	2018 ratio percent of all EU-28 electrical non-fossil fuel power systems (%)	Expanded extra required annual capacity to phase out fossil fuels (kWh)	Average Plant Capacity (Global Energy Observatory) (MW)	Power Produced by a Single Average Plant in 2018 (kWh)	Estimated number of required additional new power plants of average size to phase out fossil fuels (number)
Nuclear	8.27E+11	42.33%	1.17E+12	2 046.5 MW	1.28E+10	91
Hydroelectric	3.45E+11	17.64%	4.87E+11	225.4 MW	1.33E+09	367
Wind	3.79E+11	19.38%	5.35E+11	37. 2 MW	8.12E+07	6,581
Solar PV	1.28E+11	6.54%	1.80E+11	33.1 MW	3.30E+07	5,460
Other Renewable	2.76E+11	14.12%	3.90E+11	76.97 MW	7.70E+07	5,061
Total (kWh)	1.95E+12		2.76E+12			17,561
Total (TWh)	1,955		2,759			

Table 23.6. Estimated number of 100 MW power storage stations to be built in the European Union (EU-28) to address renewable source intermittency of supply (wind and solar) at the scope required to phase out fossil fuels entirely

Power Generation System	Expanded extra required annual European EU-28 capacity to phase out fossil fuels (kWh)	Storage capacity required for a 4 week period to manage winter period, with limited sun & wind (kWh)	Number of 100 MWh capacity power storage stations to meet power generation in a 4 week cycle (number)	Mass of Li-Ion batteries @230 Wh/kg (tonnes)
Wind	5.35E+11	4.11E+10	411,287	1.79E+08
Solar PV	1.80E+11	1.39E+10	138,761	6.03E+07
Total Storage Capacity	7.15E+11 715.1 TWh	55.0 TWh Summed Battery Capacity	550,048 number of storage stations	239,151,105 tonnes of batteries

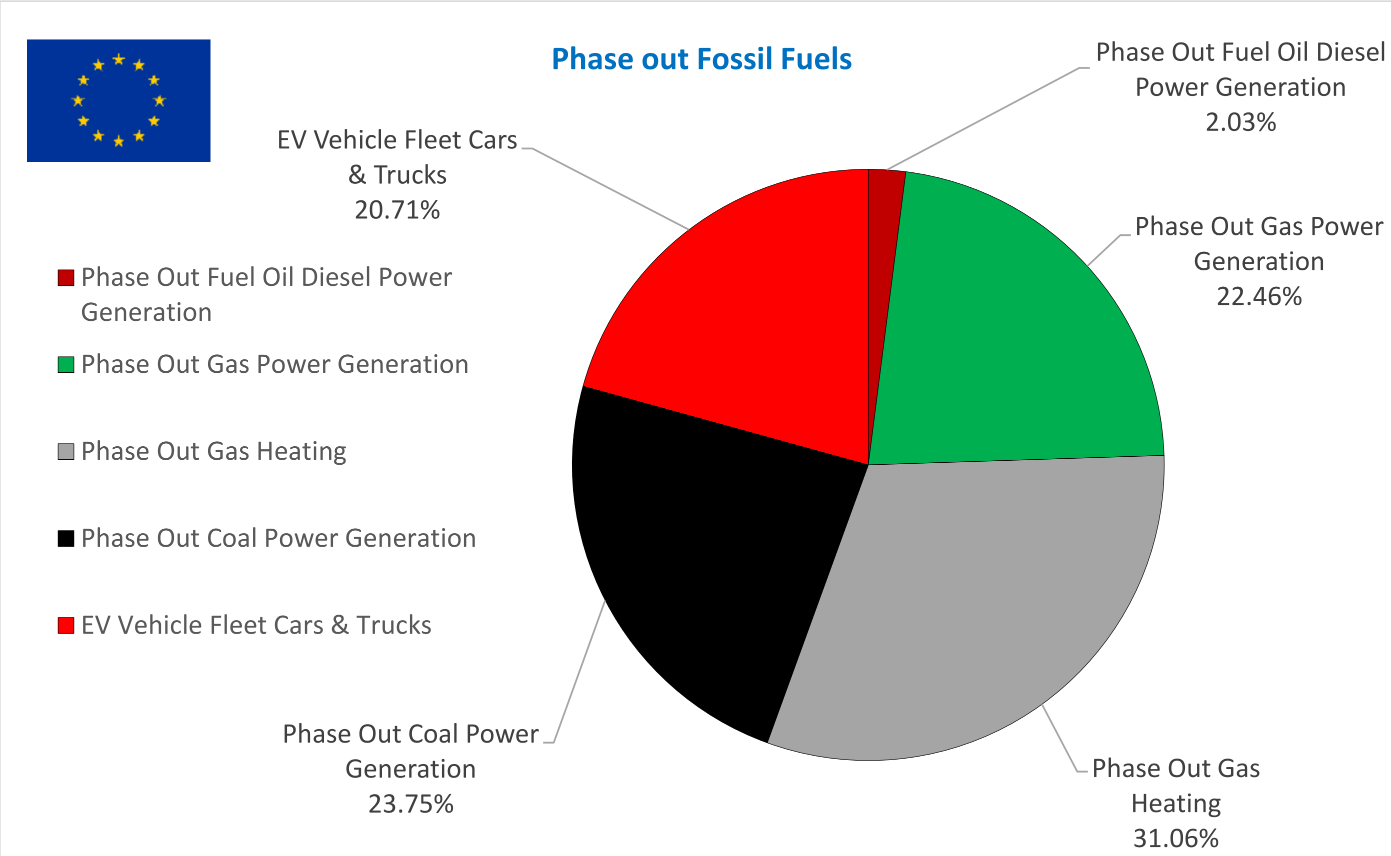


Figure 23.9. Comparison of needed extra electrical power capacity required to phase out all fossil fuels in Europe EU-28, by application proportion

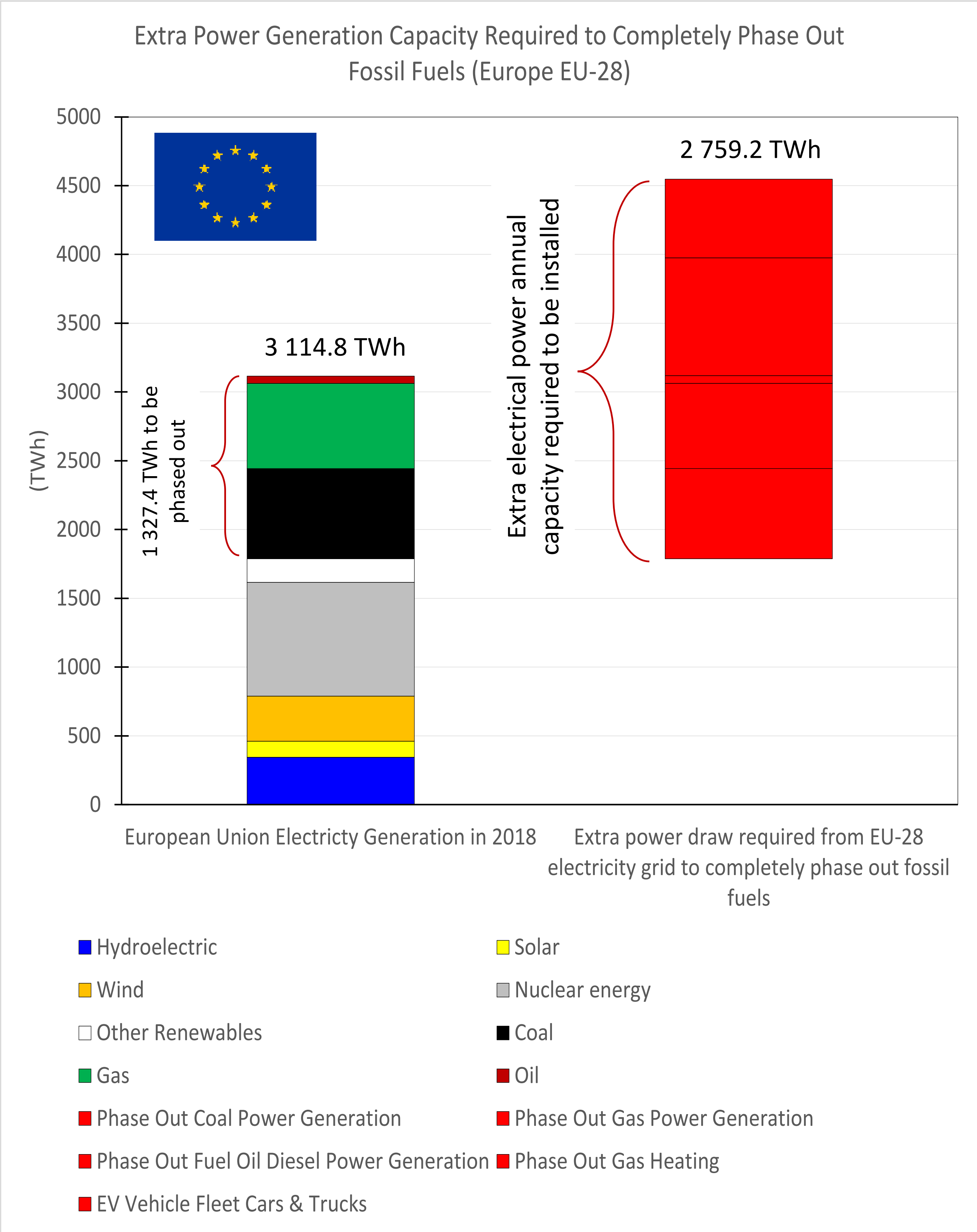


Figure 23.10. Extra capacity in the electrical power system to phase out fossil fuels in Europe (EU-28) – Part 1 (Source. for LHS column of data, BP Statistical Review of World Energy)

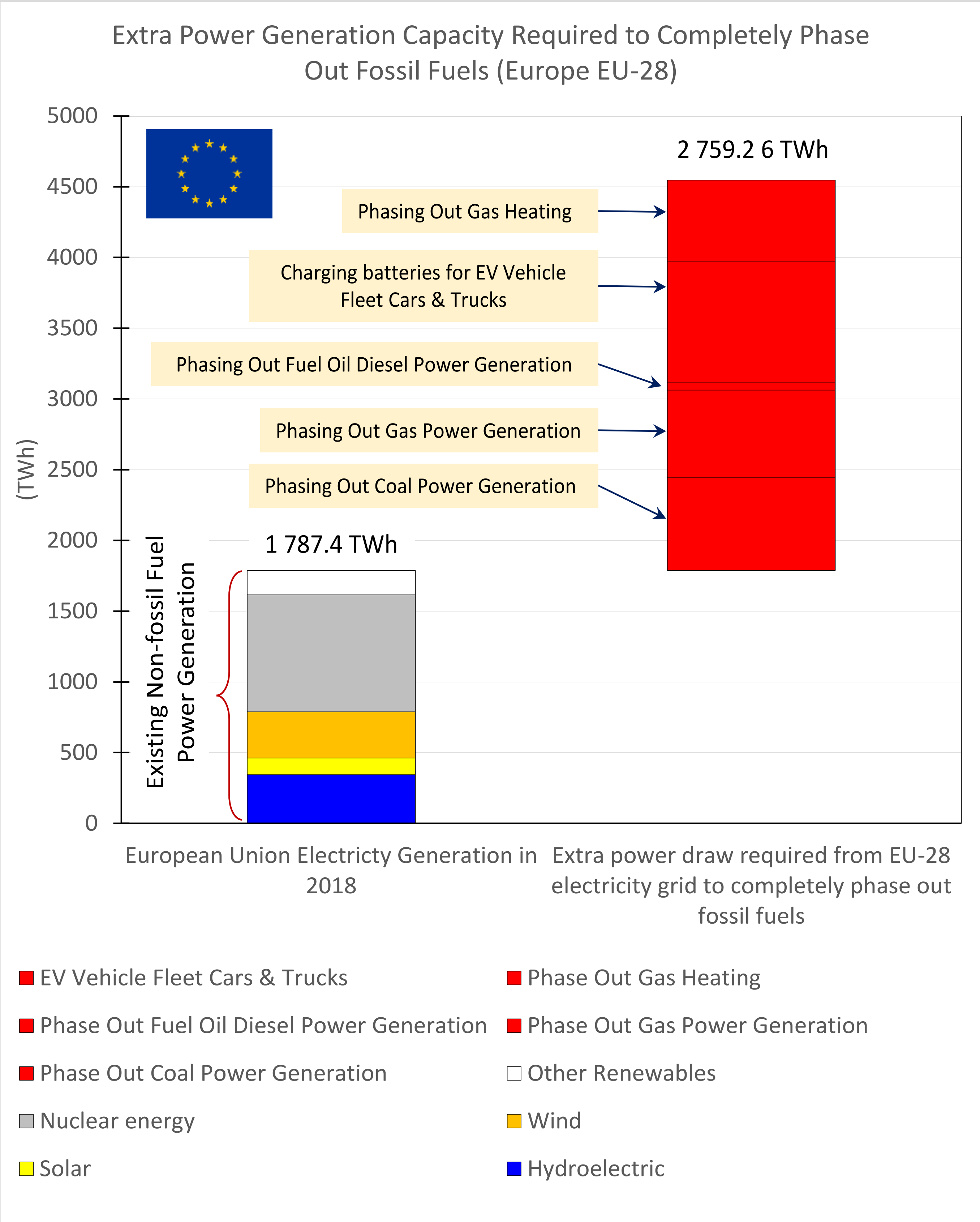


Figure 23.11. Extra capacity in the electrical power system to phase out fossil fuels in Europe (EU-28) – Part 2 (Source. for LHS column of data, BP Statistical Review of World Energy)

23.4.3 Extra electrical power required in China to completely phase out fossil fuels

Table 23.7. Estimated kilowatt hours needed to phase out fossil fuels entirely in China with the same scope of activity as in 2018

Fossil Fuel Supported Task	Fossil Fuel	Sustainable Solution	Extra capacity required from the electric power grid at the point of application (TWh)	Extra annual capacity required to be generated at power station, accounting for 10% grid transmission loss (TWh)
ICE Car & Truck Transport (Sections 9.1 & 12)	Oil, Petroleum, Gasoline	EV vehicles charged by non-fossil fuel generated electricity power (Section 21)	887.8	976.6
Electrical Power Generation (Section 8)	Oil	Non-fossil fuel electrical power generation (Sections 3 & 22)	10,7 (direct substitution)	10.7
Electrical Power Generation (Section 8)	Gas	Non-fossil fuel electrical power generation (Sections 3 & 22)	223,6 (direct substitution)	223.6
Building Heating (Sections 9.4 & 8)	Gas	Electric heating used instead	311.3	342.4
Electrical Power Generation (Sections 9.5 & 8)	Coal	Non-fossil fuel electrical power generation (Sections 3 & 22)	4732,4 (direct substitution)	4,732.4

Sum Total to Phase out Fossil Fuels **6,285.6**

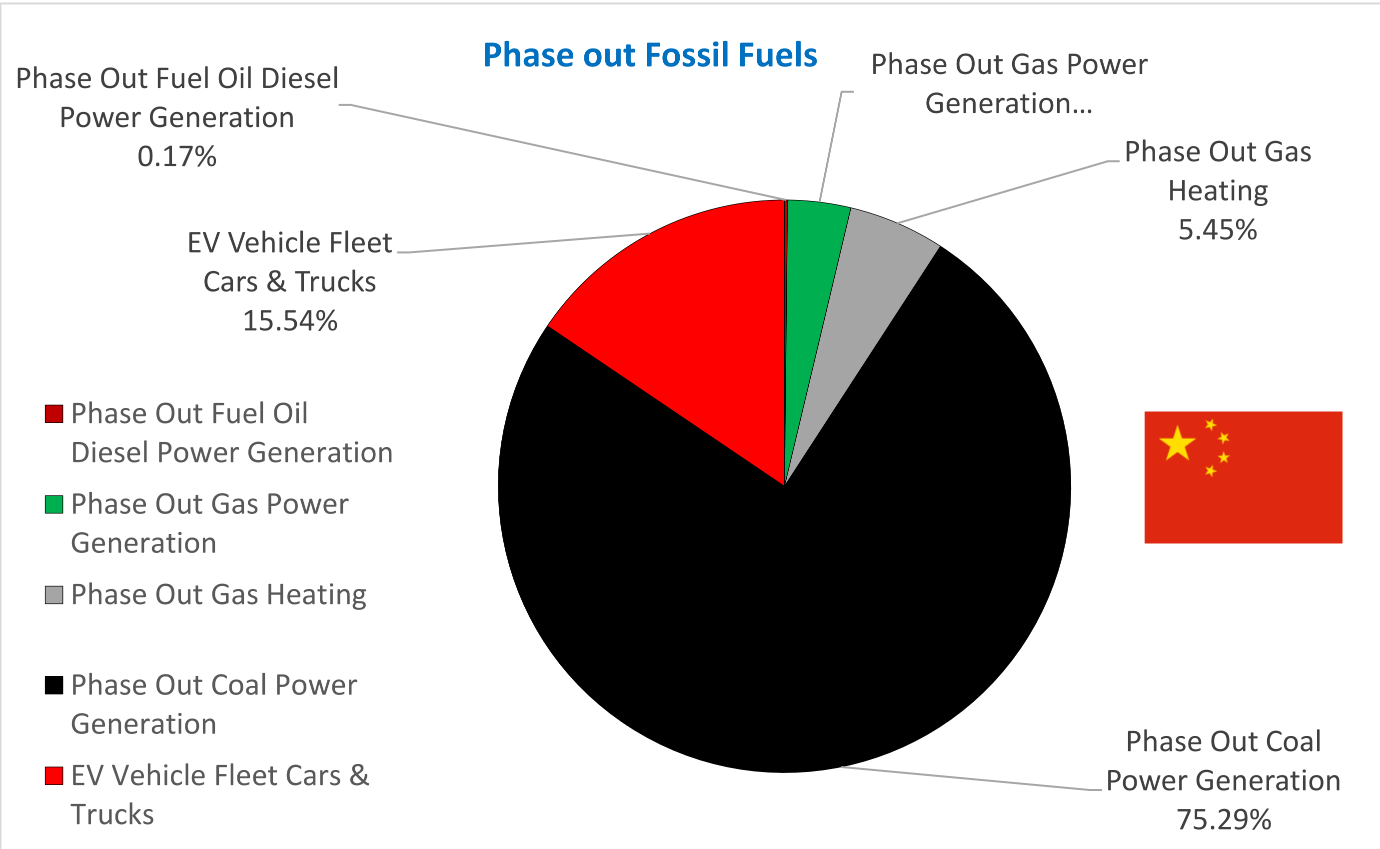


Figure 23.12. Comparison of needed extra electrical power capacity required to phase out all fossil fuels in China, by application proportion

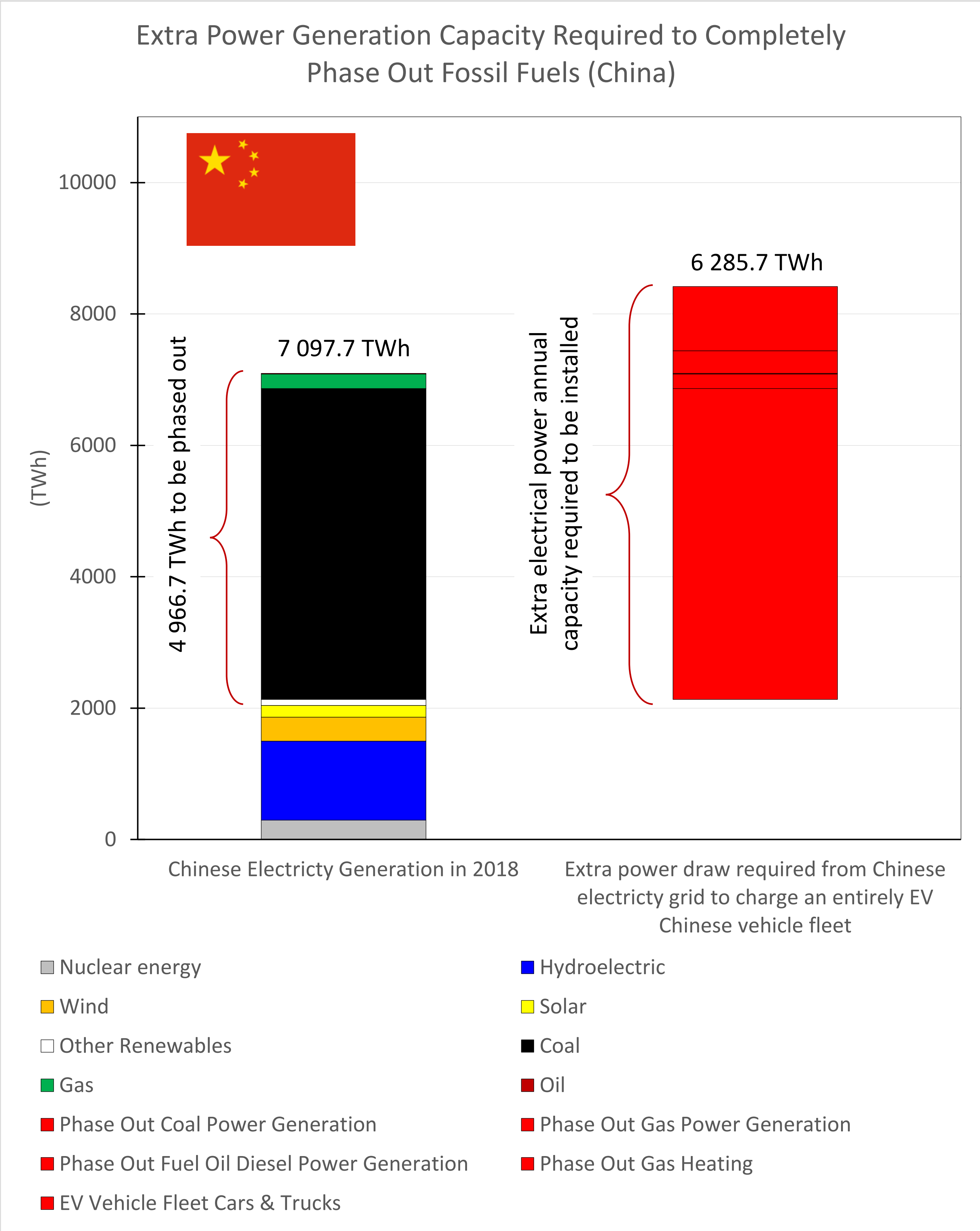


Figure 23.13. Extra capacity in the electrical power system to phase out fossil fuels in China – Part 1 (Source. for LHS column of data, BP Statistical Review of World Energy)

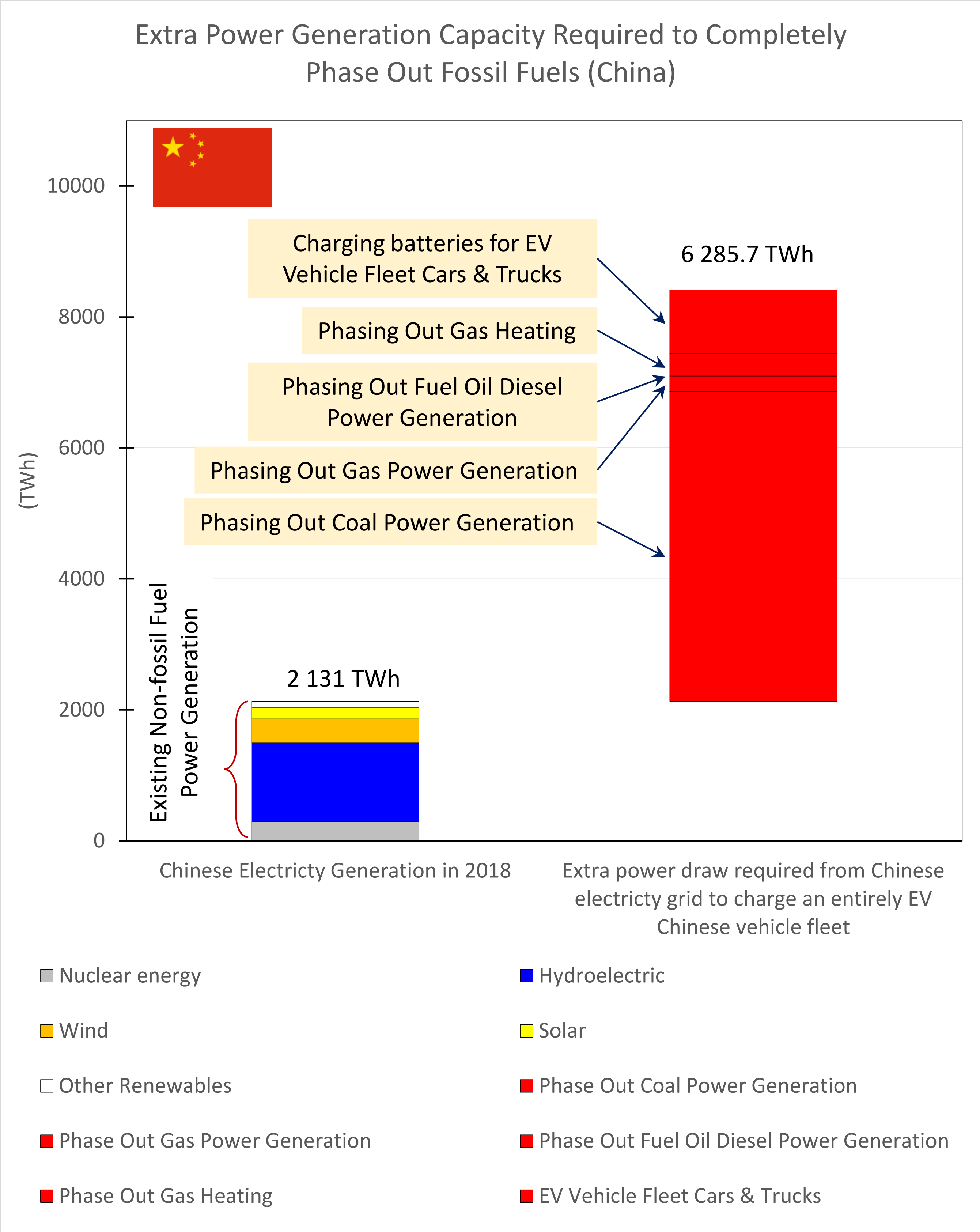


Figure 23.14. Extra capacity in the electrical power system to phase out fossil fuels in China – Part 2 (Source. for LHS column of data, BP Statistical Review of World Energy)

Table 23.8. Estimated number of new power stations to be installed in China required to phase fossil fuels entirely (Source: Appendix B, BP Statistical Review of World Energy, Global Energy Observatory)

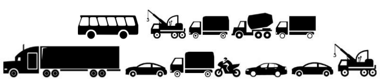
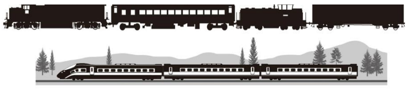
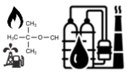
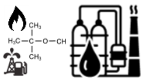
Power Generation System	Chinese electricity production in 2018 (BP Statistical Review of World Energy 2019) (kWh)	2018 ratio percent of all Chinese electrical non-fossil fuel power systems (%)	Expanded extra required annual capacity to phase out fossil fuels (kWh)	Average Plant Capacity (Global Energy Observatory) (MW)	Power Produced by a Single Average Plant in 2018 (kWh)	Estimated number of required additional new power plants of average size to phase out fossil fuels (number)
Nuclear	2.94E+11	13.72%	8.63E+11	2 046.5 MW	1.28E+10	67
Hydroelectric	1.20E+12	56.06%	3.52E+12	225.4 MW	1.33E+09	2,658
Wind	3.66E+11	17.06%	1.07E+12	37. 2 MW	8.12E+07	13,201
Solar PV	1.78E+11	8.28%	5.20E+11	33.1 MW	3.30E+07	15,742
Other Renewable	1.05E+11	4.88%	3.07E+11	76.97 MW	7.70E+07	3,986
Total (kWh)	2.15E+12		6.29E+12			35,655
Total (TWh)	2,145		6,286			

Table 23.9. Estimated number of 100 MW power storage stations to be built in China to address renewable source intermittency of supply (wind and solar) at the scope required to phase out fossil fuels entirely

Power Generation System	Expanded extra required annual Chinese capacity to phase out fossil fuels (kWh)	Storage capacity required for a 4 week period to manage winter period, with limited sun & wind (kWh)	Number of 100 MWh capacity power storage stations to meet power generation in a 4 week cycle (number)	Mass of Li-Ion batteries @230 Wh/kg (tonnes)
Wind	1.07E+12	8.25E+10	825,010	3.59E+08
Solar PV	5.20E+11	4.00E+10	400,107	1.74E+08
Total Storage Capacity	1.59E+12 1 592.7 TWh	122.5 TWh Summed Battery Capacity	1,225,117 number of storage stations	532,659,745 tonnes of batteries

23.4.4 Extra electrical power required GLOBALLY to completely phase out fossil fuels

Table 23.10. Estimated kilowatt hours needed to phase out fossil fuels entirely in the GLOBAL SYSTEM with the same scope of activity as in 2018 (World Map Image by Clker-Free-Vector-Images from Pixabay, royalty free clipart used, some purchased)

Fossil Fuel Supported Task 	Fossil Fuel	Sustainable Solution	Extra capacity required from the electric power grid at the point of application (TWh)	Extra annual capacity required to be generated at power station, accounting for 10% grid transmission loss (TWh)
ICE Car & Truck Transport (Sections 9.1 & 12) 	Oil, Petroleum, Gasoline	EV vehicles charged by non-fossil fuel generated electricity power (Section 21)	8,838.8	9,722.7
ICE Rail Transport - Freight & passenger (Sections 9.1 & 13) 	Oil, Petoleum, Diesel Fuel	EV locomotioves charged by non-fossil fuel generated electricity (Section 19)	460.0	226.6
ICE Martime Shipping (Sections 9.1 & 14) 	Oil, Petoleum, Diesel Fuel, Bunker Oil	EV maritime vessels charged by non-fossil fuel generated electricity (Section 20)	860.0	945.9
ICE Aviation (Sections 9.1 & 15) 	Oil, Petroleum, Jet fuel	No viable EV battery solution		
Electrical Power Generation (Section 8) 	Oil	Non-fossil fuel electrical power generation (Sections 3 & 8)	802.8 (direct substitution)	802.8
Petrochemical Plastic Manufacture (Section 10) 	Oil, Gas & Coal	No viable solution		
Petrochemical Fertilizer Manufacture (Section 11) 	Oil & Gas	No viable solution		
Electrical Power Generation (Section 8) 	Gas	Non-fossil fuel electrical power generation (Sections 3 and 8)	6 182.8 (direct substitution)	6,182.8
Building Heating (Sections 9.4 & 8) 	Gas	Electric heating used instead (Sections 9)	2,560.0	2,816.0
Electrical Power Generation (Sections 9.5 & 8) 	Coal	Non-fossil fuel electrical power generation (Sections 3 and 8)	10 100.5 (direct substitution)	10,100.5
Steel Manufacture (Section 9.5) 	Coal	Electric Furnace used 100% of the time (Section 9)	51.4	56.54

Sum Total to Phase out Fossil Fuels **30,853.9**

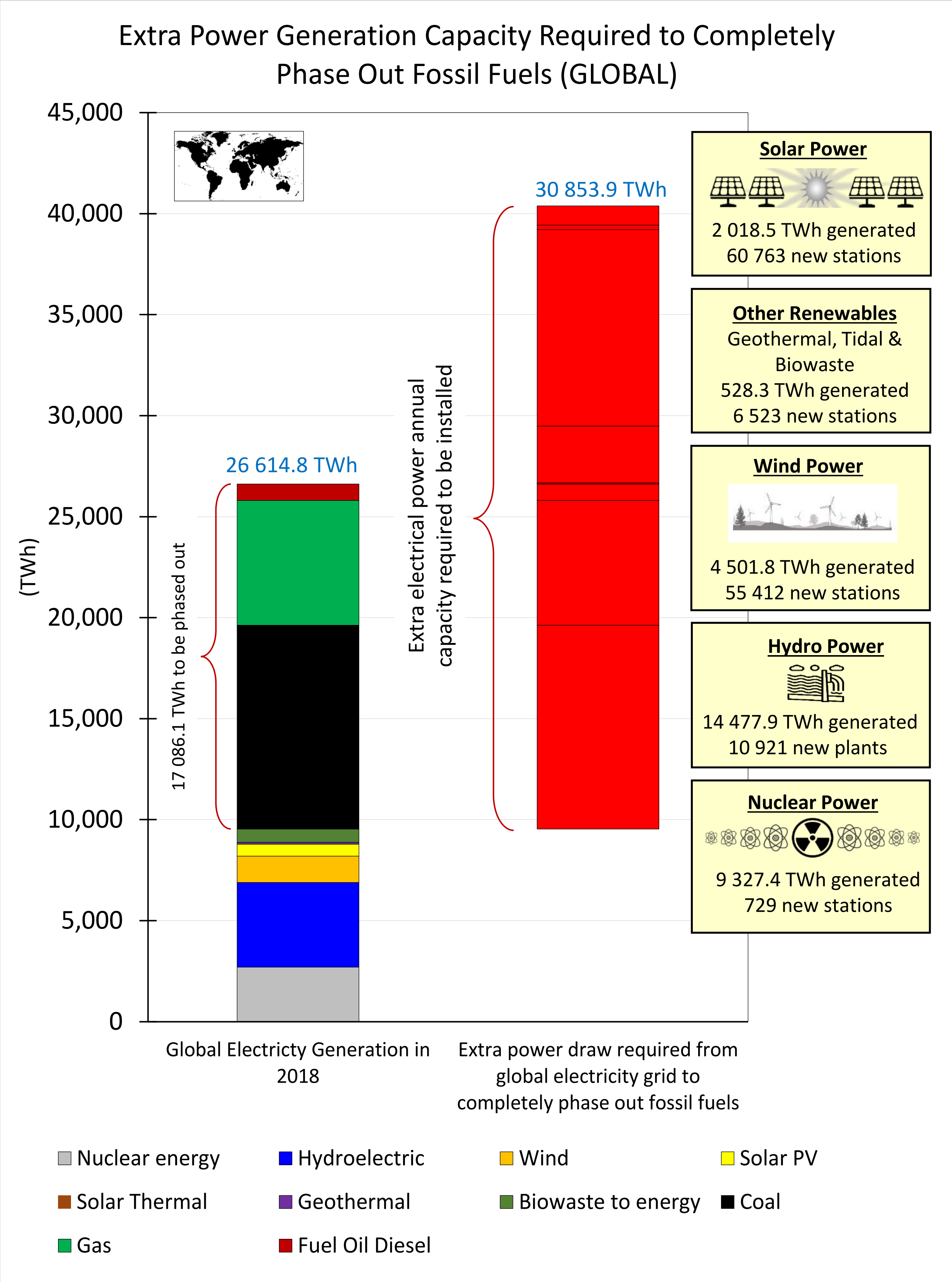


Figure 23.15. Extra capacity in the electrical power system to phase out fossil fuels in the Global System – Part 1
(Source. for LHS column of data, BP Statistical Review of World Energy)
(World Map Image by Clker-Free-Vector-Images from Pixabay)

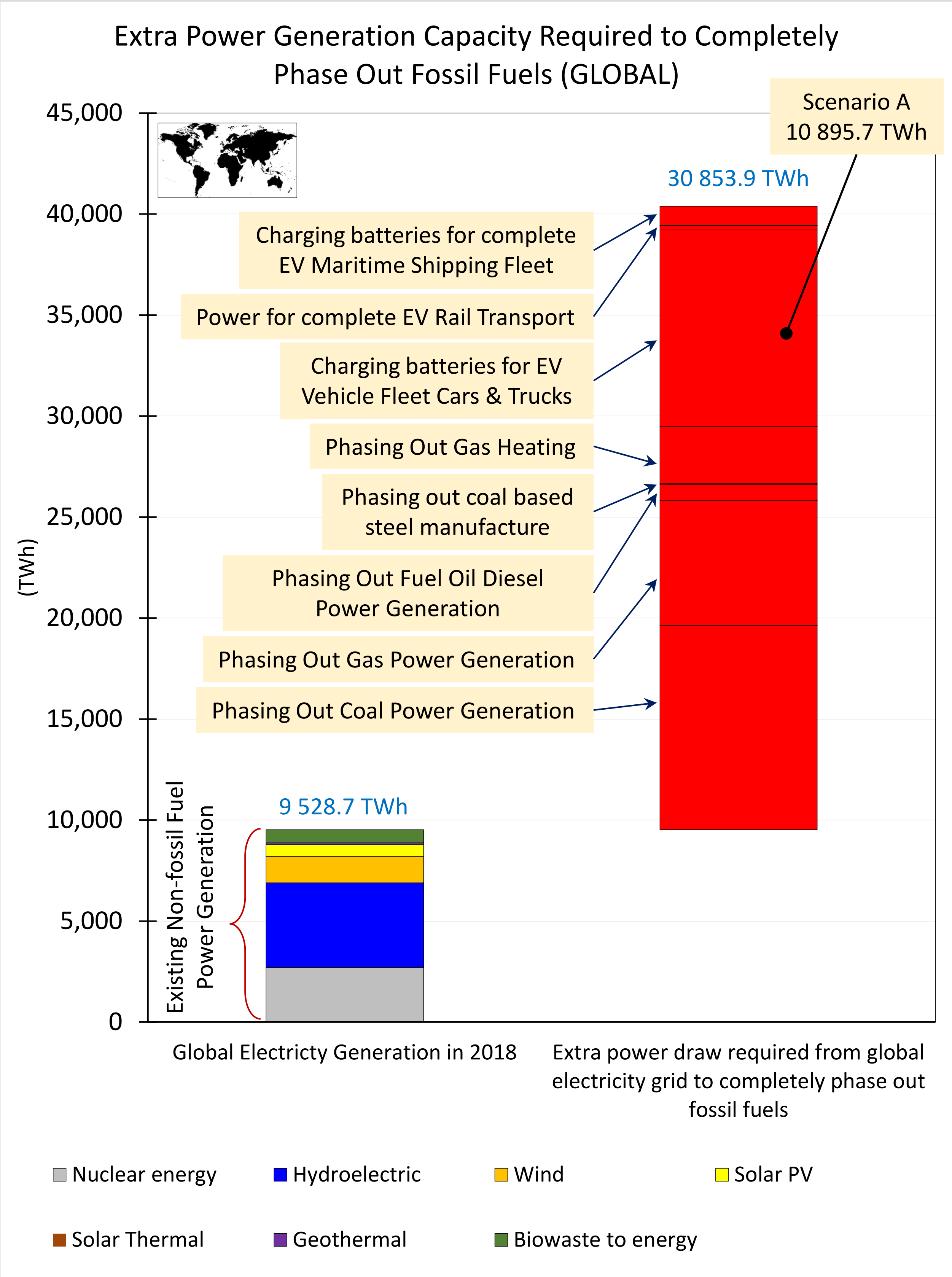


Figure 23.16. Extra capacity in the electrical power system to phase out fossil fuels in the Global System – Part 2
(Source. for LHS column of data, BP Statistical Review of World Energy)
(World Map Image by Clker-Free-Vector-Images from Pixabay)

Table 23.11. Estimated number of new power stations in the GLOBAL SYSTEM required to phase fossil fuels entirely (Source: Appendix B, BP Statistical Review of World Energy, Global Energy Observatory) (World Map Image by Clker-Free-Vector-Images from Pixabay)

Power Generation System 	Global non-fossil fuel electricity production in 2018 (Appendix B & Agora Energiewende and Sandbag 2019) (kWh)	2018 ratio percent of non-fossil fuel electrical power systems (%)	Expanded extra required annual capacity to phase out fossil fuels (kWh)	Global Number Power Plants in 2018 (Global Energy Observatory) (number)	Average Plant Capacity (Global Energy Observatory) (MW)	Power Produced by a Single Average Plant in 2018 (kWh)	Estimated number of required additional new power plants of average size to phase out fossil fuels (number)
Nuclear	2.70E+12	28.35%	8.75E+12	438	2 046.5 MW	1.28E+10	683
Hydroelectric	4.19E+12	44.00%	1.36E+13	3,163	225.4 MW	1.33E+09	10,241
Wind	1.30E+12	13.68%	4.22E+12	16048 (est)	37. 2 MW	8.12E+07	51,965
Solar PV	5.79E+11	6.08%	1.88E+12	17526 (est)	33.1 MW	3.30E+07	56,752
Solar Thermal	5.50E+09	0.06%	1.78E+10	52	76.97 MW	7.70E+07	231
Geothermal	9.30E+10	0.98%	3.01E+11	108	94.7 MW	6.03E+08	499
Biowaste to energy	6.53E+11	6.85%	2.11E+12	3,800	31.7 MW	3.46E+07	61,124
Total (kWh)	9.53E+12		3.09E+13				181,495
Total (TWh)	9,528.7		30,853.9				

Table 23.12. Estimated number of 100 MW power storage stations to be built in the GLOBAL SYSTEM to address renewable source intermittency of supply (wind and solar) at the scope required to phase out fossil fuels entirely (World Map Image by Clker-Free-Vector-Images from Pixabay)

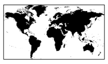
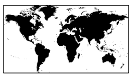
Power Generation System 	Expanded extra required annual global capacity to phase out fossil fuels (kWh)	Storage capacity required for a 4 week period to manage winter period, with limited sun & wind (kWh)	Number of 100 MWh capacity power storage stations to meet power generation in a 4 week cycle (number)	Mass of Li-Ion batteries @230 Wh/kg (tonnes)
Wind	4.22E+12	3.25E+11	3,247,459	1.41E+09
Solar PV	1.88E+12	1.44E+11	1,442,402	6.27E+08
Solar Thermal	1.78E+10	1.37E+09	13,699	5.96E+06
Total Power Storage Capacity	6.115E+12 6 114.6 TWh	470.4 TWh Summed Battery Capacity	4,703,560 number of storage stations	2,045,025,975 tonnes of batteries

Table 23.13. Estimated capacity and mass of Li-Ion batteries required in the GLOBAL SYSTEM, summed together for an entirely EV transport fleet and power storage to manage intermittent supply from wind and solar, to scope to phase out fossil fuels entirely (World Map Image by Clker-Free-Vector-Images from Pixabay)

Tasks to be powered by Li-Ion batteries 	Needed Capacity of Batteries (TWh)	Mass of batteries @ 230Wh/kg (million tonnes)	Proportion (%)
Complete EV Self Propelled Vehicle fleet	78.2	339.0	11.9 %
Complete EV Rail network	6.8	29.6	1.0 %
Complete EV Maritime vessel fleet	103.6	451.0	15.7 %
Storage Power Station to manage intermittency of supply by solar and wind over a 4 week period in winter	470.4	2,045.0	71.4 %
Sum Total	**659.0**	**2,865**	**100.0 %**

Summarizing all of the different aspects of this report is shown in Figure 23.17 in flow sheet form. If each of the fossil fuels were phased out, and a renewable sustainable substitution was, what extra power draw capacity on the electricity grid would be required?

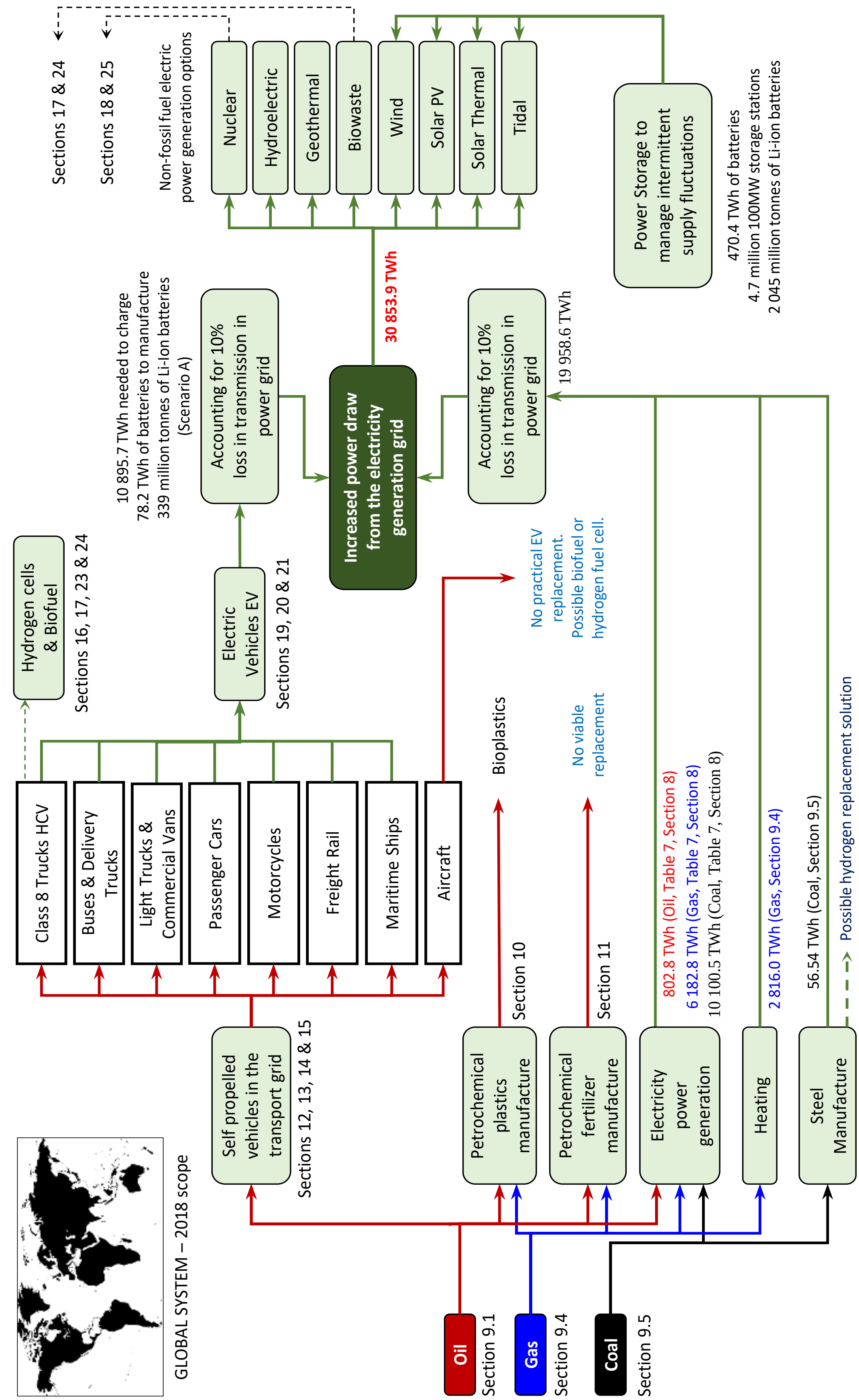


Figure 23.17. Extra power generation capacity in the global electricity grid to completely phase out fossil fuels – Scenario B (Image: Simon Michaux) (World Map Image by Clker-Free-Vector-Images from Pixabay)

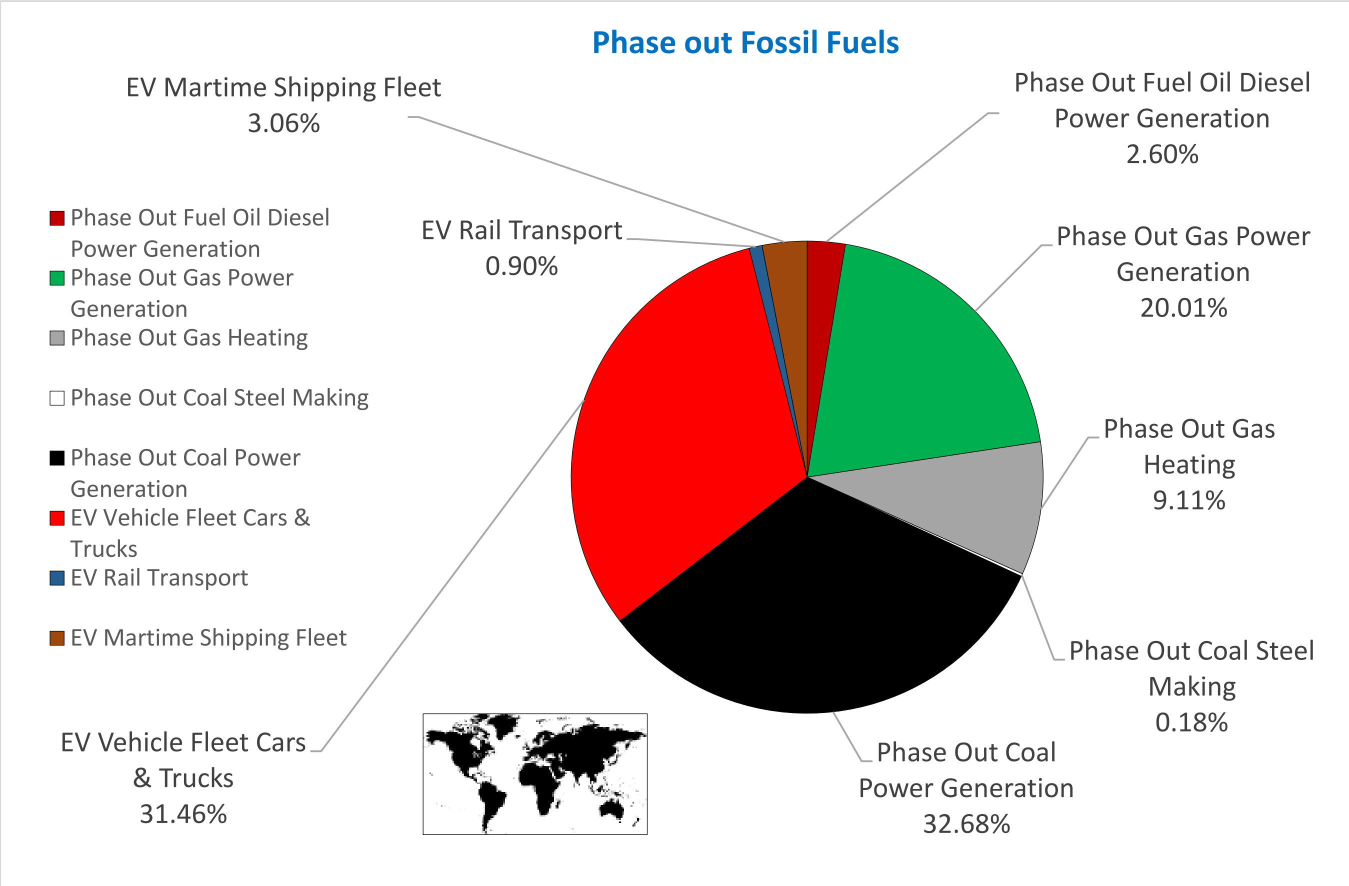


Figure 23.18. Comparison of needed extra electrical power capacity required to globally phase out all fossil fuels, by application proportion (World Map Image by Clker-Free-Vector-Images from Pixabay)

Currently energy raw materials (oil, gas and coal) are not considered to be relevant in the long term security of the European Union in the same context of the Crital Raw Materials (CRM) list compiled by the European Commisson. Uranium as an energy raw material is also not considered in this context. The general belief/assumption is that this is being tracked by others. If this is the case, the outcomes are not communicated to the relevant people developing the the rollout of the Electrical Vehicle revolution.

Today approximately 90% of all industrially manufactured products depend on the availability of oil. As the source material for various types of fuels, oil is a basic prerequisite for the transportation of large quantities of goods over long distances. Oil, alongside information technology, container ships, trucks and aircraft form the backbone of globalization and our current industrial ecosystem (Michaux 2019).

Figures 23.6 to 23.18 illustrates the point that subsituting oil is the largest and perhaps the most siginficant task ahead of us. Given that the current number of power stations globally is 46 423 (including oil, gas and coal, Table 8.3), the number of new power stations to phase out fossil fuels entirely, 181 495 new power stations are required (mostly wind and solar). This does not account for the raw material supplies to make the new systems or feed the old systems.

For this to work, a fundamental change in how our industrial systems are managed is needed. Currently, the global system is having difficulty maintaining the existing fleet of power stations. The time period required to design and construct a single coal fired power station is 3-6 years, with an incubation cycle of approximately 8 years. For a new nuclear power plant, the incubation time period is closer to 10 to 15 years. This suggests that the 2050 climate neutral target (European Commission 2019) task is much greater than current industrial planners currently understand.

23.5 Outcomes of Scenario B

The outcomes of Scenario B are summarized below. The existing global non-fossil fuel power grid has to expand from 9 528.7 TWh annual production, by adding an additional 30 853.9 TWh (annual production) in capacity. This means the global non-fossil fuel electrical power generation is required to grow to an annual capacity of 40 382.6 TWh (9 528.7 + 30 853.9). To do this, 17 086.1 TWh of fossil fuel electrical power generation (resourced with coal, gas, and oil) will have to be taken offline and substitutes phased in. In addition to this, tasks like heating of buildings (gas) and steel manufacture (coal) would need to be substituted with sustainable electric alternatives. The four largest tasks to phase out fossil fuels in the global industrial ecosystem are:

1. The largest task is replacing fossil fueled Internal Combustion Engine (ICE) vehicles, with Lithium Ion battery powered EV vehicles. An extra 10 895.7 TWh of global electrical power generation capacity is required in addition to existing capacity. The purpose of this extra capacity is to charge the required batteries, so all classes of vehicles in the global transport fleet can travel the same distance in a 365 day cycle (using 2018 scope of vehicle number, classes, and distances). This is the outcome of Scenario A in Section 21.

2. The second largest task is globally phasing out coal fired electricity generation. This would mean that 10 100.5 TWh global annual power production (using 2018 data) would have to be phased out and non-fossil fuel substitution systems of the same capacity for power generation commissioned.

3. The third largest task is globally phasing out gas fired electricity generation. This would mean that 6 182.8 TWh global annual power production (using 2018 data) would have to be phased out and non-fossil substitution systems of the same capacity for power generation commissioned.

4. The fourth largest task is globally phasing out the use of gas to heat buildings. In the Northern Hemisphere, this is a critical task to support society through the winter season. In 2018, 17% of gas (562.1 Mtoe) was used for heating applications. To phase this gas consumption out and substitute with a non-fossil application it is proposed this is to be done with electric heaters and be charged off the electric power grid. This would require an extra 2 816 TWh of electrical power generation capacity to be commissioned in addition to existing global electrical power generation capacity.

In addition to the calculations done for the global power system, the same calculations were done for the three largest economies in the global industrial economic market in 2018, United States, European Union (EU-28) and China. Each major economy had a different set of challenges.

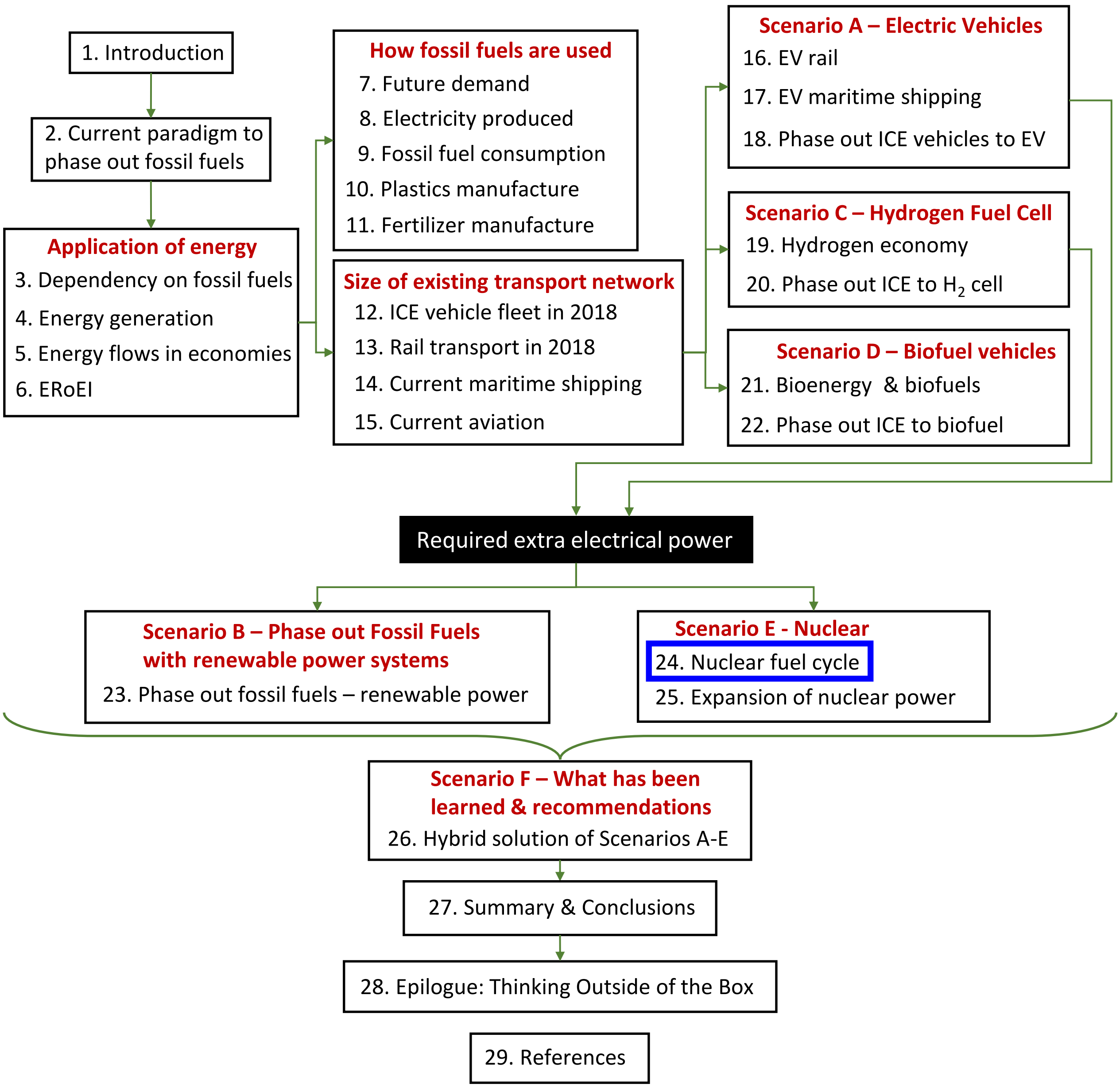
The United States covers a large geographical area and is heavily dependent on ICE vehicle transport. An extra 7 103.3 TWh of non-fossil fuel power system annual capacity is required to be commissioned. To phase out ICE vehicles and substitute with Li-Ion battery powered EV vehicles will account for 45.81% of this task.

Europe (EU-28) does not have such a large task, requiring 2 759 TWh of non-fossil fuel electrical power generation capacity is required to be commissioned. The largest EU-28 task is phasing out gas consumption for building heating, accounting for 31.06%. This will be a critical task in the winter season in particular when heating demand increases.

China is required to commission 6 285.6 TWh of annual non-fossil fuel electrical power generation. Phasing out coal fired electrical power generation accounts for 75.29% of this. This will be difficult as this is the primary power source for the largest industrial production ecosystem in the World. Industrial operations often require large quantities of electricity, that is sinusoidal quality (no power spikes) and is consistent in supply, 24 hours a day, 365 days a year. Most renewable sources like solar, tidal and wind are very intermittent. Nuclear power generation is the only non-fossil fuel power source that can do this reliably.

24 NUCLEAR POWER AS A POSSIBLE SUBSTITUTE FOR FOSSIL FUELS

Previous chapters in this report have established an estimate of what extra power generation capacity would be needed in the global electrical power grid to phase out fossil fuels. Renewable power systems like wind, solar and hydroelectricity have been proposed as substitution systems. Each of these systems have their shortcomings, ranging from being intermittent in supply to not being able to deliver concentrated quantities of electrical current in large volumes (needed to support many current industrial operations). Nuclear power has been proposed in several studies as the only viable system to replace fossil fuels for these reasons. The purpose of Section 24 is to provide a thorough background of the nuclear fuel cycle.



Assessment of the Extra Capacity Required of Alternative Energy Electrical Power Systems to Completely Replace Fossil Fuels

Approximately 10% of the world's electricity is produced from nuclear energy. This non-fossil fuel technology can deliver large volumes of concentrated power in all weather conditions. Nuclear power is the use of nuclear reactions that release nuclear energy to generate heat, which most frequently is then used in steam turbines to produce electricity in a nuclear power plant.

As of 1 January 2019, a total of 450 commercial nuclear reactors were connected to the grid globally, with a net generating capacity of 396 GWe requiring about 59 200 tonnes of uranium metal (tU) annually (OECD, 2020). The world's nuclear power plants generated a total of about 2 657 TWh of electricity in 2019.

Table 24.1. Summary statistics of globally installed capacity of nuclear power plants (Source: Global Energy Observatory 2018, Agora Energiewende and Sandbag 2019)

Nuclear Electrical Power Generation	Capacity
Installed global capacity in in 2018	431.8 (GW)
Annual global electricty production in the year 2018	2701.4 (TWh)
Maximum installed capacity	8 212.1 (MW)
Average installed capacity	2 046.5 (MW)
Minum installed capacity	20 (MW)
Standard Deviation	1339.4 (MW)
Average operating hours in practice in the year 2018	6 256 (hours)
Power produced by a single average nucelar power plant in the year 2018	12 803 184 576 (kWh) 12 803 184.6 (MWh) 12 803.2 (GWh) 12.8 (TWh)

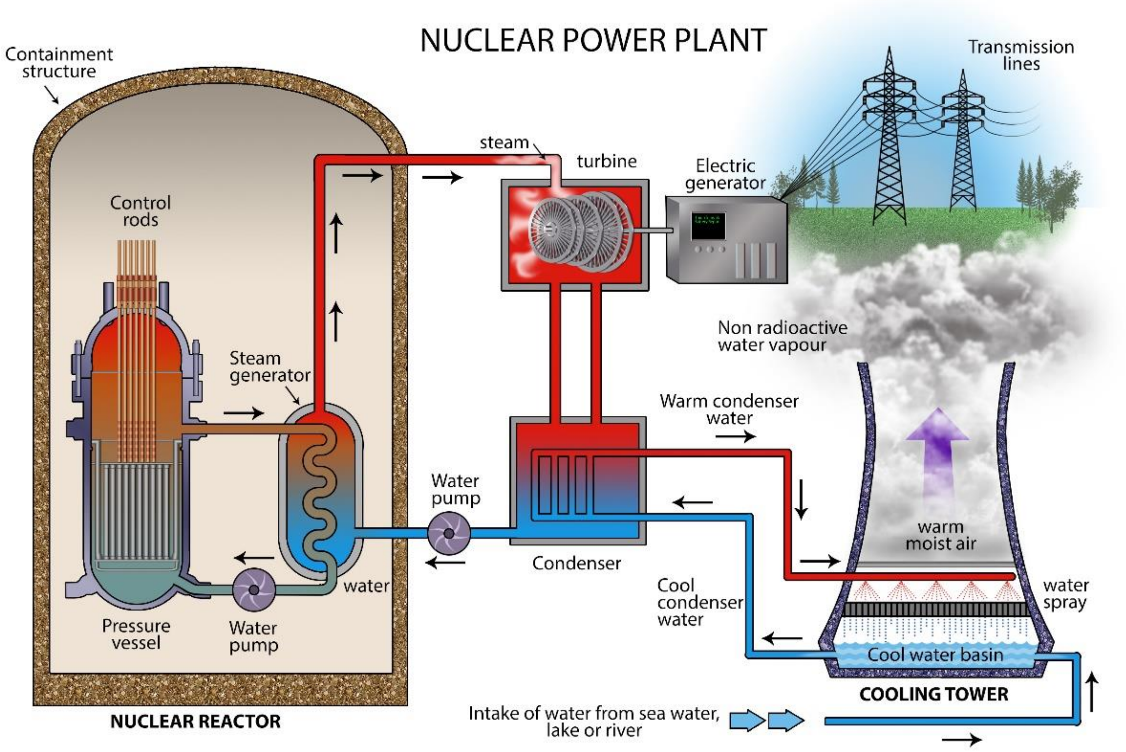


Figure 24.1. Nuclear power plant schematic
(Image: Tania Michaux)

Figure 24.2. Nuclear power plant in Switzerland
(Image by ramboldheiner from Pixabay)

Uranium is the basic fuel in nuclear reactors. Nuclear fuel is a substance that is used in nuclear reactors to produce heat to power turbines. The energy released from continuous fission of the atoms of the nuclear fuel is harnessed as heat in water to produce steam which is used to drive the turbines and produce electricity. Uranium-235, plutonium-239 and uranium-233 are the only fissile isotopes by which a nuclear fission chain reaction can be sustained, and of these three, only U-235 occurs in nature. When the unstable nuclei of these atoms are hit by a slow-moving neutron, they split, creating two new nuclei called fission products and two or three more neutrons. These neutrons then go on to split more nuclei. This creates a self-sustaining chain reaction that is controlled in a nuclear reactor, or uncontrolled in a nuclear weapon.

This heat generated in the nuclear reactor is used to generate steam, which in turn is used to turn a turbine. That turbine is used to generate electricity. For the steam turbine used to generate electricity, the Rankine thermodynamic cycle with steam temperatures at saturated conditions is used. This gives a lower thermal cycle efficiency than the high temperature coal fired power plants. Thermal efficiency is typically about one-third (33%) in light water reactors, reaching 37% in the latest pressurized water reactors (PWRs), so 3000 megawatts of thermal power (MWt) from the fission reaction is needed to generate 1000 megawatts of electrical power (MWe).Thermal cycle efficiencies are in the range of 38% (Kirschen and Strbac 2018). This value could be an overestimation, as conventionally, most nuclear power plants have an efficiency that is lower (Pohjolainen 2021).

The uranium is in the form of ceramic pellets in metal alloy tubes termed fuel rods. The fuel rods are immersed in water inside the reactor. The radiation from each fuel rod irradiates other fuel rods, which in turn creates more radiation as isotopes decay. This creates a sustaining chain reaction. The water acts as both a coolant and moderator to slow down the neutrons produced by fission to sustain the chain reaction. Control rods are made with neutron-absorbing material such as silver, cadmium, hafnium, graphite, and boron, and are inserted or withdrawn from the reactor core to control the rate of reaction, or to halt it.

In nuclear physics and nuclear chemistry, nuclear fission is either a nuclear reaction or a radioactive decay process in which the nucleus of an atom splits into smaller parts (lighter nuclei of smaller atomic mass). The fission process often produces free neutrons and gamma photons and releases a very large amount of energy even by the energetic standards of radioactive decay.

Most light water reactors (LWRs) operate through the application of the decay of the uranium isotope ^{235}U. Nuclear fuel fabricated for this purpose only has 3-5% of the ^{235}U isotope, where the remainder is ^{238}U and ^{234}U. Thus 95-97% of the mass of nuclear fuel is not useful in the generation of electricity.

A nuclear reaction in which a heavy nucleus splits spontaneously or on impact with another particle, release energy.

Only three relevant isotopes satisfy these conditions for the nuclear fission process. These are the two uranium isotopes ^{235}U and ^{233}U and the plutonium isotope ^{239}Pu. The energy liberated in the fission process is carried dominantly (about 80%) by the two fission products. This energy is relatively easily transferred to a liquid or gas, and the heat can be used to operate a generator. In order to obtain a useful amount of energy from nuclear reactions, a continuous and controllable fission must be achieved for a large number of atoms. For example, 1 020 ^{235}U atoms, i.e., 0.05 gr, the amount of ^{235}U found in 6 grams of natural uranium, need to be split every second in a 1 GWe nuclear reactor. The chain reaction is possible as each neutron induced fission reaction produces on average between 2-3 neutrons. As one neutron is needed to initiate another fission reaction, 1-2 excess neutrons minus some inevitable losses are in principle available to increase the reactor power. The introduction of neutron absorbers allows to control the reactivity of the nuclear reaction and thus to increase or decrease the reactor power. Figure 24.4 shows the decay chain for ^{235}U that is used in nuclear engineering (Littlefield & Thorley 1968).

To determine the efficiency of nuclear power generation, it is required to take into account that most nuclear reactors are light water reactors and require uranium to be enriched from 0.7% to 3-5% ^{235}U , where the energy density of natural uranium is 83,140,000/7.31 = 709 166 MJ/Kg (Feynman *et al* 1963).

The amount of energy needed for conversion, enrichment and fuel fabrication has to be taken into account. Reported values vary considerably but a value of 2000 MJ/Kg is practical (Lenzen 2008). There is also the energy needed to enrich uranium from 0.7% to 3-5% U-235. This requires approximately 7.69 separative work unit (SWU) with each SWU requiring 187KWh/SWU (Lenzen 2008) which is 5177 MJ/Kg. Taking these into account, nuclear fuel has an energy density of 701,988 MJ/Kg. Since the energy release rate in nuclear fission is extremely high, the energy transferred to steam is a very small percentage – only around 0.7%. This makes the overall plant efficiency only around 0.27 % (Lenzen 2008). All of this information should be included in an Energy Returned on Energy Invested (ERoEI) study for nuclear power generation.

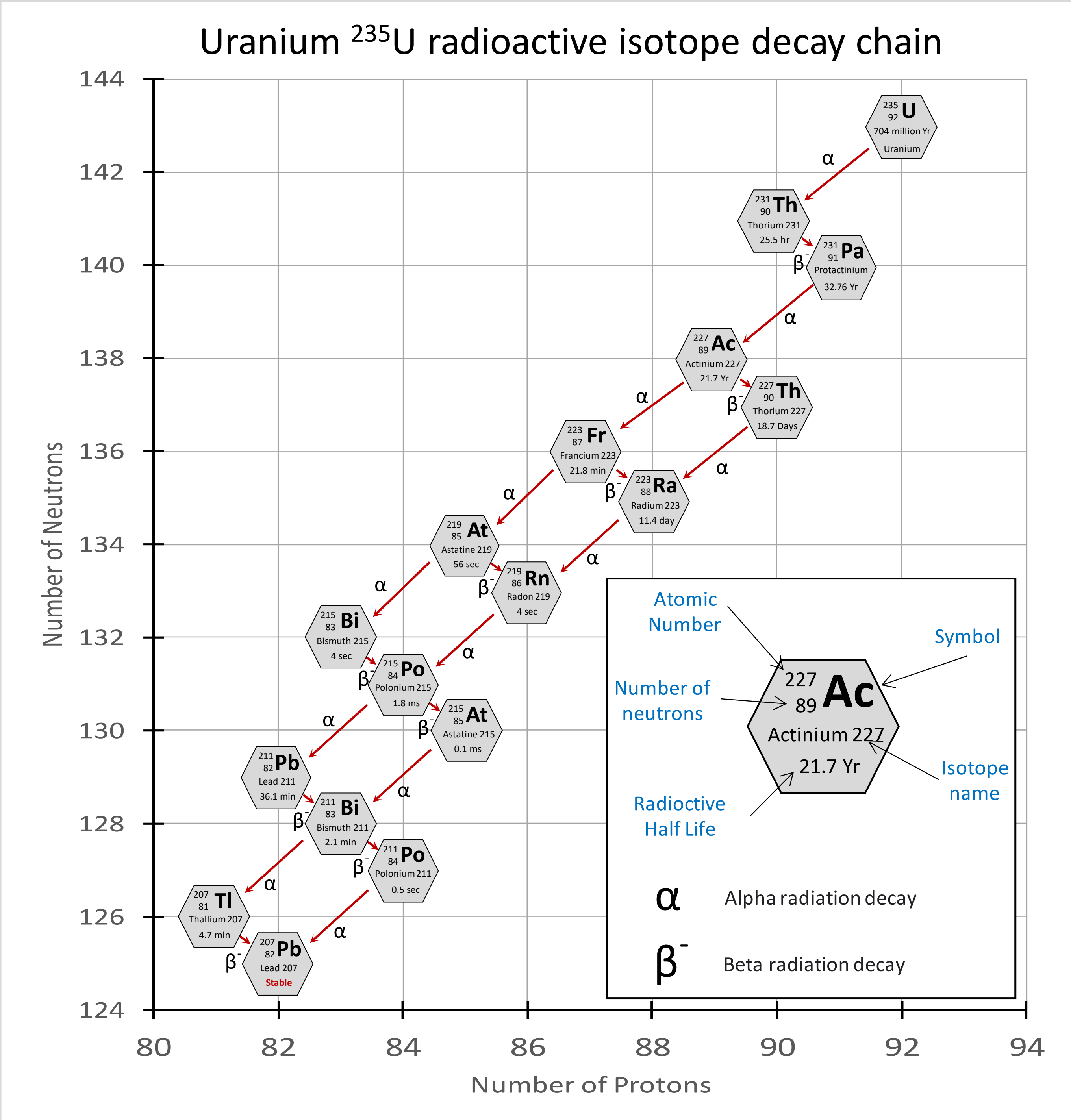


Figure 24.4. The uranium isotope ^{235}U decay chain, actinium series (Image: Simon Michaux)

24.1 Nuclear power data summary

Table 24.2. Electricity generated at nuclear power plants
(Source: NEA/OECD Uranium 2018, NEA/OECD Uranium 2020)

Country	2013 (TWh net)	2014 (TWh net)	2015 (TWh net)	2016 (TWh net)	2018 (TWh net)	2019 (TWh net)
Argentina	5.7	5.3	6.5	7.7	6.5	7.9
Armenia	2.4	2.3	2.6	2.2	1.9	2.0
Belgium	41.0	32.0	25.0	41.0	27.3	41.4
Brazil	14.6	15.4	13.9	15.0	14.8	15.2
Bulgaria	13.3	15.0	14.7	15.1	15.4	15.9
Canada	97.0	100.9	96.0	95.4	94.4	94.9
China (People's Rep. Of)	104.8	123.8	161.2	197.8	277.1	330.1
Czech Republic	29.0	28.6	25.3	22.7	28.3	28.6
Finland	22.6	22.2	22.4	22.3	21.9	22.9
France	403.7	415.9	416.8	384.0	395.9	382.4
Germany	92.1	91.8	86.8	80.1	71.9	71.1
Hungary	14.4	14.7	14.9	15.2	14.9	15.4
India	35.3	38.0	34.6	35.0	35.4	40.7
Iran, Islamic Rep. Of	3.9	3.7	3.2	5.9	6.3	5.9
Japan	0.0	0.0	9.4	17.5	49.3	65.7
Korea	133.2	150.4	164.7	154.3	127.1	138.8
Mexico	11.4	9.3	11.6	10.3	13.2	10.9
Netherlands	2.7	3.5	3.9	3.7	3.3	3.7
Pakistan	4.4	4.6	4.3	5.4	9.3	9.1
Romania	10.7	10.8	10.7	10.4	10.5	10.4
Russia	172.2	180.5	182.4	183.3	191.3	195.5
Slovak Republic	14.7	14.5	14.1	14.7	13.8	14.3
Slovenia	5.0	6.0	5.6	5.4	5.5	5.5
South Africa	13.6	14.8	11.0	15.2	10.6	13.6
Spain	54.3	54.8	54.8	56.1	53.4	55.9
Sweden	63.6	62.2	54.3	60.5	65.9	64.4
Switzerland	24.8	26.4	22.0	20.0	24.5	25.4
Ukraine	83.2	88.6	82.4	76.1	79.5	78.1
United Kingdom	64.1	57.8	63.9	65.1	59.1	51.0
United States	789.0	797.0	797.2	805.7	808.0	809.4
OECD	1,862.6	1,888.0	1,888.7	1,874.0	1,877.7	1,901.7
World Total[(a)]	2,366.5	2,431.6	2,451.3	2,473.6	2,562.7	2,657.2

(a) The following data for Chinese Taipei are included in the world total: 39.8 TWh in 2013, 40.8 TWh in 2014, 35.1 TWh in 2015 and 30.5 TWh in 2016, 26.7 TWh in 2018 and 31.1 in 2019

Source: i) government-supplied responses to a questionnaire; ii) NEA Nuclear Energy Data 2019 for OECD-NEA countries; and iii) IAEA Energy, Electricity and Nuclear Power Estimates for the Period up to 2050 (IAEA, 2019a, IAEA 2020) for non-OECD countries.

Table 24.3. Nuclear data summary (as of Jan 2019)
(Source: NEA/OECD Uranium 2018, NEA/OECD Uranium 2020)

Country	Operating Reactors	Generating Capacity (GWe net)	2018 uranium requirements (tU) +	Reactors under construction	Reactor grid connections in 2017 & 2018	Reactors shut down during 2015 & 2016	Reactors using MOX
Argentina	3	1.6	115	1	0	0	0
Armenia	1	0.4	60	0	0	0	0
Bangladesh	0	0.0	0	2	0	0	0
Belarus	0	0.0	0	2	0	0	0
Belgium	7	6.0	630	0	0	0	0
Brazil	2	1.9	400	1	0	0	0
Bulgaria	2	1.9	300 *	0	0	0	0
Canada	19	13.6	1,760	0	0	0	0
China [a]	46	42.9	6,865 *	11	10	0	0
Czech Republic	6	3.9	795	0	0	0	0
Finland	4	2.8	430	1	0	0	0
France	58	63.1	7,370	1	0	0	22
Germany	7	9.5	1,420	0	0	1	1 [(b)]
Hungary	4	1.9	325	0	0	0	0
India	22	6.3	1,100	7	0	0	1
Iran, Islamic Rep. Of	1	0.9	160	0	0	0	0
Japan	38	36.5	1,180 *	2	0	5	4
Korea	24	22.4	3,800	5	0	1	0
Mexico	2	1.6	420	0	0	0	0
Netherlands	1	0.5	65	0	0	0	1
Pakistan	5	1.3	210 *	2	1	0	0
Romania	2	1.3	230	0	0	0	0
Russia	36	27.3	5,000	6	2	1	0
Slovak Republic	4	1.8	290 *	2	0	0	0
Slovenia	1	0.7	150	0	0	0	0
South Africa	2	1.8	290 *	0	0	0	0
Spain	7	7.1	910	0	0	1	0
Sweden	8	8.6	950	0	0	1	0
Switzerland	5	3.3	385	0	0	0	0
Turkey	0	0.0	0	1	0	0	0
United Arab Emirates	0	0.0	0	4	0	0	0
Ukraine	15	13.1	2,480	2	0	0	0
United Kingdom	15	8.9	1,065	1	0	0	0
United States	98	99.0	19,340	2	0	1	0
OECD	308	291.2	41,285	14	0	10	31
World Total[(a)]	450	396.3	59,200	55	13	19	29

* NEA/IAEA estimate. +
Values rounded to 5 tU

(a) The following data for Chinese Taipei are included in the world total but not in the total for China: five NPPs in operation, 4.4 Gwe net, 705 tU as 2018 uranium requirements; two reactors under construction; none started up and one shut down during 2017 & 2018

(b) Number of units that are expected to have MOX fuel elements in the core.

Source: i) Government-supplied responses to a questionnaire; ii) NEA Nuclear Energy Data 2019 for OECD countries; and iii) IAEA Energy, Electricity and Nuclear Power Estimates for the Period up to 2050 (IAEA, 2019) for non-OECD countries.

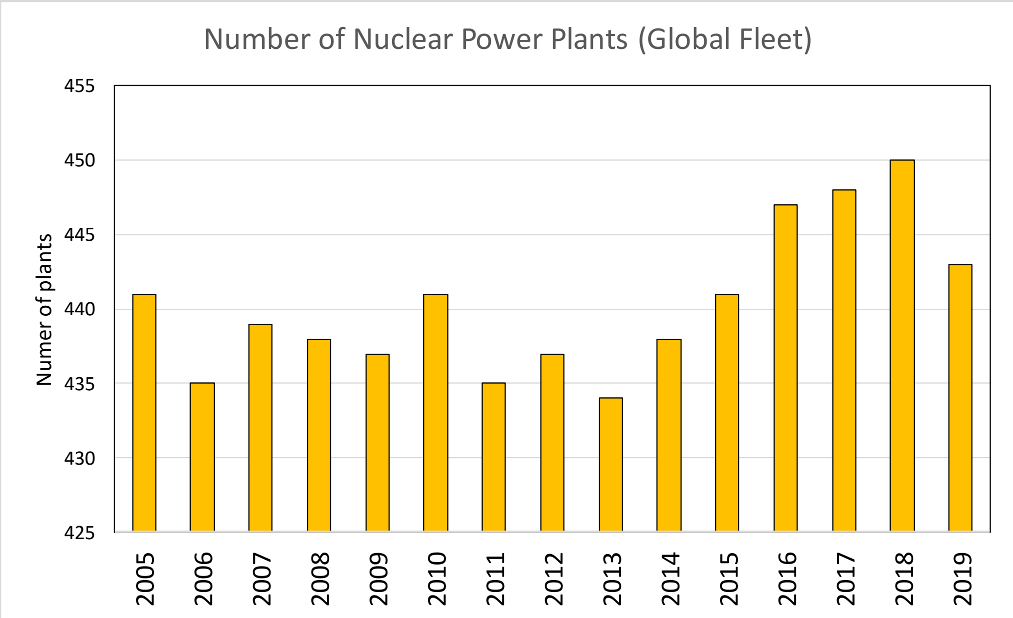


Figure 24.5. Number of nuclear power plants in operation
(Source: data from Statistica, World Nuclear Association)

Over 180 commercial, experimental or prototype reactors, over 500 research reactors, and several fuel cycle facilities have been retired from operation (World Nuclear Association). Some of these have been fully dismantled. The number of reactors connected to the power grid is shown in Figure 24.5. Between 2005 and 2019, 24 reactors were shut down and 26 new reactors were connected to the power grid. There are several different types of reactor as indicated in Table 24.4.

Table 24.4. Nuclear power plants in commercial operation or operable, Updated Nov 2020
(Source: World Nuclear Association)

Reactor Type	Acronym	Main Countries	Number	GWe	Fuel	Coolant	Moderator
Pressurised water reactor	PWR	USA, France, Japan, Russia, China, South Korea	301	286	Enriched UO_2	Water	Water
Boiling water reactor	BWR	USA, Japan, Sweden	64	65	Enriched UO_2	Water	Water
Pressurised heavy water reactor	PHWR	Canada, India	48	24	Natural UO_2	Heavy Water	Heavy Water
Advanced gas-cooled reactor	AGR	UK	14	8	Natural U (metal), Enriched UO_2	CO_2	Graphite
Light water graphite reactor	LWGR	Russia	12	8.4	Enriched UO_2	Graphite	Graphite
Fast neutron reactor	FBR	Russia	2	1.4	PuO_2 and UO_2	Liquid Sodium	none
TOTAL			441	392.8			

24.2 Global uranium reactor requirements demand

Table 24.5. Global installed nuclear power capacity and reactor uranium requirements (as of Jan 2019) (Source: NEA/OECD Uranium 2020 Resources, Production and Demand)

	World installed nuclear capacity 396 GWe net (as of 1st Jan 2019)	World urnaium requirements: 59 200 tU (as of 1st Jan 2019)
European Union	117.9	14930
North America	114.1	21520
East Asia	106.1	12550
Europe (non-EU)	44.1	7925
Middle East, Central and South Asia	8.4	1470
Central and South America	3.5	515
Africa	1.8	290

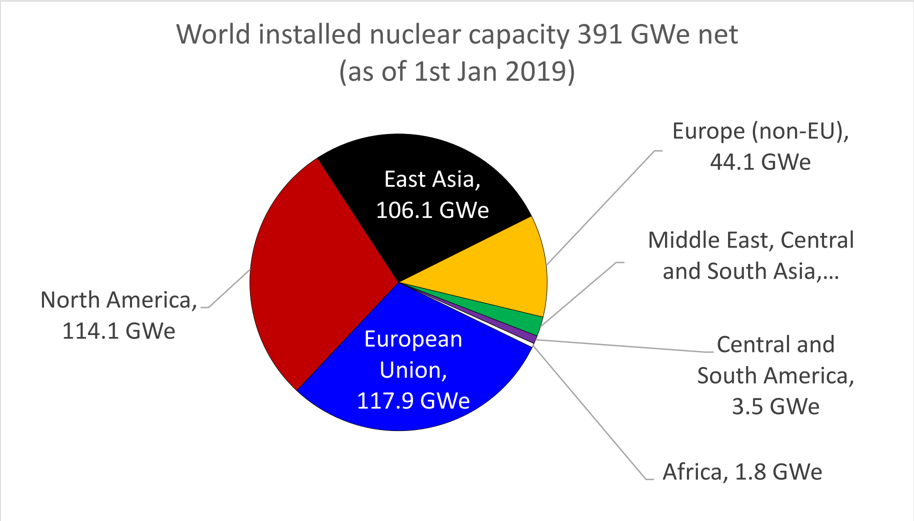


Figure 24.6. Global installed capacity for nuclear power electricity generation (Source: NEA/OECD Uranium 2020 Resources, Production and Demand)

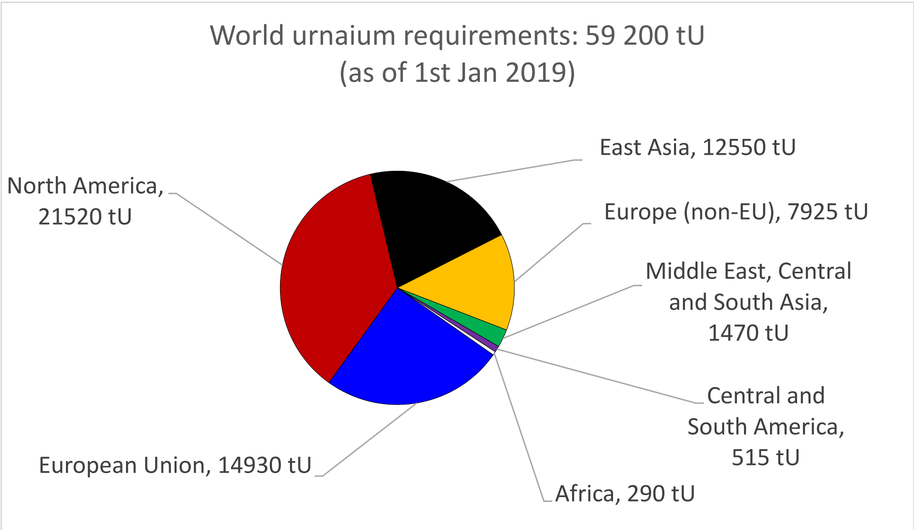


Figure 24.7. Global installed capacity for nuclear power electricity generation (Source: NEA/OECD Uranium 2020 Resources, Production and Demand)

24.3 Projected annual reactor-related uranium requirements to 2035

World reactor-related uranium requirements by the year 2040 are projected to increase to a total of between 56 640 tU/yr in the low case and 100 224 tU/yr in the high case (Table 24.6).

Table 24.6. Projected annual reactor-related uranium requirements to 2040
(Source: NEA/OECD Uranium 2020 Resources, Production and Demand)

Geographical Region	2018	2020 Low * (tonnes)	2020 High * (tonnes)	2025 Low * (tonnes)	2025 High * (tonnes)	2030 Low * (tonnes)	2030 High * (tonnes)	2040 Low * (tonnes)	2040 High * (tonnes)
European Union	14,930	18,144	18,244	15,536	16,544	13,856	17,648	9,776	17,280
North America	21,520	17,520	18,560	15,552	18,048	14,368	18,000	10,400	17,808
East Asia	12,550	17,088	17,616	16,928	20,992	18,448	27,808	21,088	40,464
Europe (non-EU)	7,925	6,928	7,392	7,008	7,552	6,720	9,408	6,992	10,560
Central and South America	515	560	560	512	560	720	896	1,024	1,712
Middle East, Central and South Asia	1,470	1,344	1,616	2,432	3,408	3,840	5,312	6,656	10,208
South-eastern Asia	0	0	0	0	0	0	0	160	480
Africa	290	288	288	288	288	480	672	544	1,712
Pacific	0	0	0	0	0	0	0	0	0
World Total	59,200	61,872	64,276	58,256	67,392	58,432	79,744	56,640	100,224

* NEA/IAEA estimate

24.4 Historical production of uranium

Figure 24.8 and Tables 24.7 and 24.8 shows the production of uranium from various sources over the previous few years.

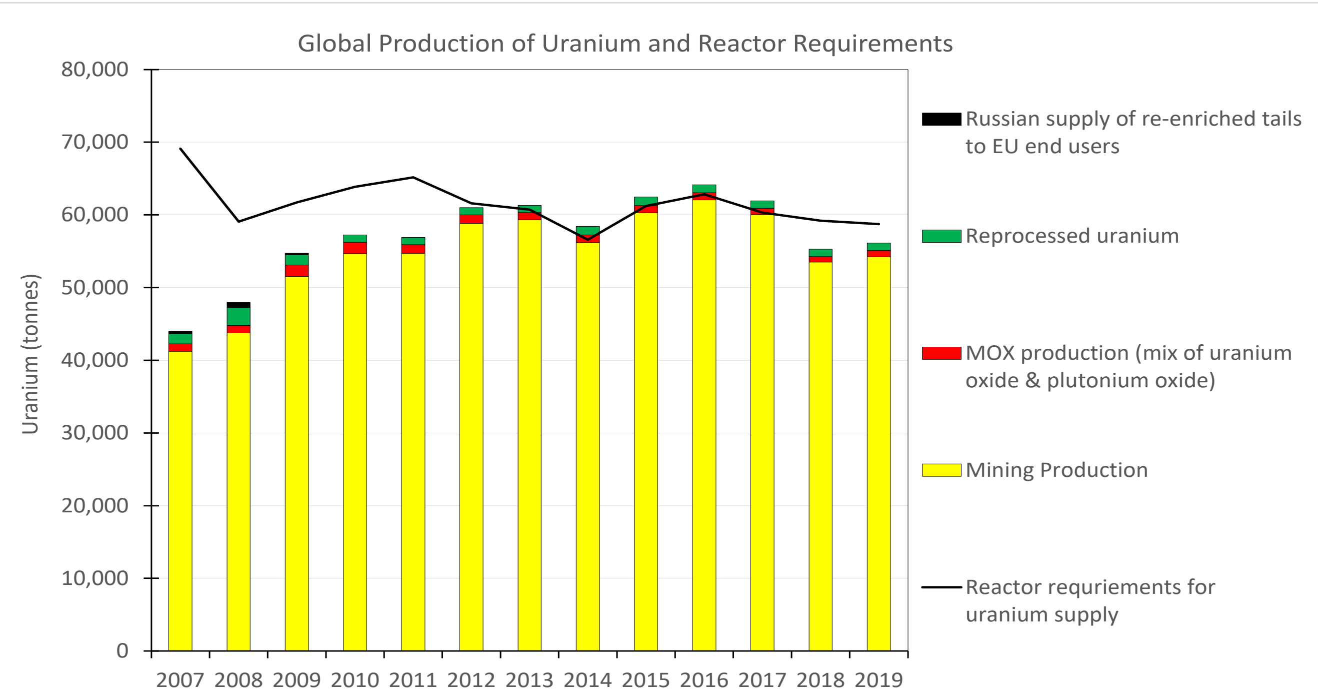


Figure 24.8. Global production of uranium from various sources 2007-2016
(Source: NEA/OECD Uranium 2020, 2018, 2016, 2014, 2011, 2009 & 2007, World Nuclear Association 2020)

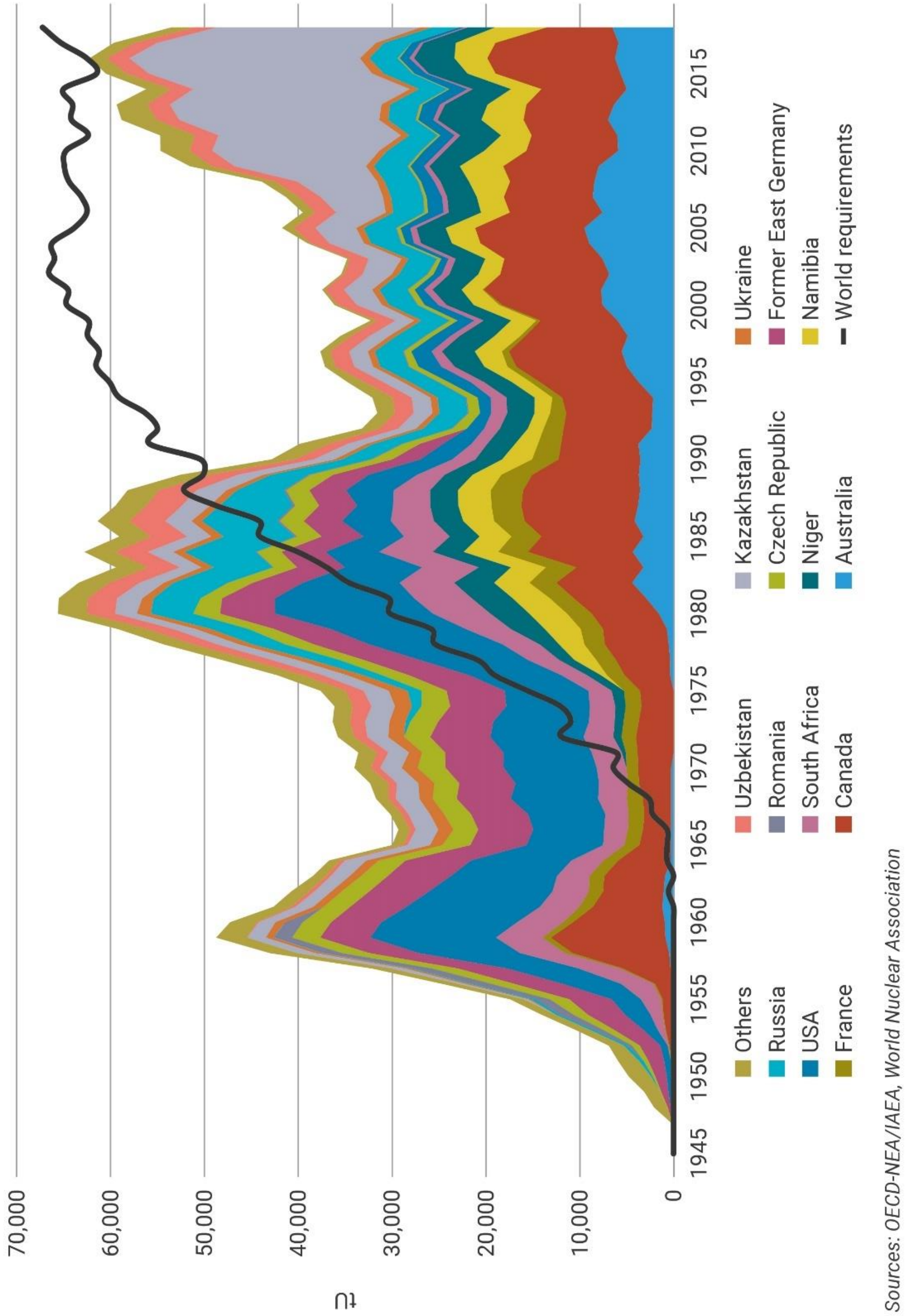


Figure 24.9. Global historical production of uranium and global reactor requirements (Source: World Nuclear Association) (Copyright granted by World Nuclear Association)

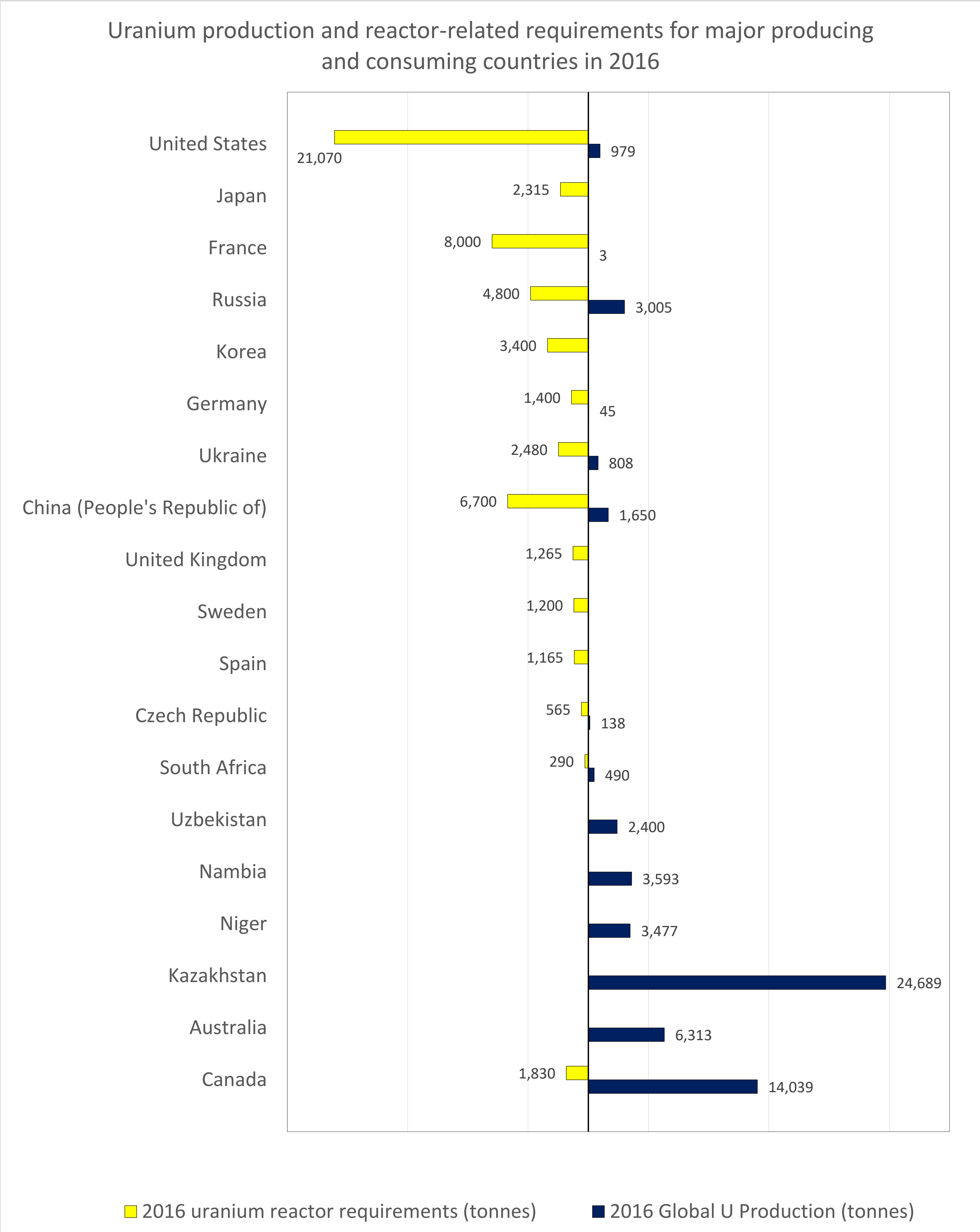


Figure 24.10. Global uranium supply and nuclear reactor requirements 2016
(Source: NEA/OECD Uranium 2018 Resources, Production and Demand, Appendix G)

Table 24.7. Historical uranium production (tonnes)
(Source: NEA/OECD Uranium 2018, NEA/OECD Uranium 2020)

Country	Pre - 2014	2014	2015	2016	2017	2018	Total to 2019	2019
Argentina	2,582	0	0	0	0	0	2,582	0
Australia	189,671	5,000	5,636	6,313	5,882	6,526	219,028	6,613
Belgium	686	0	0	0	0	0	686	0
Brazil	4,117	55	44	0	0	0	4,216	0
Bulgaria	16,364	0	0	0	0	0	16,384	0
Canada [(a)]	474,821	9,136	13,325	14,039	13,130	6,996	531,925	6,944
China	38 299*	1,550	1,600	1,650	1,580	1,620	46,299	1,600
Congo, Dem. Rep	25 600*	0	0	0	0	0	25,600 *	0
Czech Republic [(b)]	111,611	154	152	138	64	34	112,153	39
Finland	30	0	0	0	0	0	30	0
France [(d)]	80,968	3[(c)]	2[(c)]	3 [(c)]	2 [(c)]	0	80,978	2 [(c)]
Gabon	25,403	0	0	0	0	0	25,403	0
Germany [(e)]	219,653	33[(c)]	0	45 [(c)]	34 [(c)]	0	219,765	30 [(c)]
Hungary	21,065	2[(c)]	4[(c)]	4 [(c)]	3 [(c)]	5 [(c)]	21,083	3 [(c)]
India	11 013*	385*	385*	385 *	400 *	400 *	12,968	400 *
Iran, Islamic Republic of	55	11	10	8	15	15	119	21
Japan	84	0	0	0	0	0	84	0
Kazakhstan	221,926	22,781	23,806	24,689	23,391	21,705	338,298	22,808
Madagascar	785	0	0	0	0	0	785	0
Malawi	3,848	369*	0	0	0	0	4,217	0
Mexico	49	0	0	0	0	0	49	0
Mongolia	535	0	0	0	0	0	535	0
Namibia	117,173	3,246	2,992	3,593	4,221	5,520	136,744	5,103
Niger	127,960	4 223*	4,116	3,478	3,484	2,878	146,139	3,053
Pakistan*	1 394*	45*	45*	45 *	45 *	45 *	1,619	45 *
Poland	650	0	0	0	0	0	650	0
Portugal	3,720	0	0	0	0	0	3,720	0
Romania	18 819*	80*	75*	0	0	0	18,974	0
Russia	155,853	2,991	3,055	3,005	2,917	2,904	170,725	2,900
Slovak Republic	211	0	0	0	0	0	211	0
Slovenia	382	0	0	0	0	0	383	0
South Africa	158,944	566	393	490 *	308 *	346 *	161,047	346
Spain	5,028	0	0	0	0	0	5,028	0
Sweden	200	0	0	0	0	0	200	0
Ukraine	128,850	954	824	808	707	790	132,933	750
United States	371,909	1,889	1,427	979	442	277	376,923	67
USSR [(f)]	102,886	0	0	0	0	0	102,886	0
Uzbekistan	125 191*	2 700*	2 400*	3,325	3,400	3,450	140,466	3,500
Zambia	86	0	0	0	0	0	86	0
OECD	1,480,738	16,217	20,546	21,521	19,557	13,838	1,572,895	13,698
Total	2,768,421	56,173	60,291	62,997	60,025	53,516	3,061,900	54,224

Note: For pre-2010, other sources cite 6 156 tU for Spain, 91 tU for Sweden
* NEA/IAEA estimate.

(a) Includes production from refinery wastes; 14 tU in 2015 and 17 tU in 2016, 21 tU in 2017, and 61 tU recovered from cleaning out Key Lake mill circicits in 2018

(b) Includes 102 241 tU produced in the former Czechoslovakia and Czech and Slovak Federative Republic from 1946 through the end of 1992.

(c) Production from mine rehabilitation efforts only.

(d) Pre-2014 total updated after review of historic records.

(e) Production includes 213 380 tU produced in the former German Democratic Republic from 1946 through the end of 1989.

(f) Includes production in former Soviet Socialist Republics of Estonia, Kyrgyzstan, Tajikistan and partly of Uzbekistan and Kazakhstan, which shipped concentrates for processing to Kyrgyzstan and Tajikistan.

Table 24.8. Historical uranium production, 1945-2019 (Source: OECD-NEA & IAEA, Uranium 2020: Resources, Production and Demand ('Red Book'), World Nuclear Association, The Nuclear Fuel Report 2015, 2017 & 2019)

Country	Cumulative production (tonnes of U)
Canada	538,546
Kazakhstan/Uzbekistan	519,472
United States	374,858
Australia	226,289
Germany	217,161
Russia	173,780
South Africa	165,043
Niger	149,361
Namibia	141,048
Czech Republic	111,214
France	77,015
Ukraine	68,932
China	54,029
Others	148,566
Total	2,965,314

Uranium production over the period 1945-2019 can be divided into four distinct phases:

I. **A military era, from 1945 to 1960.** During the first phase of the Cold War, military requirements for uranium were a major influence on uranium production. The first nuclear power plant was connected to an electricity grid in 1954 in the town of Obninsk, near Moscow in the former USSR. To supply the manufacture of nuclear weapons, uranium production rose rapidly in the late 1950's to satisfy the requirement for highly enriched uranium and plutonium.

II. **1960 to 1980.** Uranium requirements for defense-related purposes decreased in the early 1960s and uranium demand fell sharply. As a result, uranium production declined between 1960 and 1965. The oil crisis in 1973 increased public awareness of the potential of nuclear energy as a viable alternative to fossil fuel and stimulated the demand for uranium as a source of energy. As a result, uranium production increased sharply between 1974 and 1980. Many new mines were brought into production. There were many long-term contracts agreed between electricity utilities and uranium mining in the western world. Uranium production peaked in 1980 and stayed above annual reactor requirements until 1990.

III. **1980 to 2000.** The price of uranium reached its peak in the late 1970s driven by a combination of military requirements and growth of civilian nuclear power. After this peak, uranium prices rapidly dropped and then began a steady decline over the next 20 years driven by slower than expected growth in nuclear power, because of a uranium supply over demand that resulted in the build-up of large uranium inventories, and due to impact of the Three Mile Island (1979) and Chernobyl (1986) accidents. In response to the uranium over-supply situation and declining uranium prices, uranium production declined between 1980 and 1999.

IV. **2000 to present.** At the beginning of the new millennium, there was a strong market reaction to the perception that new primary uranium production would be needed to facilitate an anticipated renaissance in nuclear growth. The uranium price hit a historic low in 2000 and thereafter began a sharp rebound as the market adjusted to the reality of potential near to mid-term uranium supply shortfalls. The uranium spot price peaked in 2007 and higher uranium prices resulted in increasing uranium exploration, the establishment of new uranium mines and growing uranium production. World uranium production increased from 32 000 tU in 1999 to 63 000 tU in 2016. After the 2007 market price peak, uranium prices rapidly dropped from USD 136/lb U_3O_8 in 2007 to USD 41/lb U_3O_8 in 2010. The Fukushima Daiichi accident (2011) was followed by even lower uranium market prices due to uncertainty about nuclear power development and the nuclear phase-out in some countries, resulting in lower uranium requirements and the slow-down in uranium mine production and uranium mine development. Global uranium production was 54 224 tU in 2019 (OECD, 2020).

24.5 Projected future production of uranium

Table 24.9 shows an estimate of future production of uranium. This estimate distinguishes between contractually committed operations of uranium production (A-II) and prospective or possible production (B-II).

Table 24.9. World uranium production capability to 2035 (in tonnes uranium/year, from RAR and Inferred Resources (IR) recoverable at costs up to $130 USD/kgU) (Source: NEA/OECD Uranium 2018, NEA/OECD Uranium 2020)

Country	2016	2025		2030		2035		2040	
	Production	A-II	B-II	A-II	B-II	A-II	B-II	A-II	B-II
Argentina*	0	0	0	0	0	0	400	0	500
Australia	6,313	5,800	5,965	3,623	6,009	3,540	10,566	3,500 *	10,500 *
Botswana*	0	0	0	0	1,440	0	1,440	0	1,440
Brazil	0	300	300	300	1,600	300 *	1,600	300 *	1,600
Canada[(a)]	14,039	18,700	18,700	12,330	18,850	12,330	18,850	12,330	18,850
China *	1,650	1,700	1,700	1,700	1,700	1,700	1,800	1,800	2,000
Czech Republic	138	50	50	50	50	30	30	20	20
Finland**	0	0	250	250	250	0	250	0	250
Greenland**	0	0	0	0	0	0	400	0	400
India *	385	700	960	960	1,300	1,300	1,300	1,300	1,300
Iran, Islamic Republic of	8	70	80	80	80	70	80	70	80
Kazakhstan	24,689	27,000	28,000	22,000	24,000	14,000	16,000	4,500	5,000
Mauritania*	0	0	0	0	0	0	400	0	600
Mongolia*	0	0	0	0	150	0	800	0	800
Namibia*	3,593	7,200	7,200	7,200	7,200	7,200	9,800	7,200	9,800
Niger*	3,477	1,700	3,500	5,000	5,000	5,000	6,800	5,000	6,800
Pakistan*	45	45	45	45	45	45	45	45	45
Russia	3,005	3,960	3,960	3,960	3,960	1,800	1,800	1,500 *	1,500 *
South Africa*	490	500	800	800	1,275	1,275	1,800	1,800	1,800
Spain *	0	0	0	0	0	0	1,670	0	1,690
Tanzania*	0	0	0	0	0	0	2,000	0	3,000
Ukraine *	808	1,500	1,500	1,700	2,000	1,700	2,000	2,000	2,000
United States [(b)]*	979	4,700	5,100	1,500	2,400	350	1,200	350	1,200
Uzbekistan*	2,400	3,500	3,500	3,000	3,000	2,500	2,500	2,000	2,000
Total	62 071[(b)]	77,425	81,610	64,238	80,309	53,140	83,551	43,715	73,175

A-II = Production capability of existing and committed production centres supported by RAR and inferred resources recoverable at <USD 130/kgU.
B-II = Production capability of existing, committed, planned and prospective centres supported by RAR and inferred resources recoverable at <USD 130/kgU.
* NEA/IAEA estimate.
** By-product production.
*** Production capability projections.
(a) For Canada, the projections consider McArthur/Key Lake operational 2025
(b) For the United States, the projections consider the hypothetical case with all the existing and idled mines being operational by 2025. Total Includes also production from mine rehabilitation.

The World Nuclear Association did a study (World Nuclear Association 2019) to, among other things, develop three future uranium supply and demand scenarios, by evaluating current and future mine production capabilities. In mid-2019, global nuclear electrical power generation capacity was 398 GWe (including Japanese reactors that taken offline and are idle). In 2019, global reactor requirements were estimated to be 67 600 tonnes of uranium. Geologically established resources of uranium globally are more than adequate to satisfy reactor requirements to well beyond 2040 for all these scenarios. Uranium resources are quite widely distributed around the world. These three scenarios were:

Scenario Reference Capacity - The Reference Scenario was considered to be the most likely outcome, where global power generation capacity was expected to rise to 462 GWe by 2030 and to 568 GWe by 2040. Global uranium reactor requirements were expected to rise to 84 850 tonnes in 2030 and 100 000 tonnes in 2040. Secondary supply of uranium provided 15% in 2019, 11% in 2025, declining to 8% in 2030 and ending up at 5% in 2040.

Scenario Upper Capacity - The Upper Scenario was considered to be the best growth case outcome for the nuclear industry, where global power generation capacity was expected to rise to 537 GWe by 2030 and to 776 GWe by 2040. Global uranium reactor requirements were expected to rise to 103 500 tonnes in 2030 and 137 600 tonnes in 2040. In this scenario, secondary supply of uranium provides 17% in 2019, 13% in 2025, declining to 10% in 2030 and ending up at 7% in 2040.

Scenario Lower Capacity – The Lower Scenario was considered to be the worst-case scenario for the nuclear industry (no new reactors connected to the power grid). In the Lower Scenario, nuclear generating capacity is effectively flat throughout the forecast period. In this scenario, secondary supply of uranium provides 13% in 2019, 9% in 2025, declining to 6% in 2030 and ending up at 3% in 2040.

Figures 24.11 to 24.13 show the outcomes of these scenarios.

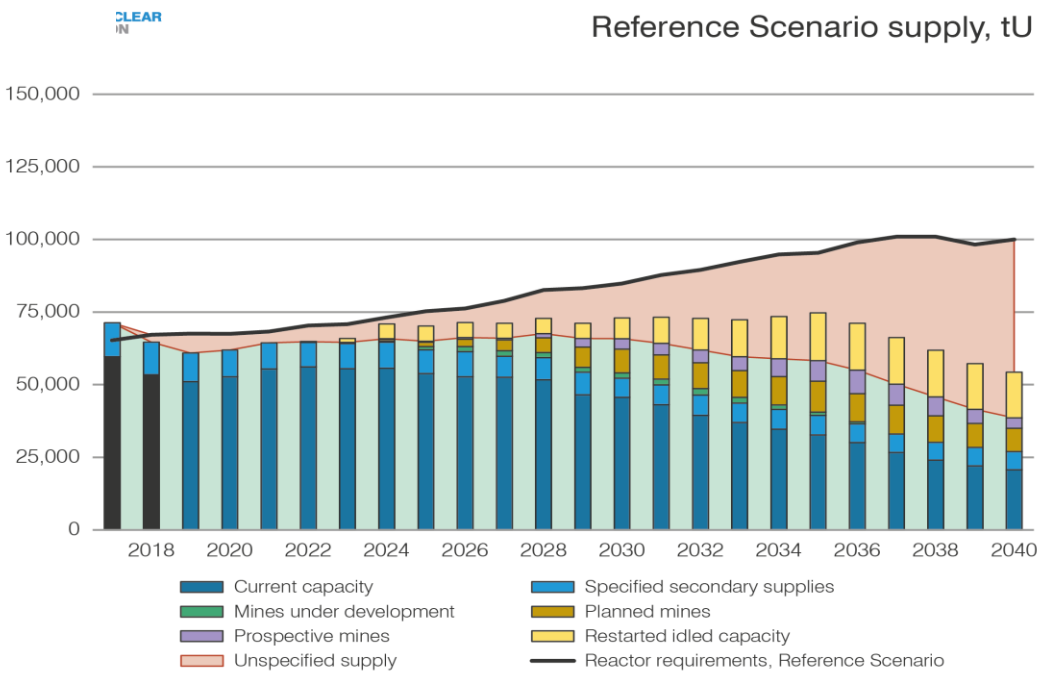


Figure 24.11. Reference scenario supply of uranium to the nuclear industry 2017 to 2040 (Source: World Nuclear Association) (Copyright granted by World Nuclear Association)

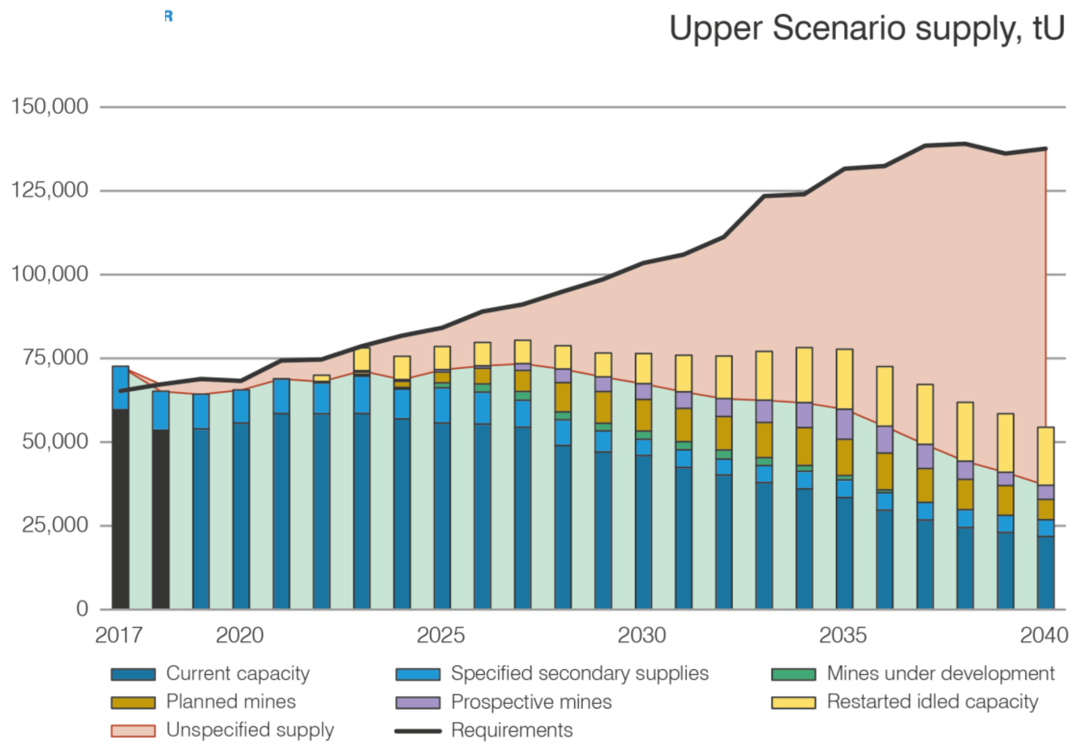


Figure 24.12. Upper scenario supply of uranium to the nuclear industry 2017 to 2040 (Source: World Nuclear Association) (Copyright granted by World Nuclear Association)

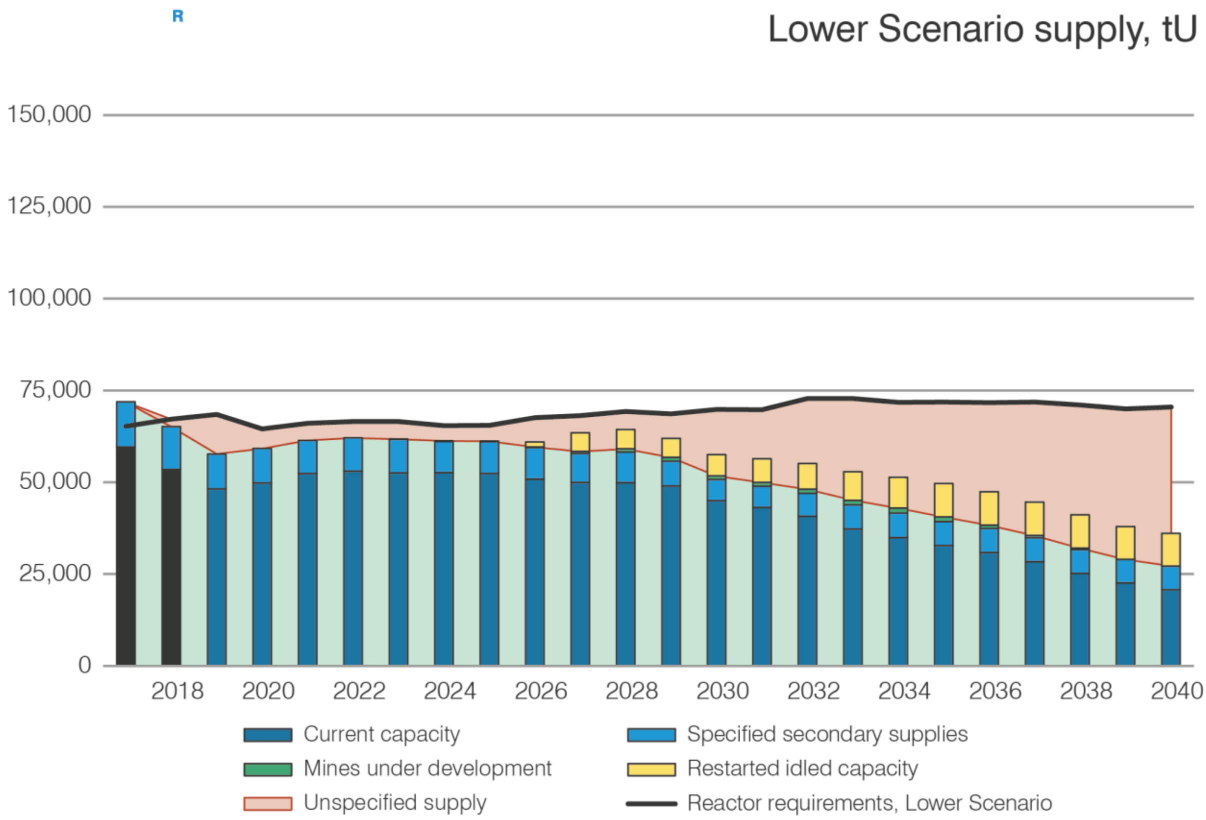


Figure 24.13. Lower scenario supply of uranium to the nuclear industry 2017 to 2040 (Source: World Nuclear Association) (Copyright granted by World Nuclear Association)

24.6 Global uranium resources

Uranium resources are classified into several subcategories. These are described below in Section 24.6.1. Defining what are economically viable resources are also classified into several sub-categories (described in Section 24.6.2). A description of these resources is shown in Section 15.6.3 and Appendix G. Table 24.10 shows the typical uranium concentrations in various natural materials.

Table 24.10. Typical natural uranium concentrations
(Source: OECD-NEA & IAEA, Uranium 2020: Resources, Production and Demand ('Red Book') World Nuclear Association, The Nuclear Fuel Report 2015, 2017 & 2019)

Natural Material	Uranium Content (ppm)
Very high-grade ore (Canada) – 20% U	200,000
High-grade ore – 2% U	20,000
Low-grade ore – 0.1% U	1000
Very low-grade ore* (Namibia) – 0.01% U	100
Granite	3-5
Sedimentary rock	2-3
Earth's continental crust (av)	2.8
Seawater	0.003

ppm = parts per million

* Where uranium is at low levels in rock or sands (certainly less than 1000 ppm) it needs to be in a form which is easily separated for those concentrations to be called 'ore' – that is, implying that the uranium can be recovered economically. This means that it needs to be in a mineral form that can easily be dissolved by sulfuric acid or sodium carbonate leaching.

Canada and Namibia represent the U grade extremes that are currently being considered for mining.

24.6.1 Definitions used in the assessment of uranium resources

Uranium is classified as a nuclear fuel, in context that it is a geological resource, not a fossil fuel (World Nuclear Association). Fossil fuels are formed from the remains of organic matter (plant, animal, and microbial) and are composed primarily of various combinations of hydrocarbons. In this report, oil, gas, and coal are treated as fossil fuels and uranium is treated as a different geological resource. The definitions and classifications for the nuclear fuel cycle and uranium resources used in this report have been drawn from the Red Book (NEA/OECD Uranium 2020 Resources, Production and Demand). The following is a description of some of these definitions.

Conventional Resources

Conventional resources are defined as resources from which uranium is recoverable as a primary product, co-product or an important by-product (e.g. from the mining of copper and gold). Conventional resources are further sub-classified, according to different confidence levels of occurrence, into four categories. How those sub-classification categories interrelate and those used in selected national resource classification systems is shown in Figure 24.14 and 24.15.

Unconventional Resources

Very low-grade resources or those from which uranium is only recoverable as a minor by-product are considered unconventional resources. For example, the uranium content of phosphate rock in Morocco (Ragheb &Khasawneh 2010).

Reasonably Assured Resources (RAR)

RAR refers to uranium deposits of known size and grade, which could be economically recovered within given production cost ranges with existing mining methods and process technology. Estimates of tonnage and grade are based on specific sample data and measurements of the deposits and on knowledge of deposit characteristics. Reasonably assured resources have a high assurance of existence. Unless otherwise noted, RAR are expressed in terms of quantities of uranium recoverable from mineable ore (see: recoverable resources).

Inferred resources (IR)

Inferred resources (IR) refers to uranium, in addition to RAR, that is inferred to occur based on direct geological evidence (OECD, 2020). This is often in extensions of well-explored deposits, or in deposits in which geological continuity has been established but where specific data, including measurements of the deposits, and knowledge of the deposit's characteristics, are considered to be inadequate to classify the resource as RAR.

Estimates of uranium content tonnage, grade, cost of extraction, and recovery are based on sampling done at other parts of the same deposit, or in deposits of similar mineralogy. This means that less reliance can be placed on the estimates in this category than on those for RAR. Unless otherwise noted, inferred resources are expressed in terms of quantities of uranium recoverable from mineable ore (see: recoverable resources).

Prognosticated resources (PR)

PR refers to uranium deposits in addition to inferred resources (IR). These resources are diagnosed as what is expected to occur in deposits which are believed to exist in well-defined geological trends or areas of mineralization with known deposits. The evidence for this assessment is mainly indirect and which are believed to exist in well-defined geological trends or areas of mineralization with known deposits. Estimates of tonnage, grade and cost of extraction are projected from known deposit characteristics. Less reliance can be placed on the estimates in this category than on those for inferred resources. Prognosticated resources are normally expressed in terms of uranium contained in mineable ore, i.e. in situ quantities.

Speculative resources (SR)

SR refers to uranium deposits in addition to prognosticated resources (PR). These are deposits that are thought to exist on the basis of indirect evidence and geological extrapolations, in deposits discoverable with existing exploration methodology. The location of deposits envisaged in this category could generally be specified only as being somewhere within a given region or geological regional structure. As the term implies, the existence and size of such resources are speculative in nature. SR are normally expressed in terms of uranium contained in mineable ore, i.e. in situ quantities. Figures 24.14 and 24.15 show how the different resource categories relate to each other and how they differ in different countries that have uranium resources.

	Identified Resources			Undiscovered Resources		
NEA/IAEA	Reasonably assured		Inferred	Prognosticated	Speculative	
Australia	Demonstrated Measured	Demonstrated Indicated	Inferred	Undiscovered		
Canada (NRCan)	Measured	Indicated	Inferred	Prognosticated	Speculative	
United States (DOE)	Reasonably assured		Estimated additional		Speculative	
Russia, Kazakhstan, Ukraine, Urbekistan	A + B + C1	C2	C2 + P1	P1	P2	P3

Figure 24.14. Approximate correlation of terms used in major resources classification systems
(Image redrawn from NEA/OECD Uranium 2020 Resources, Production and Demand)

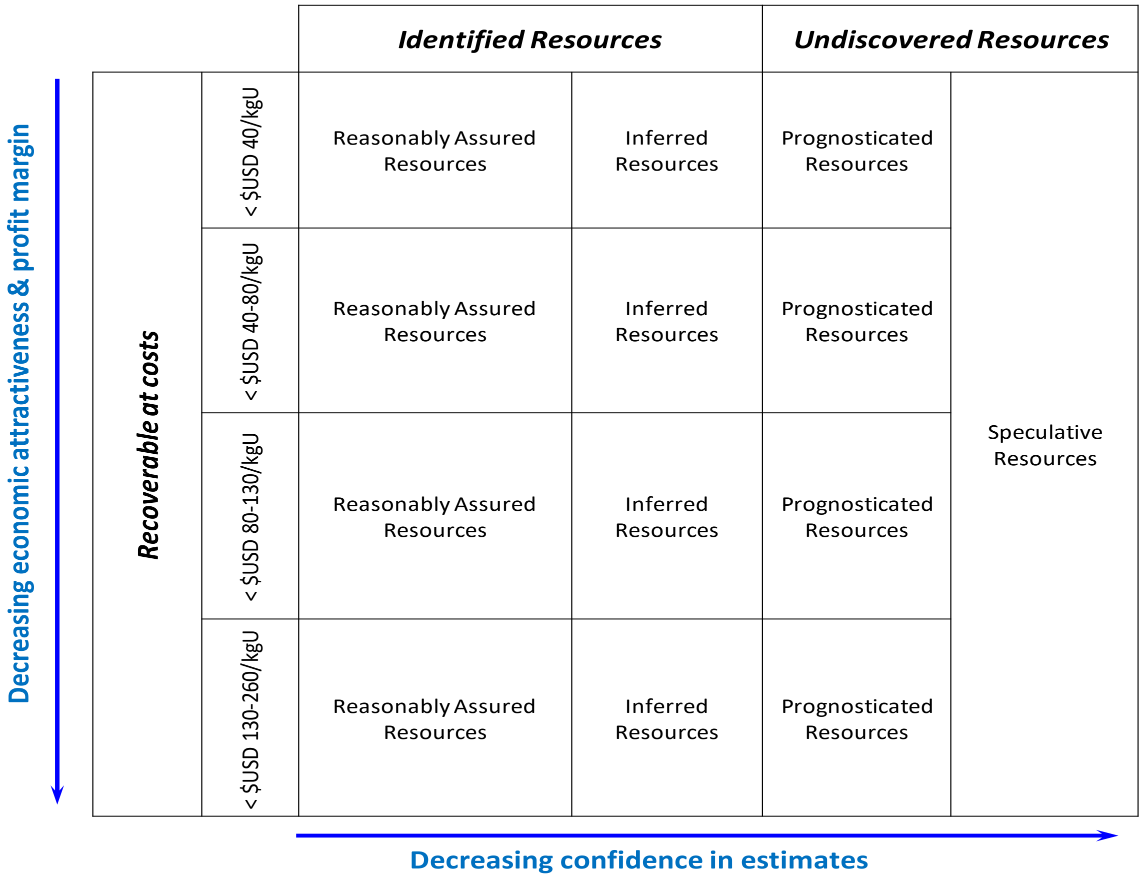


Figure 24.15. NEA/IAEA classification scheme for uranium resources
(Image redrawn from NEA/OECD Uranium 2020 Resources, Production and Demand)

24.6.2 Cost categories

The cost categories for uranium resources are estimated using United States dollars ($USD) at the time of the report analysis writing (June 2020). There are four cost categories.

- <$USD 40/kgU
- <$USD 80/kgU
- <$USD 130/kgU
- <$USD 260/kgU

All resource categories are defined in terms of costs of uranium recovered at the ore processing plant. Note: It is not intended that the cost categories should follow fluctuations in market conditions. When estimating the cost of production for assigning resources within these cost categories, account has been taken of the following costs (NEA/OECD Uranium 2020 Resources, Production and Demand):

- direct costs of mining, transporting, and processing the uranium ore
- costs of associated environmental and waste management during and after mining
- costs of maintaining non-operating production units where applicable
- in the case of ongoing projects, those capital costs that remain non-amortized
- capital cost of providing new production units where applicable, including the cost of financing
- indirect costs such as office overheads, taxes, and royalties where applicable
- future exploration and development costs wherever required for further ore
- delineation to the stage where it is ready to be mined
- sunk costs are not normally taken into consideration

24.6.3 Recoverable resources

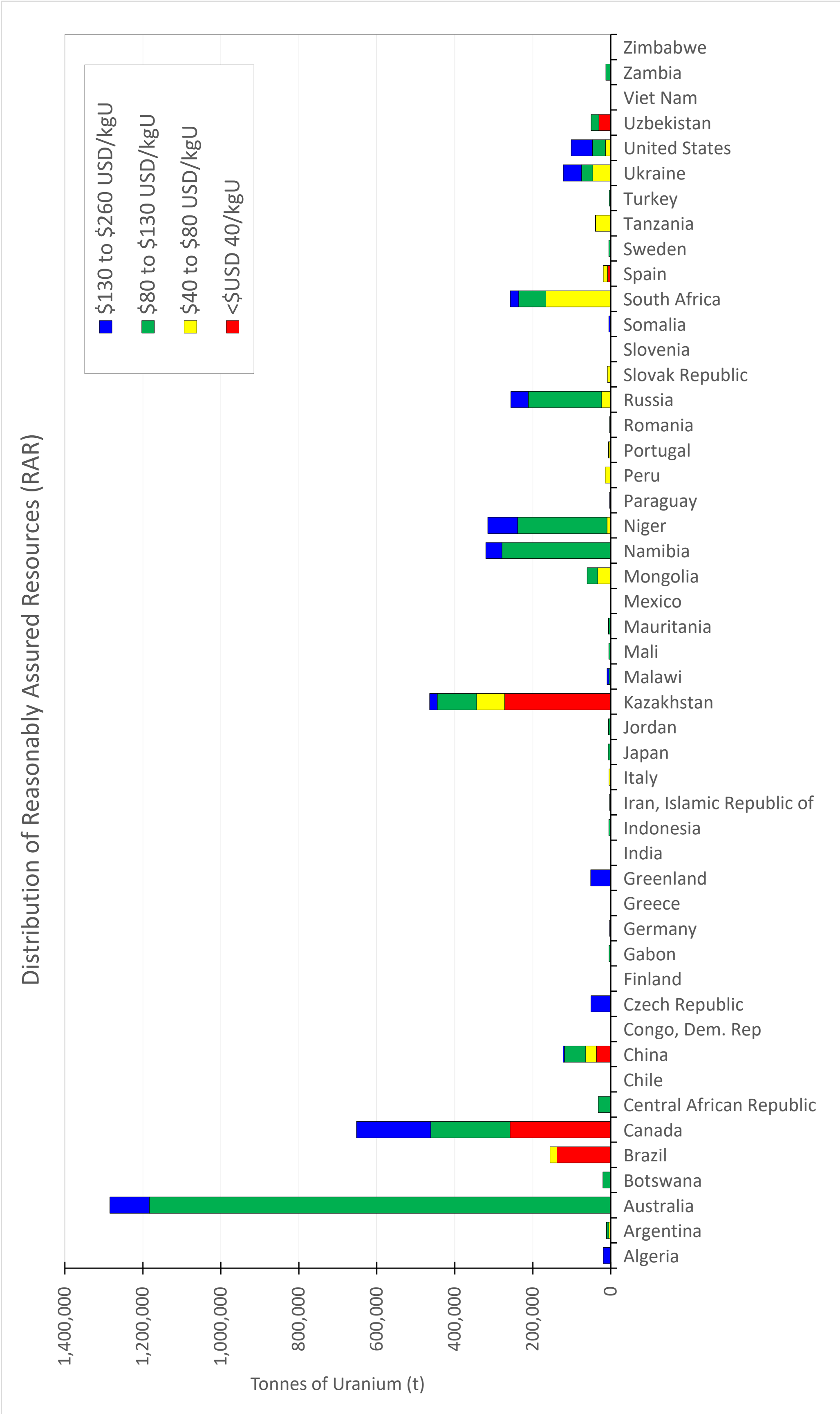
RAR and IR resource estimates are quoted in units of tonnes of uranium. An example of this is quantity of uranium recoverable from mineable ore (RAR) as opposed to quantities contained in mineable ore (or quantities in situ) (IR). The difference between these two is not considering mining, mineral processing, and refining losses. This means that expected mining and ore processing losses have been deducted in most cases. If a nation state reports its resources as in situ, and the country does not provide an estimated recovery rate/factor, the NEA/IAEA estimate assigned a recovery rate/factor to those resources based on geology and projected mining and processing methods to determine recoverable resources.

Table 24.11. Recovery rates/factors that have been applied to uranium resource estimates in NEA/OECD Uranium 2018 Resources, Production and Demand

Mining and Mineral Processing Method	Overall Recovery Rate/factor
Open pit mining with conventional mineral processing	80 %
Underground mining with conventional mineral processing	75 %
In situ leaching (acid)	85 %
In situ leaching (alkaline)	70 %
Heap leaching	70 %
Block and stope leaching	75 %
Co-product or by-product	65 %
Unspecified method	75 %

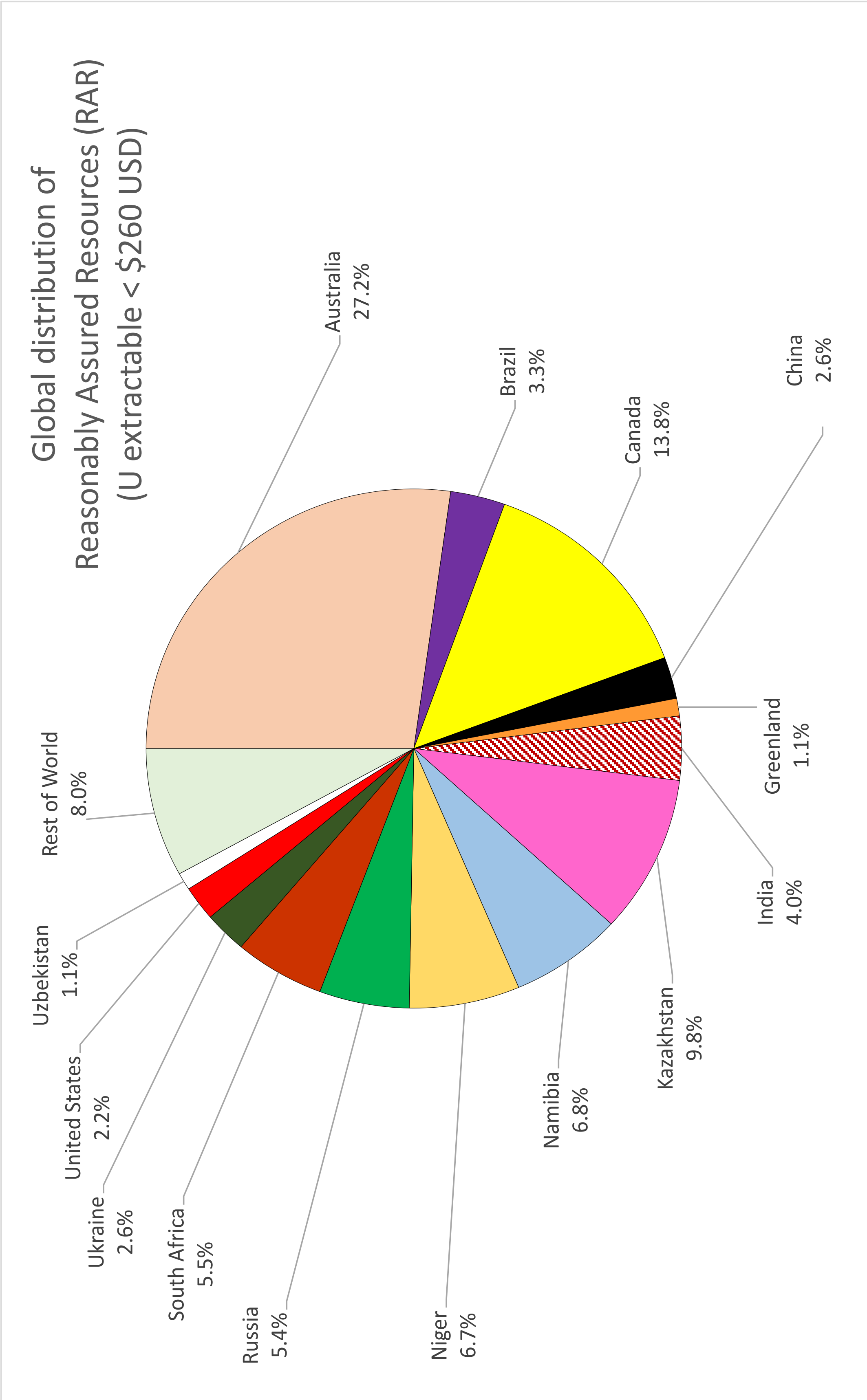
Table 24.12. Proportion of U extraction in 2019 (NEA/OECD Uranium 2020 Resources, Production and Demand)

Method of Extraction	U Production in 2015 (%)	U Production in 2016 (%)	U Production in 2017 (%)	U Production in 2018 (%)	U Production in 2019 (%)
Open pit mining with conventional mineral processing	13	12.7%	14.2%	17.1%	16.1%
Underground mining with conventional mineral processing	32	30.2%	29.2%	20.7%	20.0%
In situ leaching (acid)	48.7	50.5%	51.6%	55.2%	57.4%
In situ leaching (alkaline)	-	-	-	-	-
Co-product or by-product	6	6.0%	4.5%	6.6%	6.2%
Heap leaching	0.4	0.4%	0.3%	0.2%	0.2%
Unspecified method	0.1	0.1%	0.1%	0.1%	0.1%
Total	100.0	100.0	100.0	100.0	100.0



Reasonably Assured Resources (RAR) refers to uranium deposits of known size and grade, which could be economically recovered within given production cost ranges with existing mining methods and process technology. Estimates of tonnage and grade are based on specific sample data and measurements of the deposits and on knowledge of deposit characteristics. Reasonably assured resources have a high assurance of existence. Unless otherwise noted, RAR are expressed in terms of quantities of uranium recoverable from mineable ore.

Figure 24.17. Global distribution of Reasonably Assured Resources (RAR) at a range of extraction costs (Source: NEA/OECD Uranium 2020 Resources, Production and Demand, Appendix G)



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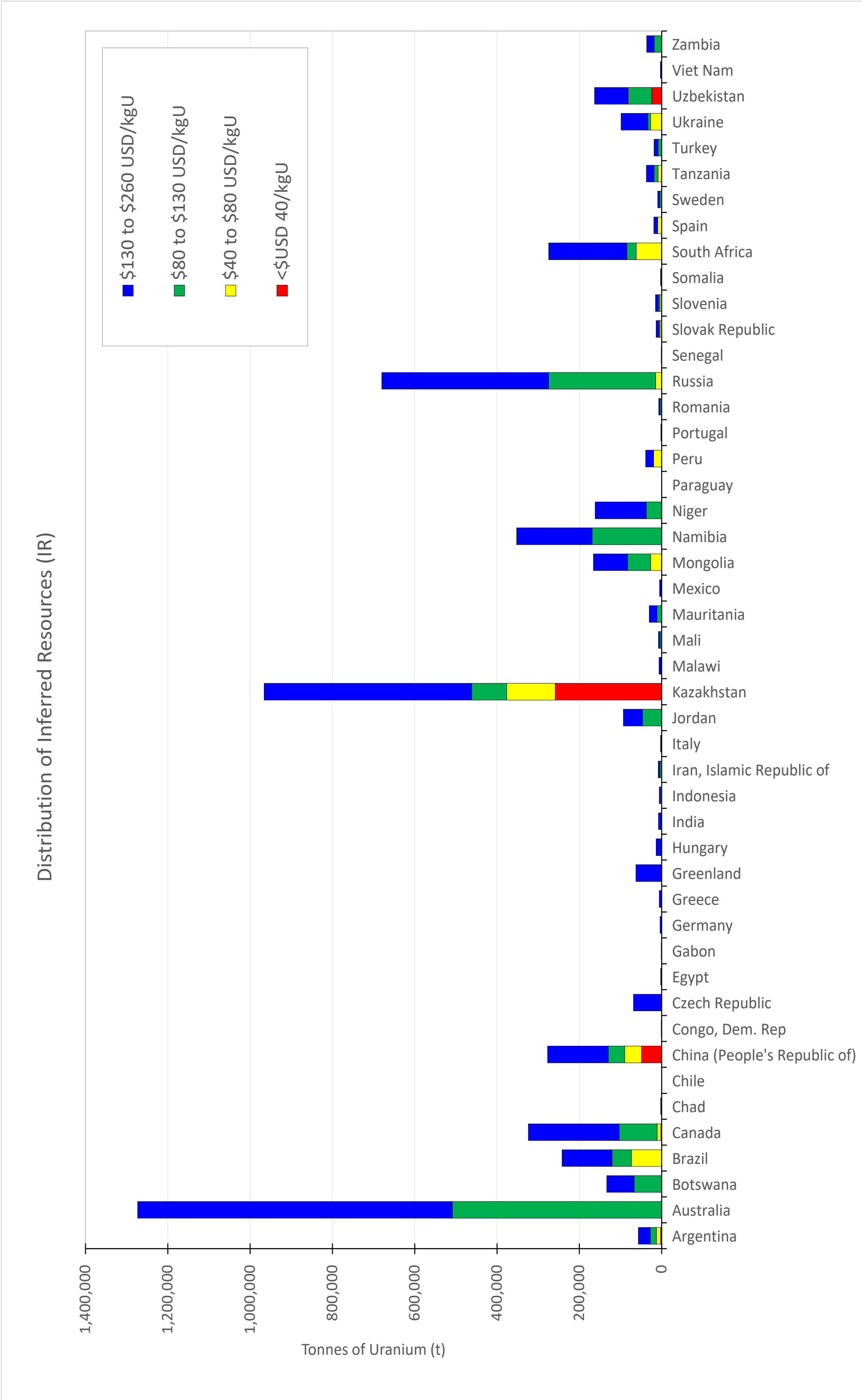

Inferred Resources (IR) IR refers to uranium deposits that are in addition to RAR deposits, that are inferred to occur base on geological measurements of geological exploration surveys. This is often in extensions of well-explored deposits, or in deposits in which geological continuity has been established but where specific data, including measurements of the deposits, and knowledge of the deposit's characteristics, are considered to be inadequate to classify the resource as RAR. Estimates of uranium content tonnage, grade, cost of extraction, and recovery are based on sampling done at other parts of the same deposit, or in deposits of similar mineralogy.

Figure 24.19. Global distribution of Inferred Resources (IR) at a range of extraction costs (Source: NEA/OECD Uranium 2020 Resources, Production and Demand, Appendix G)

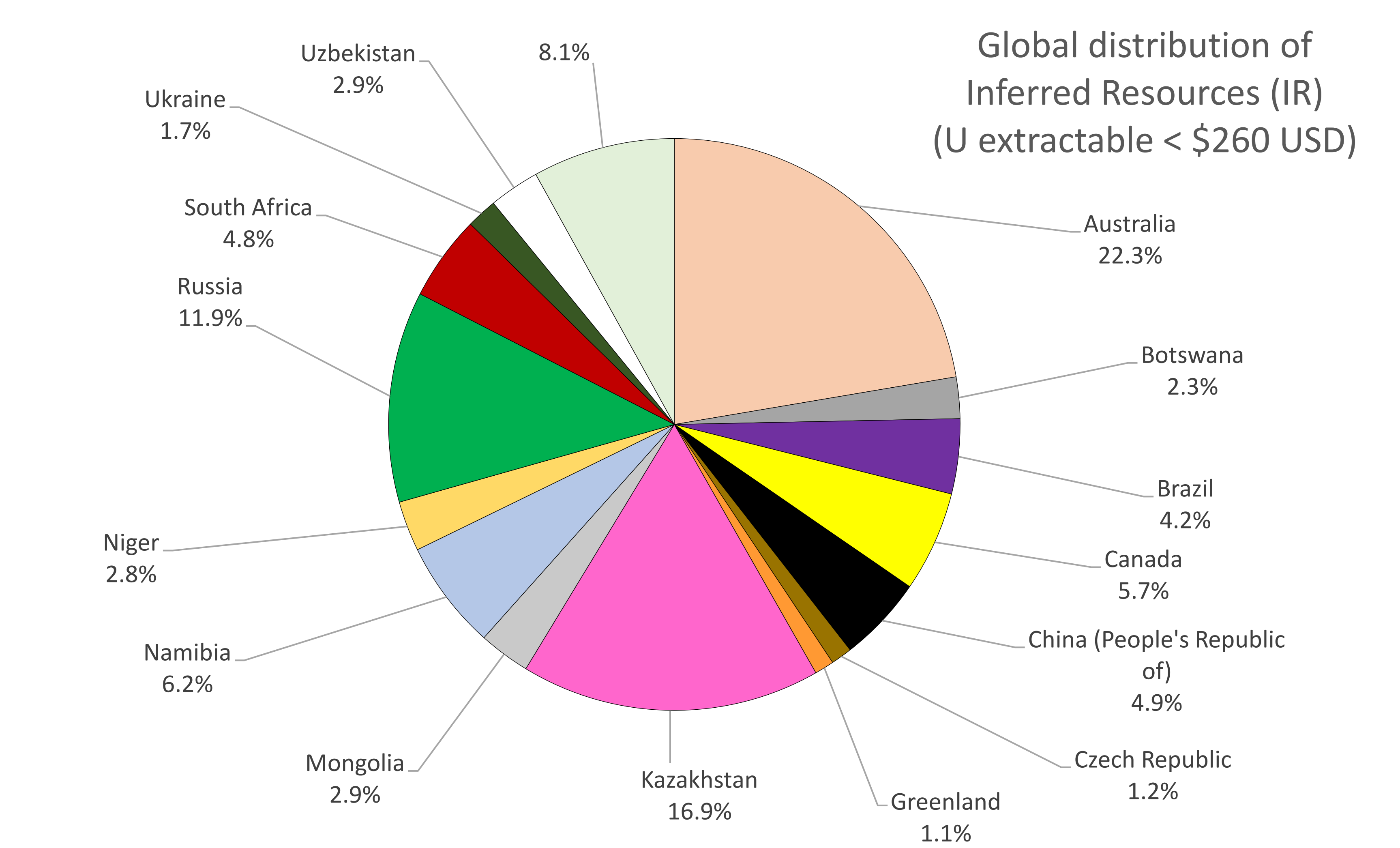

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Figure 24.20. Global distribution of Inferred Resources (IR) at a range of production costs (Source: NEA/OECD Uranium 2020 Resources, Production and Demand, Appendix G)

Table 24.13. Global uranium resources of all classifications
(Source: NEA/OECD Uranium 2018, NEA/OECD Uranium 2020)

Country	Reasonably Assured Resources (RAR) (tonnes)	Inferred Resources (IR) (tonnes)	Prognosticated Resources (PR) (tonnes)	Speculative Resources (SR) (tonnes)	Unconventional Resources (UR) (tonnes)	Sum (tonnes)
Algeria	19,500	28,800				48,300
Argentina	11,000		13,800	79,500		104,300
Australia	1,284,800	764,600				2,049,400
Botswana	20,400	66,800				87,200
Brazil	155,900	120,900	300,000	500,000	85,000	1,161,800
Bolivia				1,700		1,700
Bulgaria			25,000			25,000
Canada	652,200	220,800	150,000	700,000		1,723,000
Central African Republic	32,000					32,000
Chad		2,400				2,400
Chile	600	900	2,300	2,400	2,800	9,000
China (People's Republic of)	122,600	147,100	3,600	4,100		277,400
Columbia			11,000	217,000	60,000	288,000
Congo, Dem. Rep	1,400	1,300				2,700
Czech Republic	50,900	68,300	223,000	17,000		359,200
Egypt		1,900			100,000	101,900
Finland	1,200				1,000	2,200
Gabon	4,800	1,000				5,800
Germany	3,000	4,000		74,000		81,000
Greece	1,000	6,000	6,000		500	13,500
Greenland	51,400	62,600				114,000
Hungary		13,500	13,400			26,900
India	188,000	8,000	114,500	50,900	2,500	363,900
Indonesia	5,300	3,000	30,200			38,500
Iraq					42,800	42,800
Iran, Islamic Republic of	3,200	4,200	12,400	33,200		53,000
Italy	4,800	1,300		10,000		16,100
Japan	6,600					6,600
Jordan	6,000	46,500		50,000	123,400	225,900
Kazakhstan	464,700	504,400	230,600	300,000	58,000	1,557,700
Malawi	9,700	4,600				14,300
Mali	5,000	3,900				8,900
Mauritania	5,900	18,500		19,600		44,000
Mexico	1,800	3,200	3,000	10,000	151,000	169,000
Mongolia	60,500	82,900	21,000	1,390,000		1,554,400
Morocco					6,526,000	6,526,000
Namibia	320,700	183,500	57,000	110,700		671,900
Niger	315,500	123,900	13,600	51,300		504,300
Paraguay	2,900	700				3,600
Peru	14,000	19,400	20,000	19,700	41,600	114,700
Poland				20,000		20,000
Portugal	6,000	1,000	1,500			8,500
Romania	3,000	3,600	3,000	3,000		12,600
Russia	256,600	405,300	143,900	591,100		1,396,900
Senegal		1,100		1,500		2,600
Slovak Republic	8,800	6,700	10,900			26,400
Slovenia	1,700	7,500	1,100			10,300
Somalia	5,000	2,600				7,600
South Africa	258,000	189,700	159,000	691,000	180,000	1,477,700
Spain	19,100	9,400				28,500
Sweden	4,900	4,700			42,300	51,900
Syrian Arab Republic					80,000	80,000
Tanzania	39,700	18,500				58,200
Thailand					1,500	1,500
Turkey	3,700	9,900				13,600
Ukraine	122,100	64,800	22,500	375,000		584,400
United States	101,900				576,500	678,400
Uzbekistan	50,800	81,500	24,800			157,100
Venezuela				163,000	42,000	205,000
Viet Nam	900	3,000	81,200	321,600		406,700
Zambia	12,800	18,200				31,000
Zimbabwe	1,400			25,000		26,400
Total	**4,723,700**	**3,346,400**	**1,698,300**	**5,832,300**	**8,116,900**	**23,717,600**

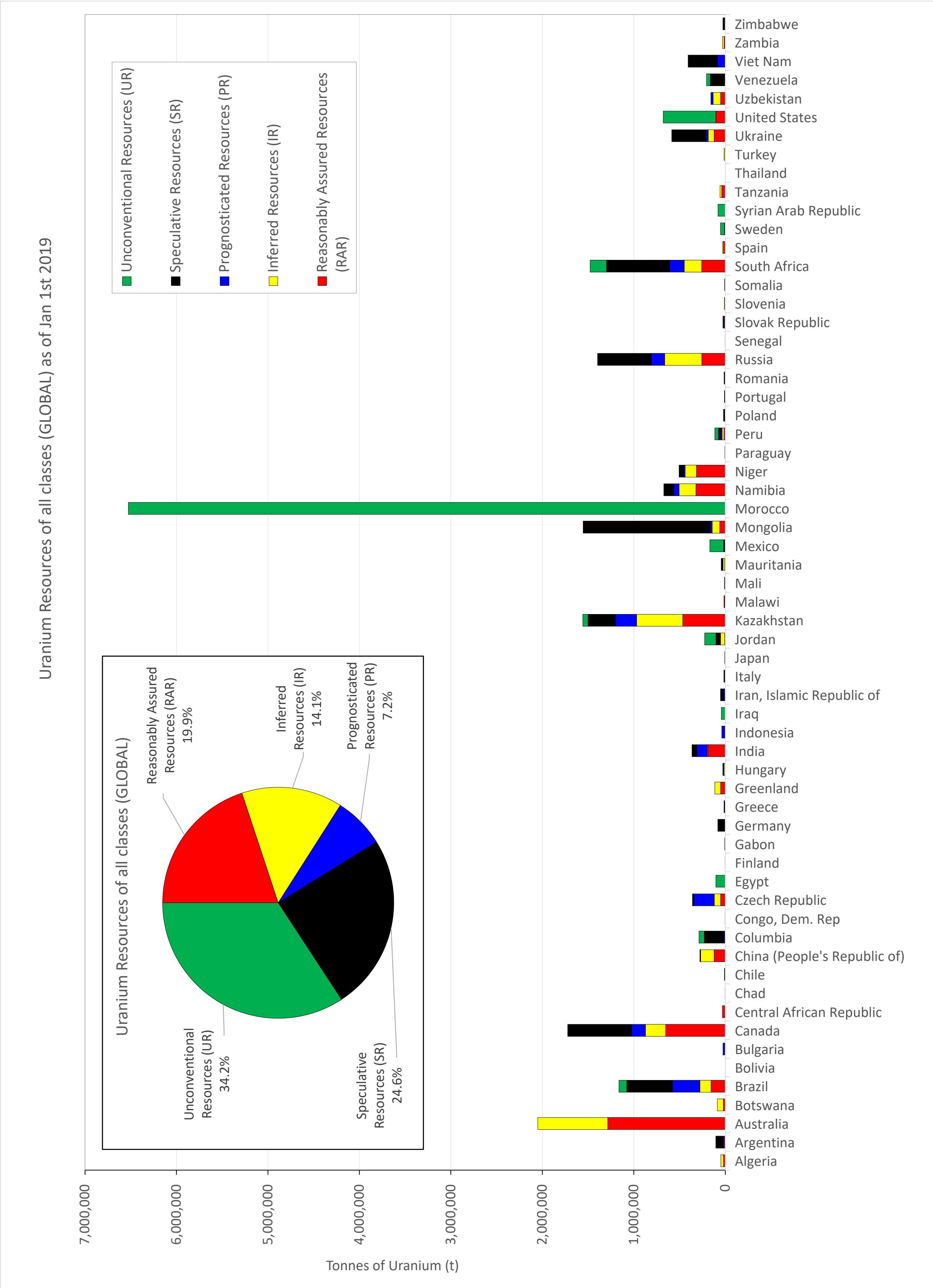

Figure 24.21. Global distribution of all resource classes
(Source: NEA/OECD Uranium 2020 Resources, Production and Demand, Appendix G)

24.7 The nuclear fuel cycle

The processes involved in mining, refining, purifying, using, and disposing of nuclear fuel are collectively known as the nuclear fuel cycle. Figure 24.22 is a compilation of the raw material systems found at various parts of the nuclear fuel cycle. Some of the numbers of waste proportions in the back end of the fuel cycle have been estimated by examining the French nuclear fuel cycle (Poinssot *et al* 2014).

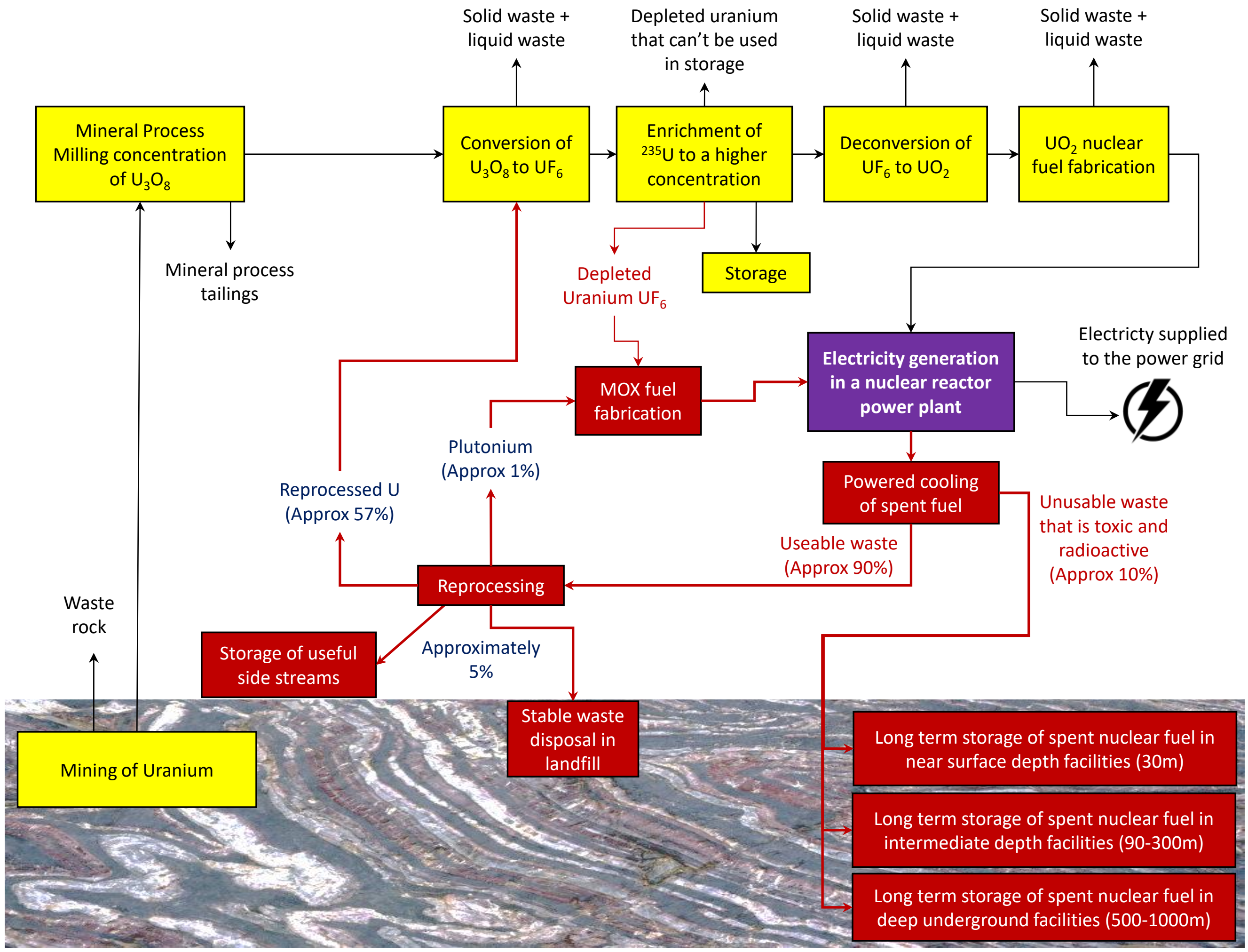

Figure 24.22. The nuclear fuel cycle
(Image: Simon Michaux)

24.8 Stages of the nuclear fuel cycle

The fuel used in a fission nuclear reactor is usually is usually based on the uranium metal oxide; the oxides are used rather than the metals themselves because the oxide melting point is much higher than that of the metal and because it cannot burn, being already in the oxidized state.

The target isotope is ^{235}U, which makes up only 0.7% of natural uranium. The uranium is mined, processed, converted, and then enriched into small ceramic pellets (approximately 10 mm in size). Those ceramic pellets are stacked together into sealed zirconium alloy metal tubes called fuel rods. Typically, more than 200 of these rods are bundled together to form a fuel assembly. A fission nuclear reactor core is typically made up of a couple hundred assemblies, depending on power level. For a typical fission nuclear reactor of capacity of 1000 MWe power generation, annual fuel consumption is approximately 18 million fuel pellets housed in over 50,000 fuel rods (approximately 27 tonnes of uranium).

The fuel used by a nuclear reactor is made with the following steps.

1. Uranium mining: uranium ore is mined.

2. Uranium milling: mineral processing is applied to the uranium ore to create uranium oxide concentrate (U_3O_8), also known as yellow cake.

3. Conversion: uranium concentrate must be **converted** into uranium hexafluoride (UF_6). The most industrially common process to do this is called the 'wet process'. The concentrate is dissolved in nitric acid. The product solution of uranyl nitrate $UO_2(NO_3)_2.6H_2O$ is fed into a solvent extraction process. This countercurrent solvent extraction process uses tributyl phosphate dissolved in kerosene. The uranium is collected and then concentrated by evaporation, then calcined to produce UO_3. This UO_3 is then reacted in kiln with gaseous hydrogen fluoride (HF) to form uranium tetrafluoride (UF_4), which is later transformed into uranium hexafluoride, UF_6 (Source: World Nuclear Association 2019).

4. Enrichment: uranium hexafluoride (UF_6) is then subject to **enrichment** which increases the 235U concentration from 0.7% to 3-5%. The uranium hexafluoride is fed into a series of centrifuges in gaseous form, which separates the isotopes ^{235}U from the atomically heavier ^{238}U isotopes (IAEA 1994). The gas centrifuge enrichment process uses several rotating cylinders in series and parallel formations. The machines are interconnected to form trains and cascades. When rotated at high speeds—from 50,000 revolutions per minute (rpm) to 70,000 rpm. The heavier UF_6 gas molecules (containing ^{238}U isotopes) move toward the outside of the cylinder, while the lighter molecules, containing ^{235}U, remain closer to the center.

   The centrifuge process has two product streams. One stream is enriched in ^{235}U. The other stream (often called centrifuge tails, or depleted uranium DU) contains a lower concentration of ^{235}U. For fission light water reactor (LWR) fuel, the uranium is enriched to various levels up to a target 3-5% ^{235}U. For a pressurized heavy water reactor (PHWR) fuel is usually natural uranium (0.7% of ^{235}U).

5. Fuel fabrication: the UF_6 gas is precipitated into a UO_2 powder. This power is compacted into ceramic pellets approximately 10 mm in size. Those ceramic pellets are packed into zirconium alloy tubes (approximately 4 m in length). The outcome is a fuel rod which are batched into nuclear fuel assemblies.

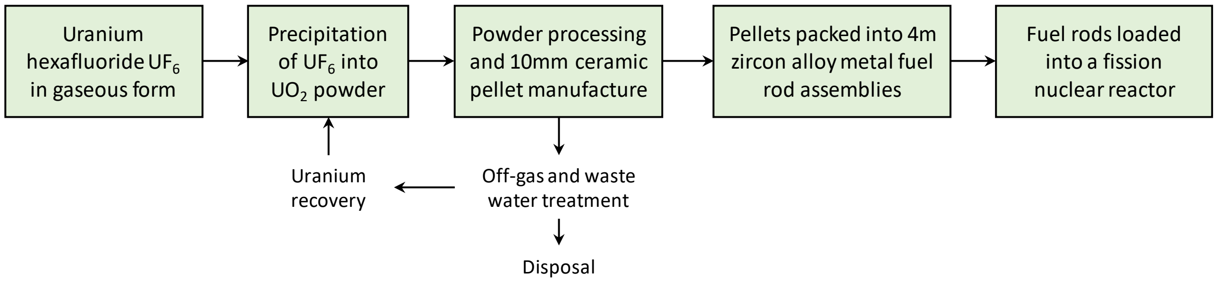

Figure 24.23. Nuclear fuel fabrication
(Image: Simon Michaux)

24.8.1 *Conversion*

Figure 24.24 shows the global supply and demand scenarios for the conversion of uranium concentrate to uranium hexafluoride (UF_6) and shows the base reference scenario for future global demand for uranium hexafluoride, developed by the WNA (World Nuclear Association 2019).

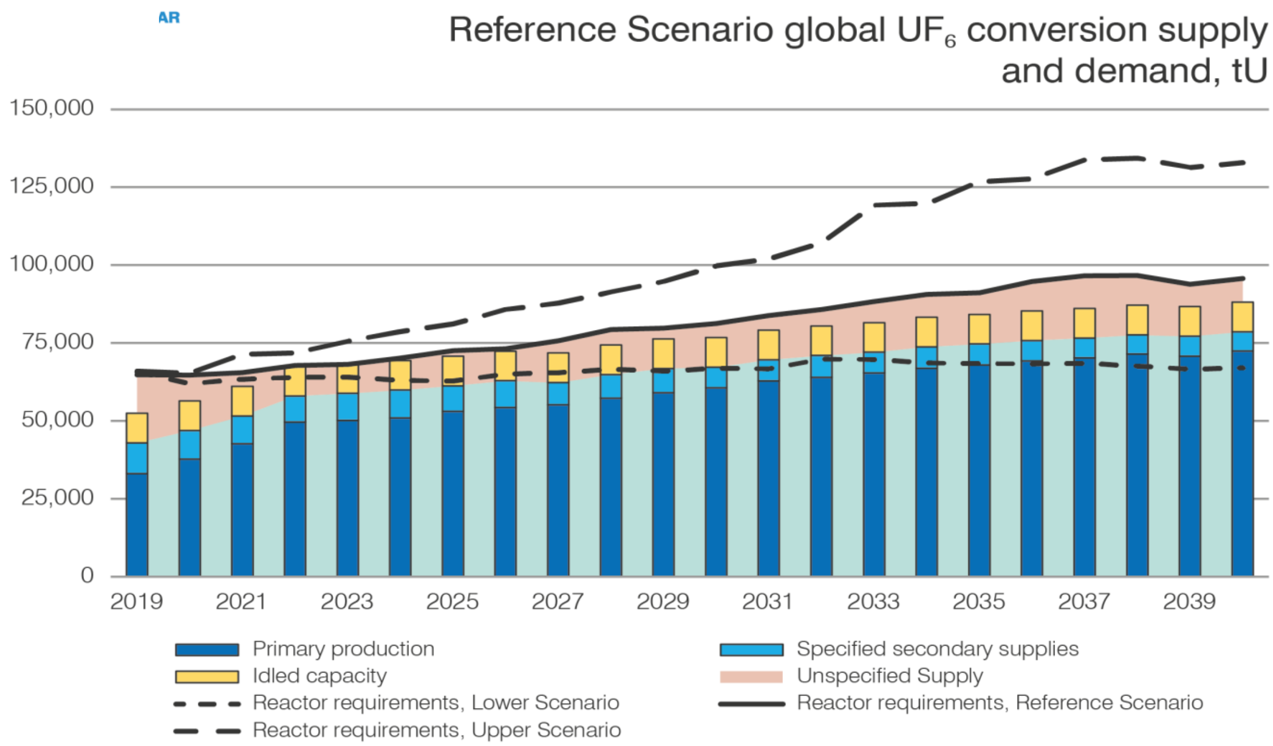

Figure 24.24. Global uranium hexafluoride conversion supply and demand (tonnes) (Reference Scenario)
(Source: World Nuclear Association) (Copyright granted by World Nuclear Association)

24.8.2 *Enrichment*

About 140,000 SWU is required to enrich the annual fuel loading for a typical 1000 MWe light water reactor at today's higher enrichment levels. Enrichment costs are substantially related to electrical energy used.

SWU, or Separative Work Units are the amount of separation done by an enrichment process. This is a function of the concentrations of the feedstock, which include the enriched output, and the depleted tailings. This form of measure (SWU) is expressed in units which are so calculated as to be proportional to the total input (energy / machine operation time) and to the mass processed. Separative work units are not the same as energy expended.

The same amount of separative work will require different amounts of energy depending on the efficiency of the separation technology. Separative work is measured in Separative work units SWU, kg SW, or kg UTA (the German definition - Urantrennarbeit), where 1 SWU = 1 kg SW = 1 kg UTA.

For enrichment, the gaseous diffusion process consumes about 2500 kWh (9000 MJ) per SWU, while modern gas centrifuge plants require only about 50 kWh (180 MJ) per SWU (World Nuclear Association). Enrichment accounts for almost half of the cost of nuclear fuel and about 5% of the total cost of the electricity generated. Table 24.14 shows the global enrichment capacity.

Table 24.14. World enrichment capacity – operational and planned (SWU/yr) (Source: World Nuclear Association, information paper on China's Nuclear Fuel Cycle, Areva 2014 Reference Document)

Country	Company and plant	2013	2015	2020
France	Areva, Georges Besse I & II	5 500	7 000	7 500
Germany, Netherlands & UK	Urenco: Gronau, Germany; Almelo, Netherlands; Capenhurst, UK.	14 200	14 400	14 900
Japan	JNFL, Rokkaasho	75	75	75
USA	USEC, Piketon	0*	0	0
USA	Urenco, New Mexico	3 500	4 700	4 700
USA	Global Laser Enrichment, Paducah	0	0	0
Russia	Tenex: Angarsk, Novouralsk, Zelenogorsk, Seversk	26 000	26 578	28 663
China	CNNC, Hanzhun & Lanzhou	2 200	5 760	10 700
Other	Various: Argentina, Brazil, India, Pakistan, Iran	75	100	170
	Total SWU/yr approx	51 550	58 613	66 708
	Requirements (WNA reference scenario)	49 154	47 285	57 456

* Diffusion, closed mid-2013, US centrifuge proposed.

'Other' includes Resende in Brazil, Rattehallib in India and Natanz in Iran. At end of 2012 Iran had about 9 000 SWU/yr capacity operating, according to Institute for Science and International Security (ISIS) and other estimates. Early in 2020 Iran had about 7 500 SWU/yr capacity operating, according to ISIS estimates based on IAEA reporting.

24.9 Fuel fabrication

Table 24.15 shows the global nuclear fuel fabrication capacity.

Table 24.15. Global World LWR fuel fabrication capacity, tonnes/yr
(Source: World Nuclear Association Nuclear Fuel Report 2019, Table 8.2)

Country	Fabricator Operator	Location	Conversion in 2016 (Tonnes/year)	Pelletizing in 2016 (Tonnes/year)	Rod/assembly in 2016 (Tonnes/year)
Brazil	INB	Resende	160	120	400
China	CJNF Jianzhong	Yibin	800	800	800
	CBNF	Baotou	0	0	400
	CNNFC	Baotou	200	200	200
France	Framatome-FBFC	Romans	1 800	1 400	1 400
	Orano	Malvési	Under construction		
Germany	Framatome-ANF	Lingen	800	650	650
India	DAE Nuclear Fuel Complex	Hyderabad	48	48	48
Japan	NFI (PWR)	Kumatori	0	383	284
	NFI (BWR)	Tokai-Mura	0	250	250
	Mitsubishi Nuclear Fuel	Tokai-Mura	450	440	440
	Global Nuclear Fuel – Japan	Kurihama	0	620	630
Kazakhstan	Ulba	Ust Kamenogorsk	0	108	0
Korea	KNFC	Daejeon	700	700	700
Russia	TVEL-MSZ*	Elektrostal	1 500	1 500	1 560
	TVEL-NCCP	Novosibirsk	450	1 200	1 200
Spain	ENUSA	Juzbado	0	500	500
Sweden	Westinghouse AB	Västeras	787	600	600
UK	Westinghouse**	Springfields	950	600	860
USA	Framatome Inc	Richland	1 200	1 200	1 200
	Global Nuclear Fuel – Americas	Wilmington	1 200	1 000	1 000
	Westinghouse	Columbia	1 600	1 594	2 154
Total			**12 645**	**13 913**	**15 276**

* Includes approx. 220 tHM for RBMK reactors
** Includes approx. 200 tHM for AGR reactors
Source: World Nuclear Association Nuclear Fuel Report 2019, Table 8.2
NB the above figures are about 40% above operational capacities, which meet demand.

* Includes approx. 220 tHM for RBMK reactors
** Includes approx. 200 tHM for AGR reactors
Source: World Nuclear Association Nuclear Fuel Report 2019, Table 8.2
NB the above figures are about 40% above operational capacities, which meet demand.
Framatome's German plant at Lingen is due to be closed.

24.10 Secondary sources

Uranium is not just sourced from primary mining. There are a number of secondary sources, which include inventories, reprocessing of spent fuel, uranium produced by the re-enrichment of depleted uranium tails, and low-enriched uranium (LEU) produced by blending down highly enriched uranium (HEU).

There are two kinds of secondary uranium sources, which could be recycled in some circumstances.

Mixed oxide fuel (MOX): MOX is the abbreviation for a fuel for nuclear power plants that consists of a mixture of uranium oxide and plutonium oxide, where current practice is to use a mixture of depleted uranium oxide and plutonium oxide.

Depleted Uranium (DU): Uranium where the uranium - 235 isotope chemical assay is below the naturally occurring 0.7110%. Natural uranium is a mixture of three isotopes:

- Uranium-238 – accounting for 99.2836%
- Uranium-235 – 0.7110%,
- Uranium-234 – 0.0054%.

Depleted uranium is a byproduct of the enrichment process, where enriched uranium is produced from initial natural uranium feed material.

24.10.1 Uranium produced by the re-enrichment of depleted uranium tails

Uranium can be produced by the re-enrichment of process tailings and through underfeeding depleted uranium stocks. This has not been done on a larger scale historically due to economic viability limitations. Up until 2009, Russia was able to supply European end users re-enriched uranium.

Table 24.16. Russian supply of re-enriched tails to EU end users (Source: ESA Annual Report 2011 Annual Report 2009, 2010, Luxembourg, NEA/OECD Uranium 2018, 2014, 2011, 2009 & 2007, World Nuclear Association 2020)

Year	Re-enriched tail deliverables (tonnes)	Percentage of total natural uranium deliveries (%)
2005	474	2,8
2006	728	3,3
2007	388	1,8
2008	688	3,7
2009	193	1,1
2010	0	0

24.10.2 Reprocessing of spent nuclear fuel

Once the spent fuel has been cooled for 5-10 years to a temperature low enough to practically handle, a portion of it can be reprocessed. When spent fuel is discharged from a commercial reactor, approximately 96% of the original fissionable material remains. There is also the plutonium isotopes created during the fission process to be subject to extraction (NEA/OECD 2011, Rodríguez-Penalonga & Yolanda-Moratilla 2017, Andrews 2008, World Nuclear Association 2019, Serp *et al* 2017).

Reprocessing is a highly specialized and sensitive operation, where very toxic products are being handled. This is often very expensive and tedious to do safely. This process has many legal oversights required to be conducted, due to the potential for this plutonium containing product to be used in the manufacture of nuclear weapons (nuclear proliferation).

This is done through the chemical separation of fission products, usable elements, and unused uranium from spent nuclear fuel. Initially, the purpose of this was to extract plutonium for producing nuclear weapons. This process was then optimized to use the reprocessed plutonium in the fabrication of MOX fuel (Mixed Oxide fuel) for thermal reactors.

There are several process paths to recycle spent nuclear fuel. The current standard method of reprocessing spent nuclear fuel is a water organic solvent extraction process called PUREX (Plutonium and Uranium Recovery by EXtraction). The PUREX process first completely dissolves the spent fuel in nitric acid. The process is then a liquid-liquid extraction method used to reprocess spent nuclear fuel, to extract uranium and plutonium, independent of each other, from the fission products (Rodríguez-Penalonga & Yolanda-Moratilla 2017, World Nuclear Association 2019). Table 24.17 shows global production of reprocessed uranium stocks. Only about 15 percent of the world's spent nuclear fuel is reprocessed (WNWR 2019).

Table 24.17. Reprocessed uranium production and use (tonnes of equivalent natural U)
(Source: NEA/OECD Uranium 2020, 2018, 2016, 2014, 2011, 2009 & 2007, World Nuclear Association 2020)

County	Pre-2008	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Total to end of 2018	2019 (preliminary)
Production														
France[a]	12,200	800	800	1,000	1,000	1,000	1,000	1,180	1,170	1,080	1,026	1,026	28,982	1,026
Japan[b]	645	0	0	0	0	0	0	0	0	0	0	0	645	0
Russia	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
United Kingdom[b]	54,079	1,689	613	N/A	N/A	N/A	N/A	N/A	N/A	0	0	0	N/A	0
World	66,924	2,489	1,413	1,000	1,000	1,000	1,000	1,180	1,170	1,080	1,026	1,026	29,627	1,026
Use														
Belgium[b]	508	0	0	0	0	0	0	0	0	0	0	0	508	0
France[a]	2,300	300	300	600	600	600	600	0	0	0	0	0	5,300	0
Germany	N/A	950	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Japan	195	0	12	8	0	0	0	0	0	0	0	0	217	0
Switzerland	1,770	320	473	291	309	291	266	273	143	273	149	149	2,573	116
United Kingdom[b]	~15,000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0	41	1,767	39
World	19,773	1,570	785	899	909	891	866	273	143	273	149	190	10,365	155

N/A = Data not available.
(a) Cumulative in storage
(b) 2019 edition of NEA Nuclear Energy Data

24.10.3 Fabrication of MOX fuel from spent nuclear fuel

Mixed Oxide fuel (MOX) is fabricated nuclear fuel that contains more than one oxide of fissile material. This is usually a blend of plutonium and natural uranium, reprocessed uranium, or depleted uranium. MOX fuel is an alternative to conventional uranium oxide fuel (UOX). For a fission reactor to use MOX, the operation must be optimized (and the reactor is required to be licensed). MOX made to specification consists of two phases, UO_2 and PuO_2, and/or a single phase solid solution $(U, Pu)O_2$, where the content of PuO_2 may vary from 1.5 % to 25–30 % of total mass, depending on the type of nuclear reactor (NEA/OECD 2011, Rodríguez-Penalonga & Yolanda-Moratilla 2017, Andrews 2008, World Nuclear Association 2019, Serp *et al* 2017). Although MOX fuel can be used in thermal reactors to provide energy, efficient fission of plutonium in MOX can only be achieved in fast reactors. Table 24.18 shows the global production of MOX fuel stocks.

Nuclear weapons can be dismantled, and the by-products can be used to manufacture MOX fuel (World Nuclear Association 2019). In September 2000, the United States and Russia signed the Plutonium Management and Disposition Agreement that committed each country to dispose of 34 tonne of surplus weapons-grade plutonium at a rate of at least 2 tonnes per year in each country, once production facilities were in place. Both countries agreed to dispose of the surplus plutonium by fabricating MOX fuel suitable for irradiation in commercial nuclear reactors that would convert the surplus plutonium into a form that cannot be readily used to make a nuclear weapon.

Table 24.18. MOX production and use (tonnes of equivalent natural U)
(Source: NEA/OECD Uranium 2020, 2018, 2016, 2014, 2011, 2009 & 2007, World Nuclear Association 2020)

County	Pre-2008	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Total to 2018	2019 (preliminary)
MOX production														
Belgium[(a)]	523	0	0	0	0	0	0	0	0	0	0	0	523	0
France	15,598 *	1008	1560	1560	1160	1200	992	1,072	997	992	880	744	24,397	870
Japan	645	4	23	37	2	0	0	0	0	0	0	0	684	0
United Kingdom	33	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
World	16799	1012	1583	1597	1162	1200	992	1072	997	992	880	744	25604	870
MOX use														
Belgium	520	0	0	0	0	0	0	0	0	0	0	0	520	0
France	N/A	N/A	800	880	880	880	880	917	961	960	712	582	N/A	N/A
Germany	6,070	250	210	100	100	100	260	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Japan	532	0	135	146	64	0	0	0	72	18	N/A	N/A	N/A	N/A
Switzerland	1,407	0	0	0	0	0	0	0	0	0	0	0	1,407	0
World	8,529	250	1,145	1,126	1,044	980	1,140	917	1,033	978	712	582	1,927	0

N/A = Not available or not disclosed
* Includes Cadarache historical production and Marcoule production adjustment.
(a) Data from the 2016 edition of the Red Book

24.11 Waste management of spent nuclear fuel

Nuclear power generation of electricity generates highly radioactive waste that needs to be managed. During the use of nuclear fuel rods in a Light Water Reactor (LWR) fission thermal nuclear reactor, there comes a point when those fuel rods are no longer useful in sustaining the nuclear chain reaction (NEA/OECD 2011). After a period of time in the reactor core (estimated 3 to 4 years) the irradiated fuel rod assembly is termed 'spent'. In some circumstances the decayed isotopes in the fuel rods absorb neutrons and hinder further atomic reactions and is sometimes referred to as fuel burnout. This term 'burnout' is due to the accumulation of larger amounts of fission products through the process of isotope decay in the ^{235}U and ^{238}U decay chain. These isotopes have high cross sections for thermal neutron capture and are classified as reactor poisons (NEA/OECD 2011, Serp *et al* 2017).

Irradiation of the ^{235}U isotope decaying produces a variety of fission products and actinides. This significantly increases the radioactivity of the fuel rod assembles, by more than 100 million times compared to the original U_3O_8 uranium ore. Lower-level waste is produced in large volumes but contributes very little to the overall inventory of radioactivity. Conversely, high-level waste is present in very small volumes but makes up the vast bulk of radioactivity.

An unshielded spent fuel delivers a lethal dose at one-meter distance in less than one minute. After ten years' cooling, dose rates from unshielded used fuel assemblies can range from 1 to 100 Gy per hour depending on the type of fuel (what isotopes were used in construction and their decay), its burnup, and how long it has been out of the reactor. A dose of 4 to 5 Gy is usually considered lethal to an average adult human (U.S. Nuclear Regulatory Commission 2019).

This highlights the safety precautions required in handling spent nuclear fuel (SNF). It is often transferred underwater or heavily shielded dry storage casks. Radiation exposure rates near these casks vary according to the type of fuel they contain (uranium oxide or uranium-plutonium mixed oxide). What also has an impact is the degree of fuel utilization (termed 'burnup') and age of the spent fuel. Dose rates are estimated at 1 meter from German Castor dry store casks to be approximately 0.1 mSv/hour, and for French TN28 flasks 0.04 mSv/hour (Wilkinson 2006).

The nuclear age started about 70 years ago (WNWR 2019). Since then, there has been no sustainable long-term solution for the management of spent nuclear fuel. Most waste has been put in storage facilities that have not been designed for long term operation (thousands of years), often without back-up power supply. According to the World Nuclear Waste Report published in 2019, there is a projected shortage of appropriate storage capacity for spent nuclear fuel (SNF).

As of 2020, no country in the world has a deep geological repository for spent nuclear fuel in operation. Currently, Finland is constructing a permanent deep underground geological repository. There are several interim storage facilities, where waste could be stored for a number of decades. The US is operating the Waste Isolation Pilot Project (WIPP). However, this repository is only used for long-lived transuranic waste from nuclear weapons, not for spent nuclear fuel from commercial reactors (WNWR 2019).

If spent fuel is reprocessed (currently about 15 % of global SNF), then large volumes of waste is generated that is reclassified at a lower level of radioactive content. This means that the total volume of waste to be managed is increased, but the total radiation activity remains the same, compared to spent fuel is treated directly as a waste.

Currently in Europe, approximately 60 000 tonnes of High Level Waste (HLW) spent nuclear fuel are stored in multiple countries. About 20 % of this waste is being stored, waiting for final disposal.

In a study done in 2007, the IAEA estimated that an operating 1000 MW (1 GW) light water reactor generates around 30-50 tonnes of spent nuclear fuel annually (IAEA 2007). Applying this estimate to the worldwide installed operating capacity of 363 GW would roughly indicate that 11,000 to 18,000 tons of SNF are produced annually. A waste generation rate of 12 000 tonnes a year was selected for use in Scenario E shown in Section 25.

The rate of waste generation varies with power plant technology and its age in operation. Table 24.19 shows a very approximate estimate produced by the IAEA.

Table 24.19. Generation of unconditioned LLW and ILW per 1-Gigawatt nuclear power by reactor technology (Source: WNWR 2019)

Nuclear Power Reactor Technology	Acronym	Generation of unconditioned (LLW & ILW) waste per 1-Gigawatt of electricity generated
Pressurized Heavy Water Reactor	PHWR	200 m^3
Light-water Reactor	LWR	
• Pressurized (Light-) Water Reactor	PWR	250 m^3
• Boiling (Light-) Water Reactor	BWR	500 m^3
• PWR VVER		600 m^3
Fast Breeder Reactor	FBR	500 m^3
Advanced Boiling Water Reactor	ABWR	500 m^3
Advanced Gas-Cooled Reactor	AGR	650 m^3
Light-Water Gas-Cooled Reactor	RBMK	1 500 m^3
Gas-Cooled Reactor	GCR	5 000 m^3

As of 2013 approximately 370 000 tons have been generated worldwide since the first reactor was connected to the grid, of which roughly one third (124 000 tons) has been reprocessed (IAEA 2018). This shows that there is approximately 246 000 tonnes of spent nuclear fuel in the global storage facilities.

24.11.1 The IAEA nuclear waste classification

The International Atomic Energy Agency has a waste classification system (WNWR 2019). These classifications were developed around the following three concepts.

- By level of radioactivity: low, intermediate, and high
- By time period of radioactive decay: short-lived and long-lived
- By management option: type of storage/disposal facility.

Figure 24.25 shows conceptually how these waste classes relate to each other.

Exempt Waste

This waste class has very low concentrations of radionuclides. The hazard profile of this waste has very low environmental and human health impact. In principle, such material can thus be transferred from one country to another without any form of regulatory oversight.

Very Short Lives Waste (VSLW)

This waste class contains radionuclides with a very short half-life (100 days or less), which are often stored until their activity levels allow them to be re-categorized as Exempt Waste. VSLW can be liquid, gases or solids in form.

Very Low-Level Waste (VLLW)

The quantity of radiation coming from this waste class is between ten and a hundred times those of levels for exempt waste (depending on the nuclide). The IAEA suggests that safe management for this waste will involve engineered surface landfill facilities, requiring both active and passive institutional controls over a significant but unspecified period.

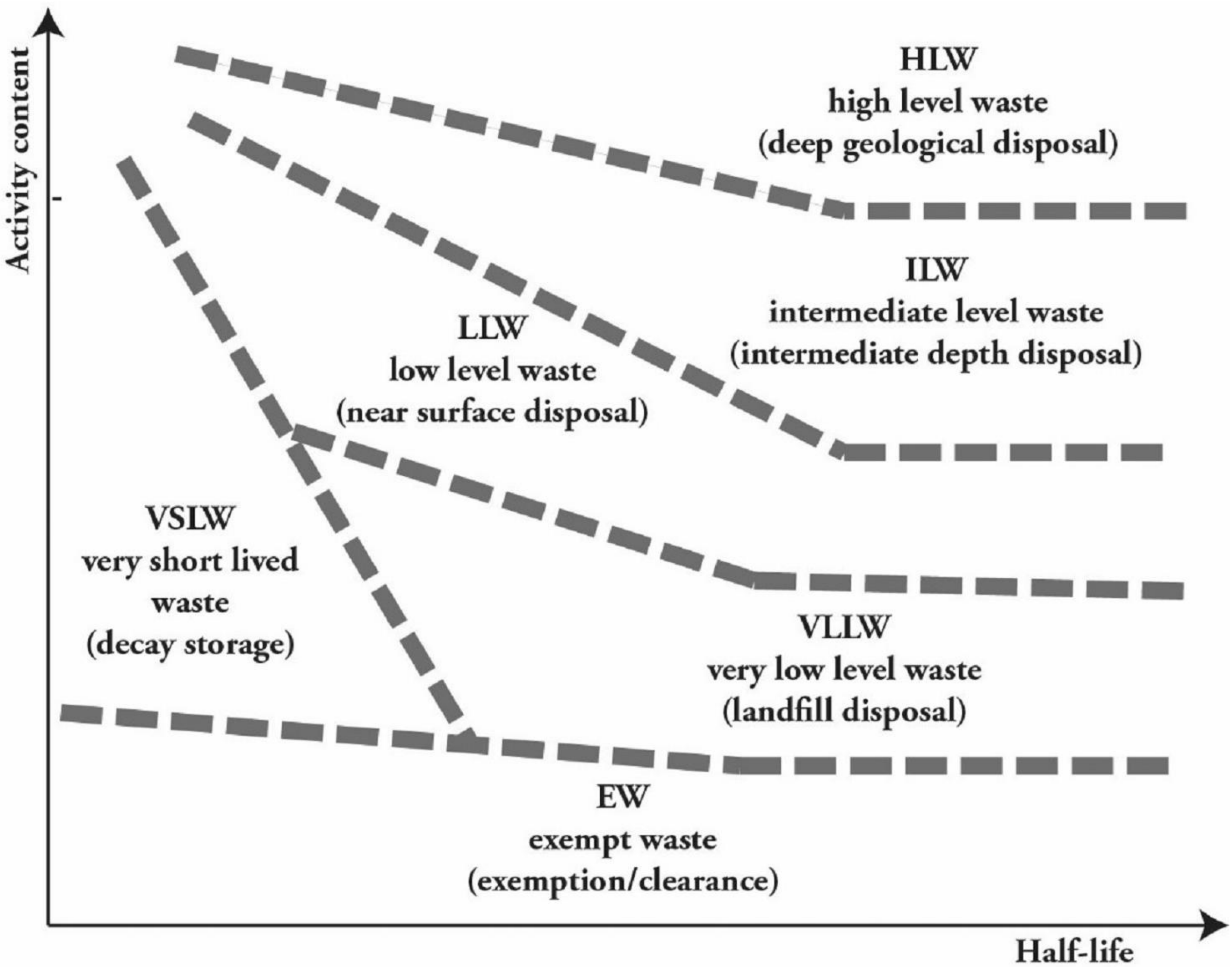

Figure 24.25. Conceptual illustration of the waste classification scheme (Source: IAEA 2018) (Creative Commons Copyright License: http://creativecommons.org/licenses/by-nc-nd/3.0.)

Low Level Waste (LLW)

This waste category has radiation coming from it to the level requiring storage for several hundred years (up to 300 years). This storage can be in near-surface (depth of 30 m) or sub-surface disposal sites, if the disposal sites offer robust containment and isolation. Typical materials that fall into the LLW category include clothing, packaging material, soil, and significant products of reactor decommissioning, such as steel and piping.

Intermediate-Level Waste (ILW)

This waste class has large quantities of long-lived radionuclides. It is required to have sophisticated long-term storage facilities to be engineered (for time periods of several thousand years). This waste class (ILW) does not produce heat from radioactive decay and thus does not need to take heat into account in its management. Characteristic sources of ILW are nuclear fuel cladding, some reactor components during decommissioning, and various types of sludge from treating radioactive liquid effluents. In addition, where spent fuel is reprocessed, large volumes of ILW are also created.

This waste is often cast into cement blocks and stored in steel drums. The IAEA recommends disposal at depths of between a few tens and a few hundreds of meters below ground in sites where natural geological barriers and engineered barriers have the potential to achieve long periods of isolation from the surface environment (depth 90-300m). This is what is stored in deep underground geological repositories.

High-Level Waste (HLW)

This class of waste contains the highest quantity of radioactive nuclides. It contains large concentrations of isotopes with both short and long term half-lives. This waste class also generates a lot of heat from radioactive decay and will continue to do so for long time periods into the future.

This waste class is required to be stored under water in powered cooling facilities for time periods up to 10 years. If this is not done, then there is a high risk of this spent nuclear fuel class catching fire. The hazard of this risk involves a very highly toxic and radioactive aerosol waste plume that would cover a wide geographical area. If cooling were to fail for any reason, the pools would fully evaporate within a few days and the fuel assemblies could ignite as their zirconium cladding would react strongly with oxygen in air.

Once the heat dissipation of this waste class has been reduced low enough, this waste is recommended to be stored in deep geological repository facilities (depth 400-1000m), in stable geological formations, and with the additional use of multiple engineered barriers to try to ensure that the chances of radioactive substances returning to the biosphere are extremely low. This is to be done for time periods of approximately 10 000 years to several hundred thousand years. The SNF storage standard is 100 000 years.

Figure 24.26 shows how each of the waste classes interact with the nuclear fuel cycle. Figures 24.27 and 24.28 shows the comparative volumes of each waste class in storage.

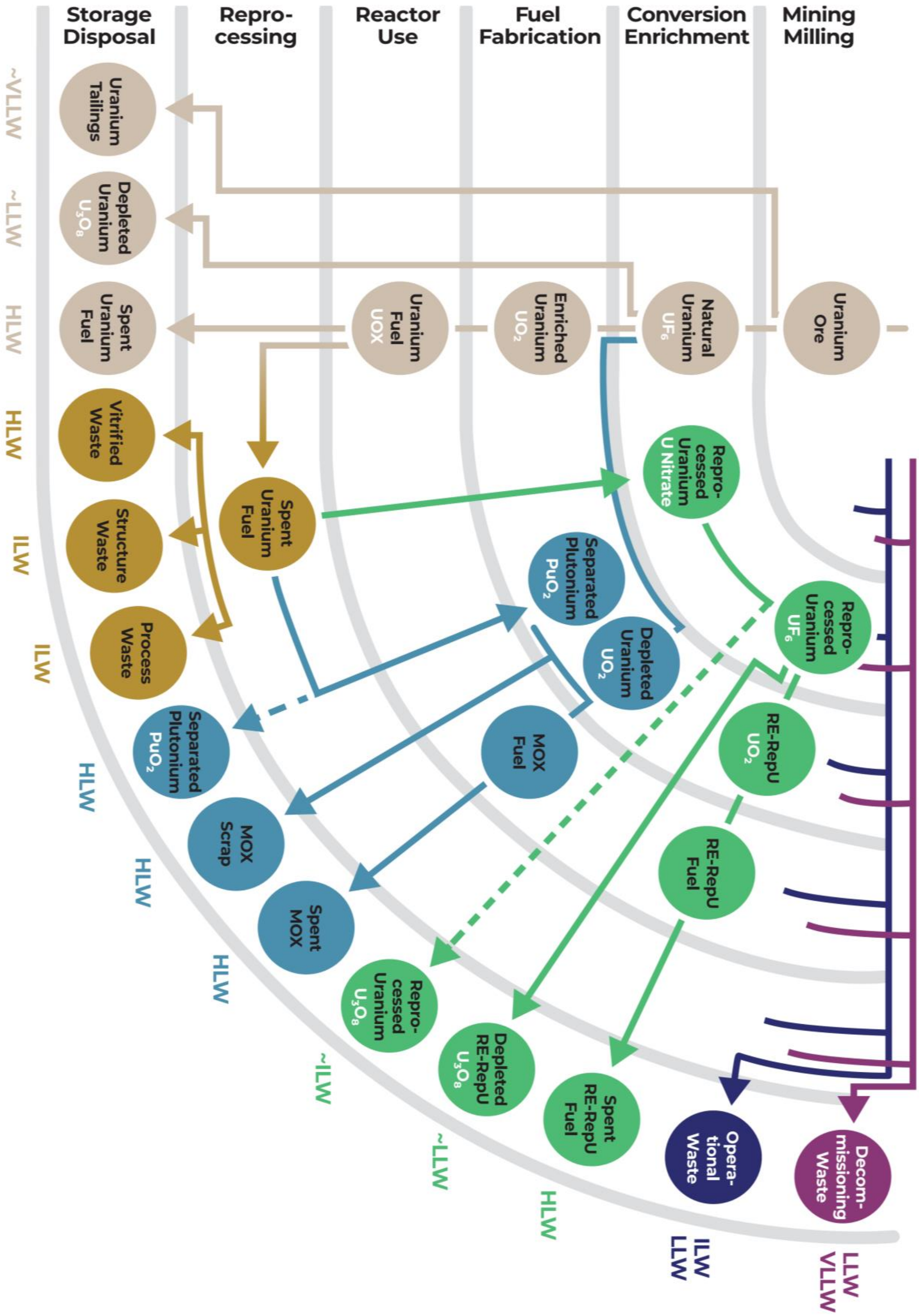

Figure 24.26. The nuclear fuel chain (Source: WNWR 2019, WISE-Paris)
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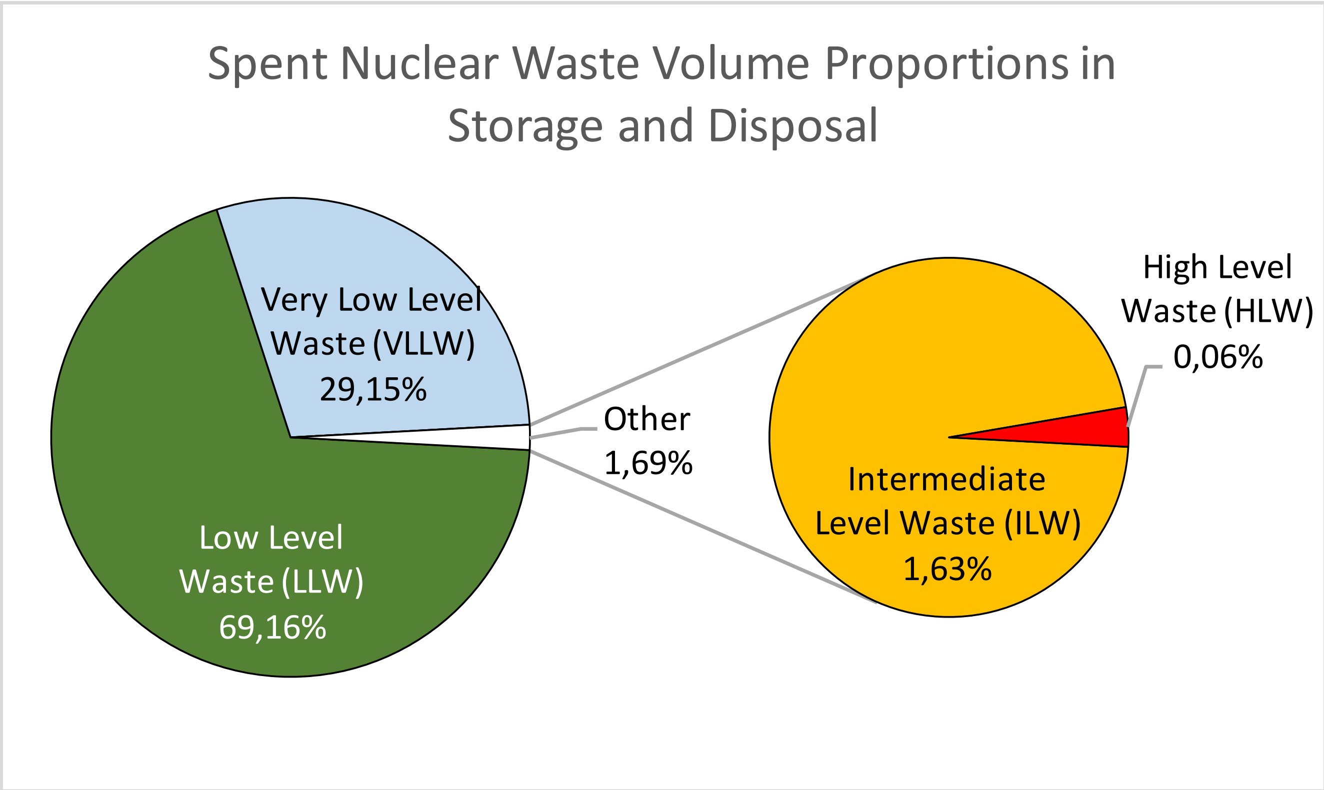


Figure 24.27. Spent Nuclear Waste Volume Proportions in Storage and Disposal
(Source: IAEA 2018)

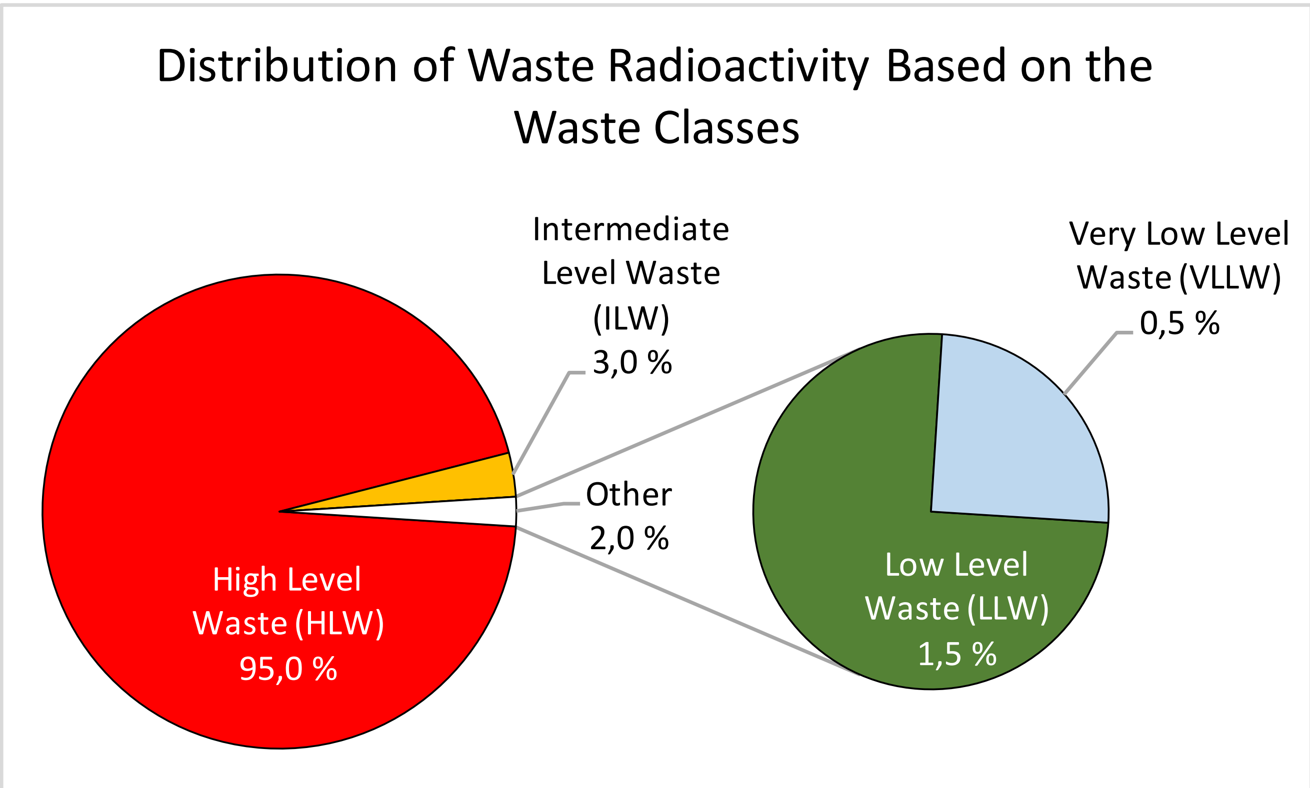


Figure 24.28. Distribution of Waste Radioactivity Based on the Waste Classes
(Source: IAEA 2018)

24.11.2 The world's first deep geological repository

The world's first deep geological repository for the final disposal of spent nuclear fuel is being built in Olkiluoto, on the west coast of Finland (Gil 2020, McEwan & Savage 1996, Deign 2012). This facility (called Onkalo) is near the Olkiluoto Nuclear Power Plant in the municipality of Eurajoki in Finland and is being constructed by Posiva. The facility is expected to be operational in 2023.

This storage site has been designed to apply the KBS-3 method of nuclear waste burial. KBS-3 (an abbreviation of kärnbränslesäkerhet, nuclear fuel safety) is a technology for disposal of high-level radioactive waste developed in Sweden by Svensk Kärnbränslehantering AB. The disposal method consists of the following steps (SKB 2021):

- The waste is first stored in intermediate storage for 30 years.
- The waste is encapsulated in cast iron canisters.
- The cast iron canisters are encapsulated in copper (CuOFP alloy) capsules.
- The capsules are deposited in a layer of bentonite clay, in a circular hole, eight meters deep and with a diameter of two meters, drilled in a cave 500 metres down into crystalline rock.
- After the storage facility is full, the drill hole is sealed, and the site marked.

The main disposal level at Olkiluoto is around 420 m. Storage levels cannot go much deeper due the increase of groundwater salinity. At the time of writing this report, the contracting company Posiva has license to dispose 6 500 tonnes of SNF. The planned start for SNF disposal is currently around 2025.

The planned storage capacity of the site is a conservative estimate, and the true storage capacity of the site is unknown. It may be possible to expand the storage footprint in future developments. It depends on various things: the final criteria the regulator is putting on the bedrock quality, the volume of tunnels eventually fulfilling the criteria and the allowed density of disposal holes per tunnel (Ruskeeniemi 2021). In 1985, GTK did an assessment across Finland, and located approximately 100 potential suitable sites to construct a deep geological repository. From this list, six candidate sites were studied thoroughly, and all would have been technically suitable. The Olkiluoto site was selected as the best and final site for this SNF long term storage facility.

24.11.3 Nuclear waste content

Nuclear waste contains a range of isotopes of uranium, plutonium, minor actinides and their fission products. One ton of the spent nuclear fuel irradiated in a typical operational cycle contains approximately 10 kg of plutonium isotopes; 0.5 kg of ^{237}Np, and approximately 40 kg of fission products.

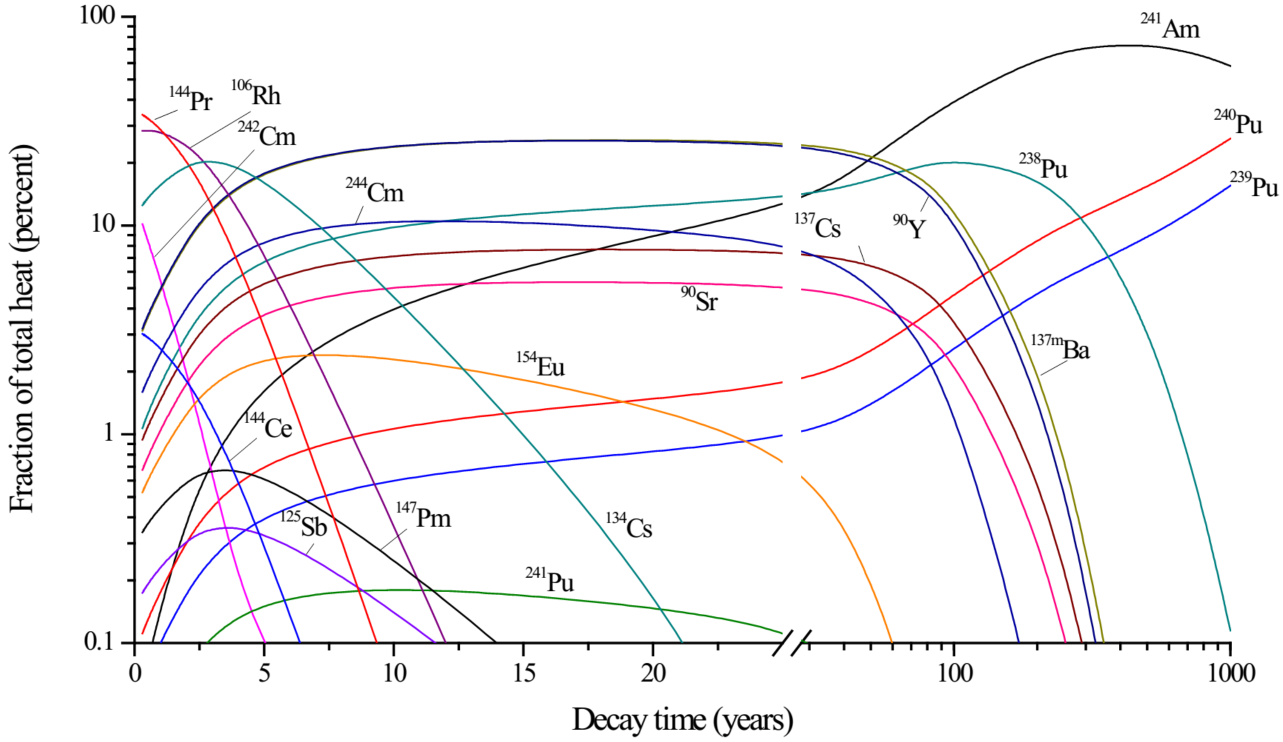


Figure 24.29. Important nuclides contribution to decay heat for typical LWR fuel for cooling times from about 1 year to 1000 years (Source: Spent nuclear fuel assay data for isotopic validation NEA/OECD 2011)

The spent fuel is highly radioactive (primarily beta radiation β^-, and gamma radiation γ) and generates a lot of heat (RWMAC 2002). These spent fuel rod assemblies are required to be stored, under water in powered cooling facilities. This is required to happen for 5-10 years (for some sites, 20 years) depending on the nature of the fuel rod assemblies being stored, and where the contents are in their respective nuclear decay chain (EIA 2020). After 1 year in cooled storage, the heat load drops to an estimated 10.8 W/kg (RWMAC 2002).

For the typical reactor, there is an average 18-month fuel cycle, where approximately one-third of the fuel must be replaced to sustain the nuclear reaction (EIA 2020).

Table 24.20 lists the actinides and fission products commonly considered in burn-up credit for interim spent fuel storage configurations. Figure 24.30 shows the half-life of the isotopes shown in Table 24.20. Many actinides are generated through the processes of neutron reactions, mainly neutron capture and (n,2n) reactions, and radioactive decay (β and α decay). Different nuclides may be important for different fuel types.

Table 24.20. List of nuclides commonly considered in burn-up credit criticality analyses (Source: NEA/OECD 2011)

Nuclide	Half-life (years)	Context in spent UOX PWR fuel[a] (g/MTHM) 52 GWd/t at discharge	Approximate proportion of nuclide in spent UOX PWR fuel[a]	Thermal neutron capture cross-section[b] (barns)	Thermal neutron fission cross-section[b] (barns)	Relative importance rank for 40 GWd/MTHM PWR fuel - 5 years cooling[c]
^{234}U	2.446×10^5	143	0,01 %	99.8		24
^{235}U	7.038×10^8	6 050	0,63 %	98.8	582.6	1
^{236}U	2.342×10^7	5 650	0,59 %	5.09		11
^{238}U	4.468×10^9	927 000	96,49 %	2.68		3
^{238}Pu	87.74	372	0,039 %	540	17.9	22
^{239}Pu	2.411×10^4	5 810	0,60 %	269.3	748	2
^{240}Pu	6 550	2 840	0,30 %	289.5		4
^{241}Pu	14.4	1 820	0,19 %	362.1	1 011	5
^{242}Pu	3.763×10^5	1 020	0,11 %	18.5		19
^{237}Np	2.14×10^6	811	0,084 %	175.9		14
^{241}Am	432.6	228	0,024 %	587	3.2	10
^{243}Am	7 370	1.74	0,00018 %	75.1		11
^{243}Cm[d]	28.5	0.624	0,00006 %	130	617	
^{244}Cm[d]	18.11	141	0,0147 %	15.2	1.04	
^{245}Cm[d]	8 532	11	0,0011 %	369	2 144	
^{133}Cs	Stable	1 630	0,17 %	30.3		12
^{143}Nd	Stable	1 070	0,11 %	325		7
^{145}Nd	Stable	989	0,10 %	50		17
^{147}Sm	1.06×10^{11}	196	0,020 %	57		20
^{149}Sm	2.0×10^{15}	3.36	0,00035 %	40 140		6
^{150}Sm	Stable	446	0,046 %	100		23
^{151}Sm	93	14.7	0,0015 %	15 170		9
^{152}Sm	Stable	134	0,014 %	206		15
^{153}Eu	Stable	184	0,019 %	312		18
^{155}Gd	Stable	3.93	0,000409 %	60 900		13
^{95}Mo	Stable	1 180	0,123 %	13.4		21
^{99}Tc	2.1×10^5	1 120	0,117 %	22.8		16
^{101}Ru	Stable	1 210	0,126 %	5.2		26
^{103}Rh	Stable	540	0,056 %	243.5		8
^{109}Ag	Stable	119	0,012 %	91.0		25
^{113}Cd[d]	9.10×10^{15}			20 615		

a - Measured content from ARIANE experimental programme data.

b - From S.F. Mughabghab, Atlas of Neutron Resonances – Resonance Parameters and Thermal Cross Sections Z = 1-100, 5th Edition, Elsevier, Amsterdam (2006).

c - Based on relative sensitivity coefficients from G. Radulescu, D.E. Mueller, J.C. Wagner, Sensitivity and Uncertainty Analysis of Commercial Reactor Criticals for Burn-up Credit, NUREG/CR-6951, Nuclear Regulatory Commission (2008)

d - Important for MOX fuel only.

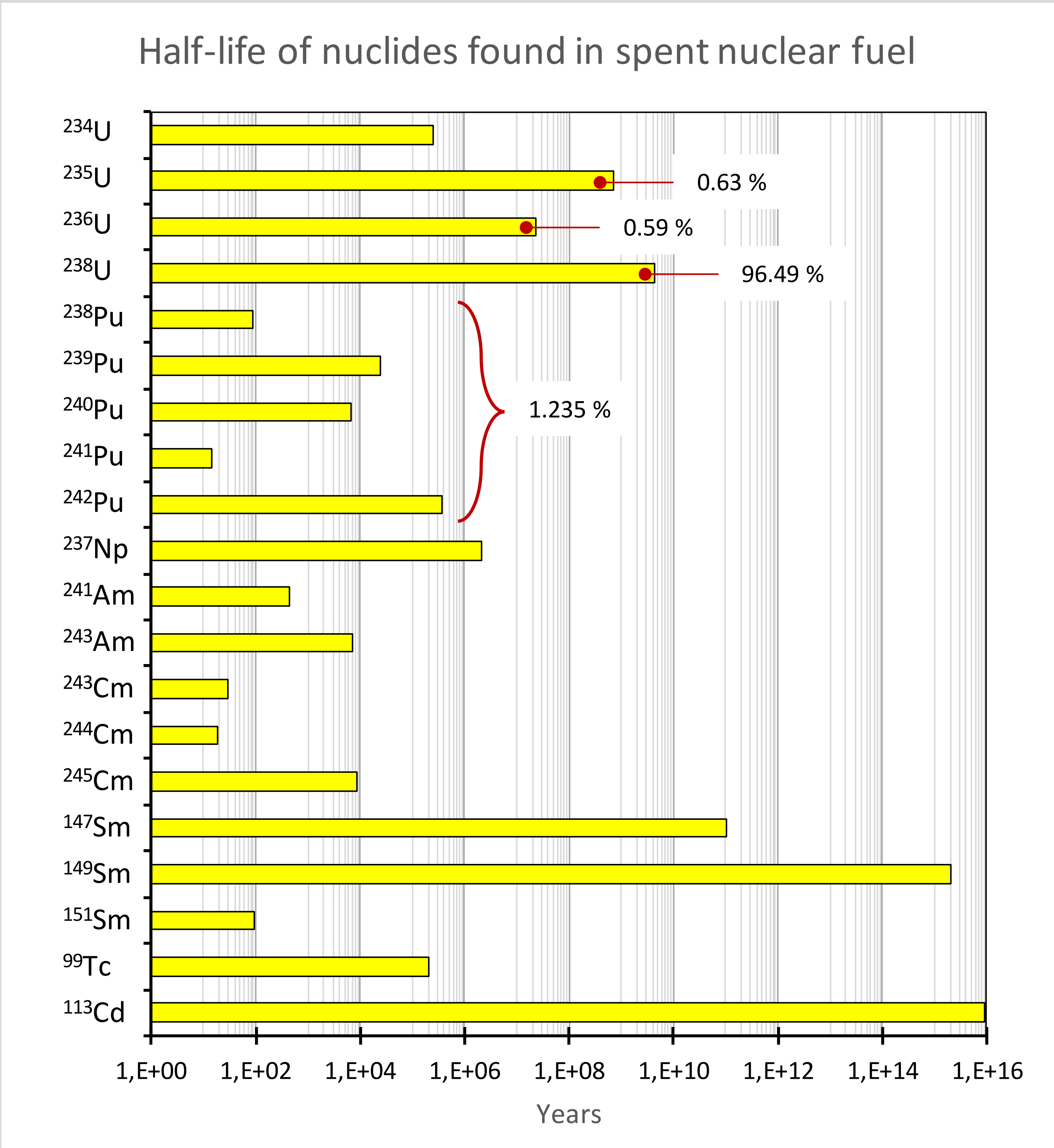


Figure 24.30. Atomic half-life of nuclide isotopes commonly found in spent nuclear fuel (Source: NEA/OECD 2011) (Simon Michaux)

24.12 Different generations of nuclear power plants

There have been several generations of development in the engineering design of nuclear reactors over the last 70 years.

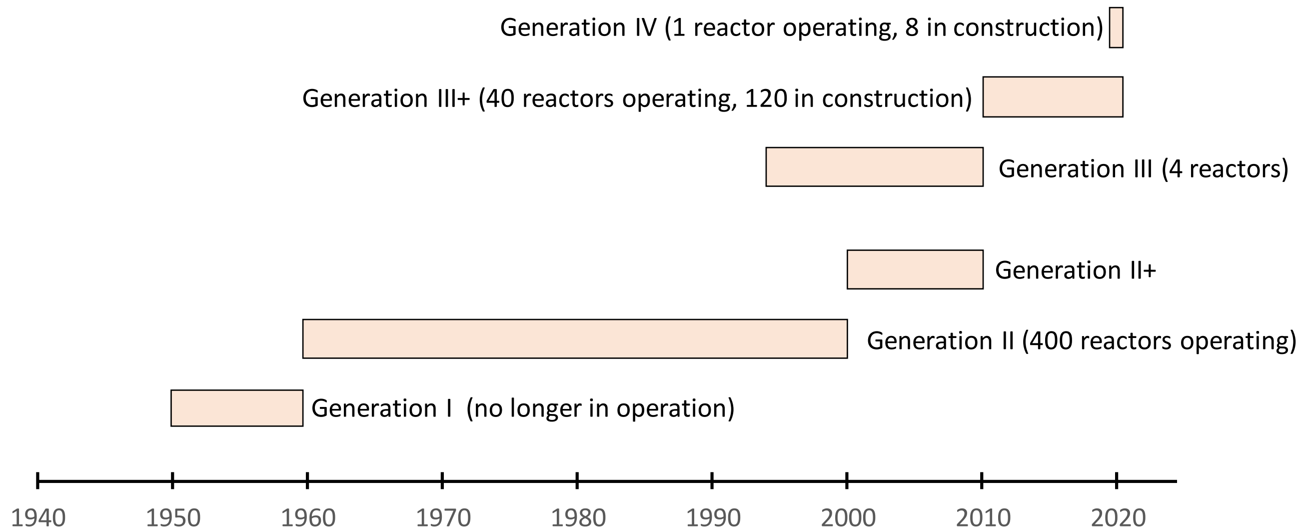


Figure 24.31. Different generation of nuclear plants and when they were connected to the power grid (as of 2019) (Image: Simon Michaux)

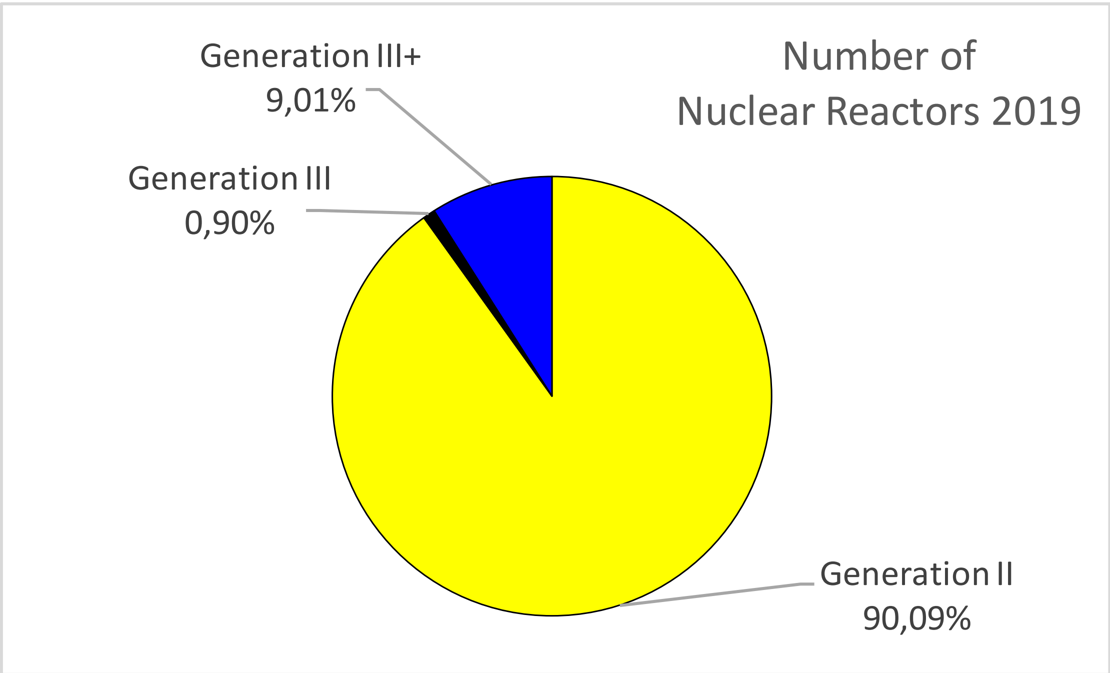


Figure 24.32. Number of nuclear reactors in the global fleet in 2019 (Source: World Nuclear Association)

Generation I – Early Prototype Reactors

These were the first prototype nuclear reactors employed for the commercial generation of electricity to the grid in the 1950's and 1960's. The last remaining commercial Gen I plant, the Wylfa Nuclear Power closed on 30 December 2015, after nearly 45 years of successful and safe operations. (IEA/NEA 2019, Goldberg & Rosner 2011).

Generation II – Commercial Electrical Power Generation

The first generation of thermal nuclear reactors were technologically developed to become more economical and reliable. The most common examples of a Generation II reactor are water-cooled and moderated reactors (LWRs). These include pressurized water reactors (PWR), and boiling water reactors (BWR), CANDU, AGR, RBMK and VVER are among them. Generation II systems began operation in the late 1960s-1990s and comprise the bulk of the world's current commercially operating PWRs and BWRs.

The kinds of developments that distinguish the Generation II from the Generation I reactors are active safety features involving electrical or mechanical operations that are initiated automatically and, in many cases, can be initiated by the operators of the nuclear reactors. The outcome of each of these designs could point to particular features that lead to economic or operational advantages, for example online refueling, or a non-enriched fuel. The majority of Generation II reactors were designed for a typical operational lifetime of 40 years. Many Generation II reactors are being life extended. (NEA/IEA 2019, Goldberg & Rosner 2011).

Generation II+

There were a number of technological advances which allowed the further modernization of Generation II reactors. Typically, the modernization includes improved safety systems and a 60-year design life. Generation II+ are reactors commissioned after the year 2000 (NEA/IEA 2019).

Generation III – Advanced Light Water Reactors (LWR)

Generation III reactors are designs that are an evolution of current light and heavy water reactor technology. Implications of these designs are improved performance, superior thermal efficiency, extended design lifetimes (60 years), with much greater reduction of risk of shut down incidents and core damage (NEA/IEA 2019). Generation III designs facilitates longer time interval between refueling (giving higher reactor availability) and higher burnup rates of fuel to reduce the amount of waste produced. Also standardized designs were able to reduce licensing and construction time, as well as capital cost. The first Generation III reactor to begin operation was Kashiwazaki 6 (an ABWR) in 1996 (Wheeler 2011).

The first Generation III+ reactor was commissioned in Russia in 2017 (Reuters 2017). An example of a Generation III+ nuclear power plant is the third reactor of the Olkiluoto Nuclear Power Plant in Finland. This plant is located on Olkiluoto Island, on the shore of the Gulf of Bothnia, in the municipality of Eurajoki in western Finland.

The Olkiluoto plant consists of two boiling water reactors (BWRs), each producing 890 MW of electricity. A third unit (Olkiluoto 3) will be the EPR reactor (a type of third generation with capacity of 1600 MW. Unit 3 is expected to be online in February 2022 (Pukkila 2020) and has been under construction since 2005. Japan Steel Works and Mitsubishi Heavy Industries manufactured the unit's 526-ton reactor pressure vessel (TVO 2009). This reactor is designed to operate flexibly to follow loads, have fuel burn-up of 65 GWd/t and a high thermal efficiency, of 37%, and net efficiency of 36% (WNA and NEA/IEA 2019). It is capable of using a full core load of MOX. Availability is expected to be 92% over a 80-year service life. This reactor is used as an example in Scenario E – Generation III+ shown in Section 25, where nuclear fuel consumption is assumed to be reduced by 30% compared to the conventional Generation II reactor, for the same power output.

Generation IV

Generation IV is a series of concepts to engineer nuclear power plants to multiple new metrics in conjunction with all existing metrics that Generation III was designed to. The Generation IV development goals have been defined into these broad areas (NEA/IEA 2019, Goldberg & Rosner 2011):

- Sustainability focus on fuel utilization and waste management
- Economics focus on competitive life cycle and energy production costs and financial risk
- Safety focus on safety, accident avoidance, minimization of consequences, and eliminating the technical need for off-site emergency response
- Reliable operation, stable power supply, reactor availability investment protection
- Proliferation resistance
- Physical protection focuses on safeguarding nuclear materials and facilities

Generation IV designs will use fuel more efficiently, reduce waste production, be economically competitive, and meet stringent standards of safety and proliferation resistance. From over one hundred concepts in the development of Generation IV reactors, six were selected that had the most technological promise to be viable (Table 24.21).

Table 24.21. Most promising Generation IV nuclear reactor systems (Source: IEA/NEA 2019)

Generation IV System	Acronym
Gas-cooled Fast Reactor	GFR
Lead-cooled Fast Reactor	LFR
Molten Salt Reactor	MSR
Sodium-cooled Fast Reactor	SFR
SuperCritical-Water-cooled Reactor	SCWR
Very-High-Temperature Reactor	VHTR

The most developed Generation IV reactor design, the sodium fast reactor, has received the greatest share of funding over the years with a number of demonstration facilities operated. It is thought that a reliable and stable Generation IV reactor is at least decades away. That being stated, in January 2018, it was reported that "the first installation of the pressure vessel cover of the world's first Gen IV reactor" had been completed on the HTR-PM (Zhang et al 2016, Nuclear Engineering International 2020). A Generation IV reactor has the potential to improve in efficiency by 72 % over a Generation II reactor (Bamshad & Safarzadeh 2020).

An example of Generation IV technology could be the traveling-wave reactor (TWR) concept, which is a proposed type of nuclear fission reactor (Weaver *et al* 2009, Rusov *et al* 2011, Ellis *et al* 2010). This technology, if it becomes viable, has the potential to convert fertile material into usable fuel through nuclear transmutation, in tandem with the burnup of fissile material.

The TWR reactor has often been referred to as the Nuclear Candle (Sekimoto *et al* 2001), which refers to the characteristic of the fission reactions are confined to a boundary zone in the reactor core, that slowly advances over time. The reactor would burn through its fuel like a 'candle'. TWRs could theoretically run self-sustained for decades without refueling or removing spent fuel.

A TWR reactor in theory would use a small amount of enriched uranium ^{235}U (or another fissile material) to initiate the start of the nuclear reaction (Weaver *et al* 2009). The remainder of the fuel could be natural or depleted uranium ^{238}U. In theory,a TWR has the capacity using unconventional fuels like depleted uranium, natural uranium, thorium, spent fuel removed from light water reactors, or some combination of these materials (Ellis *et al* 2010, Rusov *et al* 2011, Sekimoto *et al* 2001). While these concepts have yet to be proven, this potential has the capacity to reorganize the nuclear fuel cycle.

In principle, TWRs are capable of burning spent fuel from LWRs, which is currently discarded as radioactive waste. TWRs are also capable, in principle, of reusing their own fuel. In any given cycle of operation, only 20–35% of the fuel gets converted to an unusable form. This means that in theory (not proven) a TWR Generation IV nuclear reactor would consume only 17 to 32% of what a conventional Generation II would consume to produce a similar quantity of electricity.

24.13 Thorium as a nuclear fuel

Thorium can be used as a nuclear fuel. The desired isotope is ^{232}Th, which is not fissile but can be transmuted into ^{233}U in the reactor through a process of neutron absorption.

$$\overset{\text{neutron}}{\boldsymbol{n}} + {}^{232}_{90}\boldsymbol{Th} \rightarrow {}^{233}_{90}\boldsymbol{Th} \xrightarrow{\beta^-} {}^{233}_{91}\boldsymbol{Pa} \xrightarrow{\beta^-} {}^{233}_{92}\boldsymbol{U}_{\text{fuel}}^{\text{fissile}}$$

Most of the ^{233}U will then be subject to fission in the reactor producing products that are much easier to waste manage than conventional nuclear fuel. The used fuel can be extracted from the reactor, and the remaining ^{233}U can be chemically separated from the inert waste products.

The thorium fuel cycle has several potential advantages over a uranium fuel cycle, superior physical and nuclear properties, reduced toxic isotope production (plutonium and actinide) (Hargraves & Moir 2011). A very interesting unique advantage that the thorium cycle has compared to the uranium cycle is a breeder reactor that runs with slow neutrons, otherwise known as a thermal breeder reactor (IAEA-TECDOC 2005). A breeding reactor in the uranium - plutonium cycle needs to use fast neutrons.

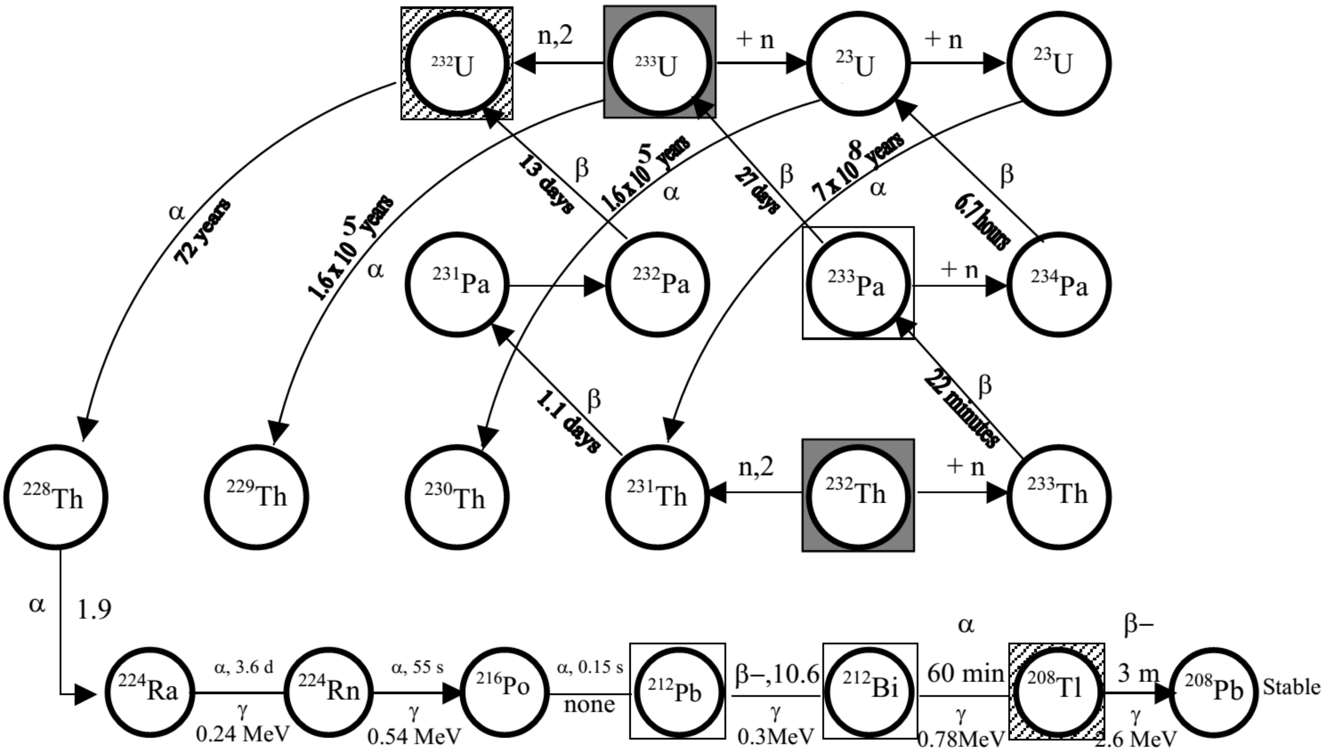


Figure 24.33. Main isotopes in 232Th – 233U fuel cycle
(Source: IAEA 2005)

Table 24.22. Summary of neutronic properties of 'Fissile' (^{233}U, ^{235}U and ^{239}Pu) and 'Fertile' (^{232}Th, and ^{238}U) isotopes in thermal storage (average over Maxwellian spectrum at 300°C (0.05eV)) and Epithermal region (Source: IAEA 2005)

Nuclear Data	^{232}Th	^{233}U	^{235}U	^{238}U	^{239}Pu	^{241}Pu
Thermal						
Cross-section (barns)						
Absorption σ_a	4.62	364	405	1.73	1045	1121
Fission : σ_f	0	332	346	0	695	842
$\alpha = \sigma_c / \sigma_f$		0.096	0.171		0.504	0.331
η_{th}		2.26	2.08		1.91	2.23
Epithermal Resonance Integral (RI) barns ($\propto$ dilution)	0	764	275	0	301	
RI_a	85.6	882	405	278	474	740
RI_f		746	272		293	571
$\alpha = RI_c / RI_f$		0.182	0.489		0.618	0.296
η_{epi}		2.10	1.63		1.77	2.29
Neutron Yield υ		2.48	2.43		2.87	2.97
Delayed Neutron Yield β		0.0031	0.0069		0.0026	0.0050
Capture:						
2 200 m/s value	7.6	54	100	2.7	267	
Resonance integral	85	140	144	275	200	
Neutron/fission (on average)		2.5	2.4			2.9

Table 24.23. Comparative physical properties of UO_2, PuO_2 and ThO_2 fuels (Source: IAEA 2005)

Property	U	UO_2	Pu	PuO_2	Th	ThO_2
Crystal structure	- Orthorhombic [RoomTemp(RT). up to 935 K] - Tetragonal (935 K- 1045K) - B.C.C (1045 K – MP)	FCC (CaF_2 type)	6 Phases Important Phases: - Monoclinic (RT upto 392 K) - F.C.C. (583 K– 723 K) - B.C.C. (745 K – MP)	FCC (CaF_2 type)	- F.C.C (RT-1673K) - B.C.C. (1673 K-MP)	FCC (CaF_2 type)
Melting point (MP), K	1405	~3123	913	~2623	2025	~3643
Theoretical Density, g/cm^3 at 298K	19.05	10.96	19.86	11.46	11.68	10.00
Thermal conductivity Wm^{-1} K^{-1}						
773 K	30	4.80	30	4.48	43.1	6.20
1773 K	-	2.40	-	1.97	-	2.40
Co-efficient of thermal expansion (K^{-1})	14.2×10^{-6} Randomly oriented Polycrystal (30-600 K)	10×10^{-6} (298-1223 K)	56×10^{-6} (main value α-phase)	11.4×10^{-6} (298-1223 K)	11.9×10^{-6} (30-600K)	9.67×10^{-6} (298-1223 K)

Thorium-based fuels are characterized with favorable physical and chemical properties that improve reactor and repository performance. Compared to the most commonly used nuclear fuel, uranium dioxide (UO_2), thorium dioxide (ThO_2) has several superior material properties: a higher melting point, a higher thermal conductivity, and lower coefficient of thermal expansion. Thorium dioxide also exhibits greater chemical stability and, unlike uranium dioxide, does not further oxidize (IAEA-TECDOC 2005).

Table 24.24. Types and geometry of thorium-based fuels and fuel elements (Source: IAEA 2005)

REACTOR TYPE	COMPOSITION	FUEL SHAPE	FUEL ELEMENT
High temperature Gas cooled reactors	ThO_2, $(Th,U)O_2$, ThC_2, $(Th,U)C_2$ (^{235}U or ^{233}U)	Microspheres 200-800 μ coated with multiple layers of buffer & pyrolytic carbon and SiC	Mixed with graphite and pressed into large spheres (~60 mm) for Pebble-Bed Reactor or fuel rods for HTGRs with prismatic fuel elements
Light water reactors	ThO2, (Th,U)O2, (Th,Pu)O2 (<5%Pu, 235U or 233U)	• High-density Sintered Pellets • High-density Microspheres	• Zircaloy clad Pin Cluster encapsulating Pellet-Stack • Zircaloy clad 'vi-pac' Pin Cluster encapsulating fuel microspheres
Heavy water reactors			
PHWR	ThO_2 for neutron flux flattening of initial core		
AHWR	$(Th,U)O_2$ $(Th,Pu)O_2$ (<5%Pu, ^{235}U or ^{233}U)	High-density Sintered Pellets	Zircaloy clad Pin Cluster encapsulating Pellet-Stack
Fast reactors	• ThO_2 blanket • $(Th,U)O_2$ & $(Th,Pu)O_2$ (~25%Pu, ^{235}U or ^{33}U) fuels • Th metal blanket • Th-U-Zr & Th-U-Pu-Zr fuels	High-density Sintered Pellets Injection-cast Fuel Rods	Stainless steel (SS) clad Pin Cluster encapsulating Pellet-Stack SS clad Pin Cluster encapsulating Fuel Rods
Molten salt breeder reactor	$Li^7F + BeF_2 + ThF_4 + UF_4$	Molten salt liquid form	Circulating molten salt acting as fuel and primary coolant

There have been several serious attempts to make thorium nuclear power feasible and viable. Research and development have been conducted in Canada, Germany, India, Japan, the Russian Federation, the United Kingdom, and the United States.

- **Germany** – A 15 MWe of electrical output plant, AVR (Arbeitsgemeinschaft Versuchsreaktor) has operated between 1967 and 1988 in Jülich. This is an experimental pebble bed reactor, where this plant has been used periodically as a test bed for various fuel pebbles, including thorium. From this plant, a 30 MWe thorium high temperature reactor (THTR) was developed by AVR, which operated between 1983 and 1989.

- **United Kingdom** – A thorium/uranium fuel mix (10:1 of Th/U) was irradiated in the 20MWth Dragon reactor at Winfrith for 741 full power days of production. The Dragon reactor was run between 1964 and 1973 as an OECD/Euratom co-operation project.

- **United States** – Thorium fuel was tested in a light water reactor (Shippingport) and in two gas-cooled reactors (General Atomics' Peach Bottom and Fort St. Vrain). At Fort St. Vrain, almost 25 tonnes of thorium were used as fuel for the reactor, and this achieved 170 GWd/t burn-up.

- **Canada** - Atomic Energy Canada Limited has conducted several trails over 50 years using thorium-based fuels, including burn-up to 47 GWd/t. As of 2014, an estimated 25 tests have been performed in 3 research reactors and 1 pre-commercial reactor.

- **India** – In 1996, the Kalpakkam Mini reactor (Kamini) 30 kWth experimental neutron-source research reactor using ^{233}U started up. The Kalpakkam Mini reactor was built adjacent to the 40 MWt fast breeder test reactor (FBTR), in which the ThO_2 is irradiated, producing ^{233}U for the Kamini power plant.

A possible nuclear reactor that could use thorium as a fuel is a liquid fluoride thorium reactor (LFTR), which is a type of molten salt reactor. This kind of reactor applies the thorium cycle through the use of a fluoride-based, molten, liquid salt for fuel. The liquid is pumped between a critical core and an external heat exchanger where the heat is transferred to a non-radioactive secondary salt. The secondary salt then transfers its heat to a steam turbine or closed-cycle gas turbine, which is used to generate electricity (IAEA-TECDOC 2005).

In a LFTR reactor, thorium (^{232}Th) is transmuted into uranium (^{233}U) with the irradiation of neutrons, instead of using uranium directly as a fuel. The opportunity is that all the thorium fuel is used, producing stable fission products, whereas a uranium-based reactor will only use a fraction of the uranium, producing highly radioactive fission products. A LFTR reactor could be refueled by pumping without shutdown and their liquid salt coolant allows higher operating temperature and much lower pressure in the primary cooling loop.

24.14 Disadvantages and challenges for thorium to be viable

The concept of thorium as a nuclear fuel has been discussed and trial for some years. This interesting idea has many advantages, but it also has several disadvantages which have contributed to why it has not adopted at an industrial scale by the nuclear industry. There are several practical challenges to the industrial scale application of thorium fueled nuclear technology.

- The thorium fuel cycle produces hard gamma radiation emissions, which damage electronics (also creating a radiological hazard which requires remote handling during reprocessing). This limits the use of the thorium cycle in nuclear weapons.

- In current proposed power reactor designs, the ^{233}U produced in thorium fuels is significantly contaminated with ^{232}U. Remote handling procedures are necessary for fuel fabrication because of the high radiation levels resulting from the decay products of ^{232}U. This has been a significant limitation and has resulted in this technology yet to be accepted by the nuclear industry (Kan & Von Hippel 2001). The contamination could be avoided by using a molten-salt breeder reactor and separating the ^{233}Pa before it decays into ^{233}U.

- Thorium is not naturally fissile (unlike uranium-235). Additional fissile material or another neutron source is necessary to initiate the thorium fuel cycle. Generally, ^{233}U, ^{235}U or plutonium, must be added to achieve criticality.

- The sintering temperature to make thorium dioxide fuel is very high (550˚C melting temperature), which complicates high-quality solid fuel manufacture. Thorium is also chemically inert, which results in difficulties in chemical engineering.

- Another challenge associated with the thorium fuel cycle is the comparatively long interval over which ^{232}Th breeds to ^{233}U.

- Thorium is not as energetically effective as uranium/plutonium in a fast reactor. So, for reactors that require excellent neutron economy (such as breed-and-burn concepts), thorium is not ideal.

- There is a possible nuclear weapons proliferation concern with the use of thorium fuel. Protactinium can be chemically separated shortly after it is produced and removed from the neutron flux ($^{232}Th \rightarrow {}^{233}Th \rightarrow {}^{233}Pa \rightarrow {}^{233}U$). Separating ^{233}Pa in this path is highly logistically challenging but can be done. The isotope ^{233}Pa has a 27 day half-life, which limits its use as a weapon.

- Due to the very sensitive nature of the nuclear power value chain, the industry has developed an extremely conservative approach to new technological developments. A challenge for a thorium reactor to be accepted is a general lack in operational experience, which means there is not industry confidence in this technology.

At the time of the writing of this report, a thorium reactor was still largely experimental and had yet to be demonstrated at full industrial scale. It may be possible for this to be developed into a viable solution in the future.

24.15 Thorium resources

Thorium (Th) is a radioactive metal found in small quantities in most rocks and soils. Its global crustal abundance in the earth's crust is four times that of uranium. Thorium in mineral form occurs as oxides, silicates, and phosphates, often with rare earth elements (REE), niobium and tantalum. Tables 24.25 and 24.26 show the deposit style and known resources of thorium.

Table 24.25. Major thorium deposit types and resources* (Source: NEA/OECD 2014)

Deposit type	Resources ('000 tonnes of Thorium)
Placer	2 182
Carbonatite	1 783
Vein-type	1 528
Alkaline rocks	584
Other/unknown	135
Total	**6 212**

Note
* IAEA ThDEPO report

Table 24.26. Identified thorium resources (in situ) (Source: IAEA 2019)

Region	Country	Total thorium resources (in situ) (tonnes)
Europe	Turkey*	374 000
	Norway	87 000
	Greenland (Denmark)	86 000 - 93 000
	Finland*	60 000
	Russian Federation	55 000
	Sweden	50 000
	France	1 000
	Total	**713 000 -720 000**
Americas	United States**	595 000
	Brazil	632 000
	Venezuela*	300 000
	Canada	172 000
	Peru	20 000
	Uruguay*	3 000
	Argentina	1 300
	Total	**1 723 300**
Africa	Egypt*	380 000
	South Africa	148 000
	Morocco*	30 000
	Nigeria*	29 000
	Madagascar*	22 000
	Angola*	10 000
	Mozambique	10 000
	Malawi*	9 000
	Kenya*	8 000
	Democratic Republic of Congo*	2 500
	Others*	1 000
	Total	**649 500**
Asia	CIS* (excluding Russian Federation)	1 500 000
	~ includes Kazakhstan, estimated	(>50 000)
	~ includes Russian Federation, Asian part, estimated	(>100 000)
	~Uzbekistan, estimated	(5 000 - 10 000)
	~others	Unknown
	India	846 500
	China, estimated	>100 000 (including 9 000* Chinese Taipei)
	Iran, the Islamic Republic of*	30 000
	Malaysia	18 000
	Thailand*, estimated	10 000
	Viet Nam*, estimated	5 000 - 10 000
	Korea, Republic. Of*	6 000
	Sri Lanka*, estimated	4 000
	Total	**>2 647 500 - 2 684 500**
Australia		595 000
World Total		**6 355 300 - 6 372 300**

24.16 Thorium Fuel Production

Figures 24.34 to 24.37 show several flowsheets to show how thorium is mined, then processed, then fabricated into fuel pellets.

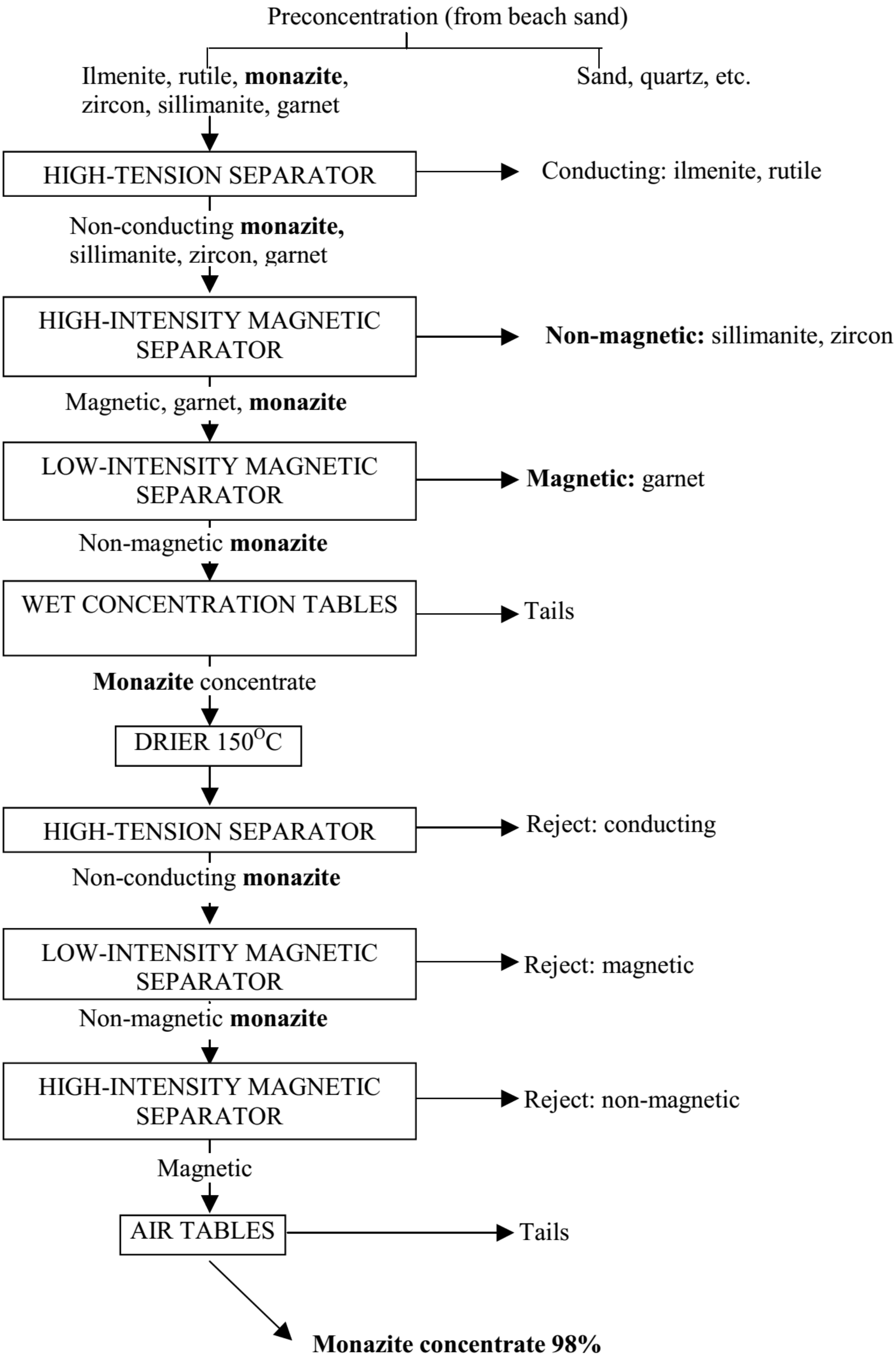


Figure 24.34. Typical flowsheet for separating monazite from heavy mineral in beach sand (Source: IAEA 2005, Marshall 1983)

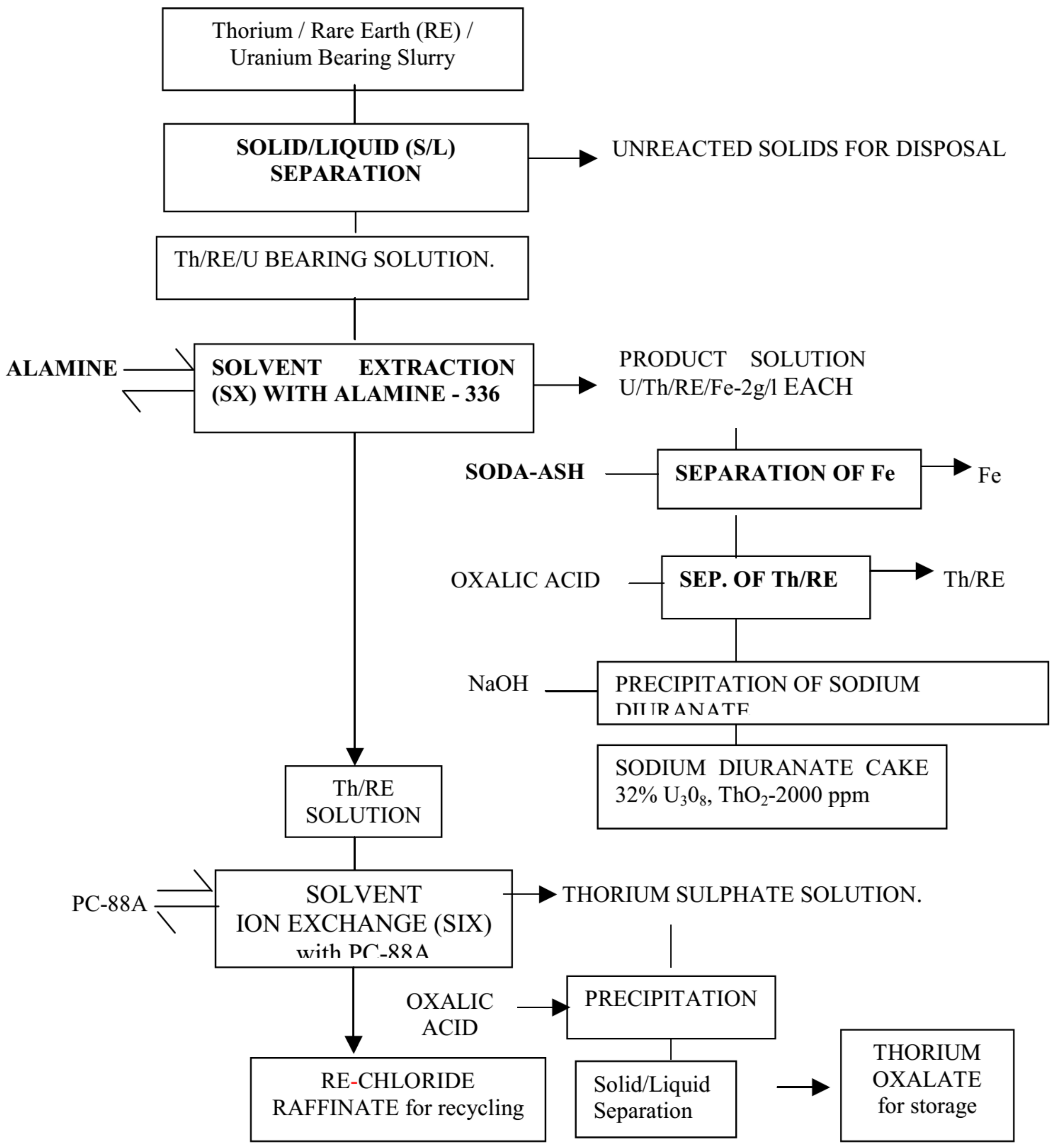


Figure 24.35. Recent techniques of processing monazite in India
(Source: IAEA 2005, Mukherjee 2003)

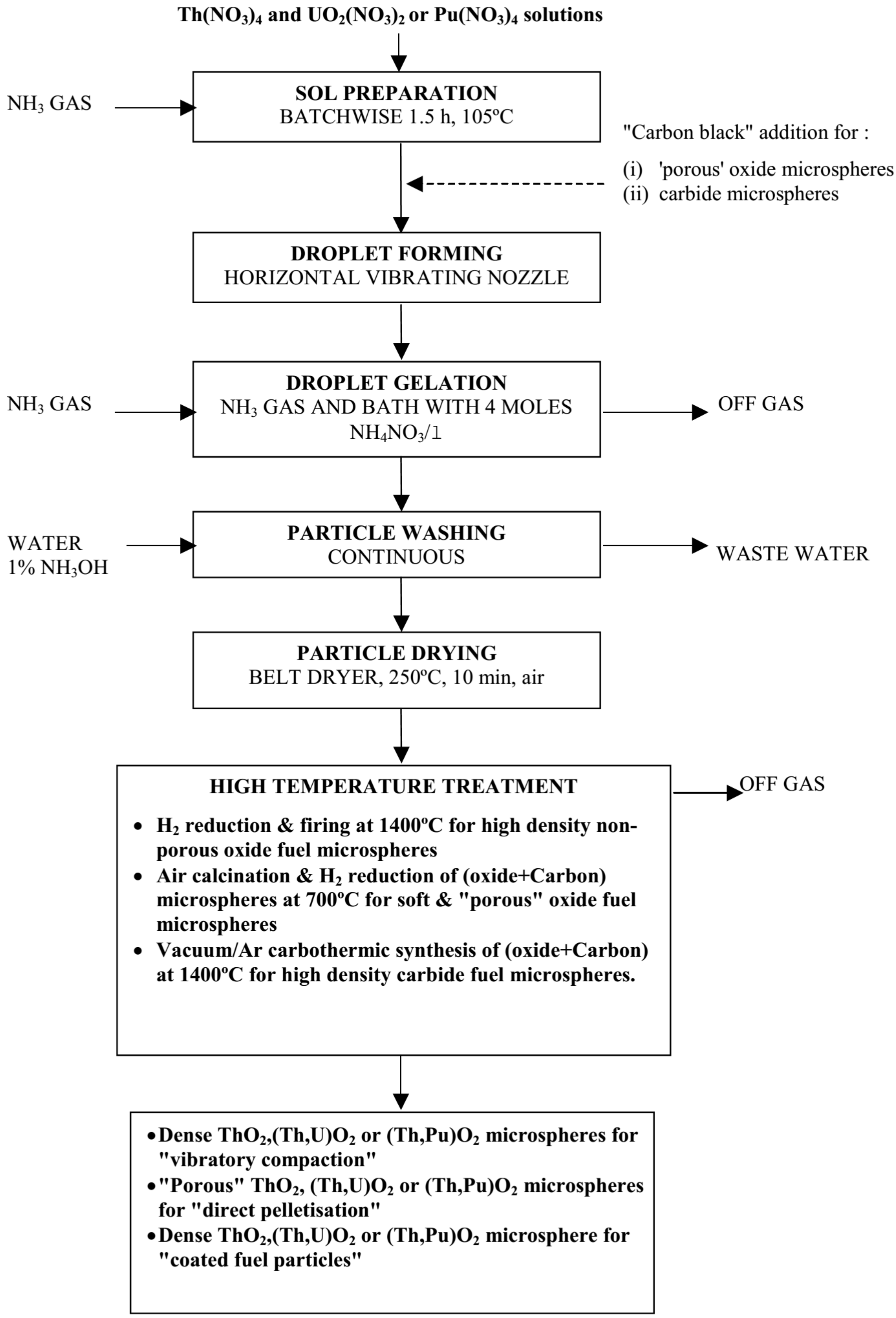


Figure 24.36. Flowsheet based on KfA-EGT process of Germany for preparation of Th based “oxide” & “non-oxide fuel” fuel microspheres for fabrication of “pellet pin”, “vipac pin” and “coated fuel particles” (Source: IAEA 2005)

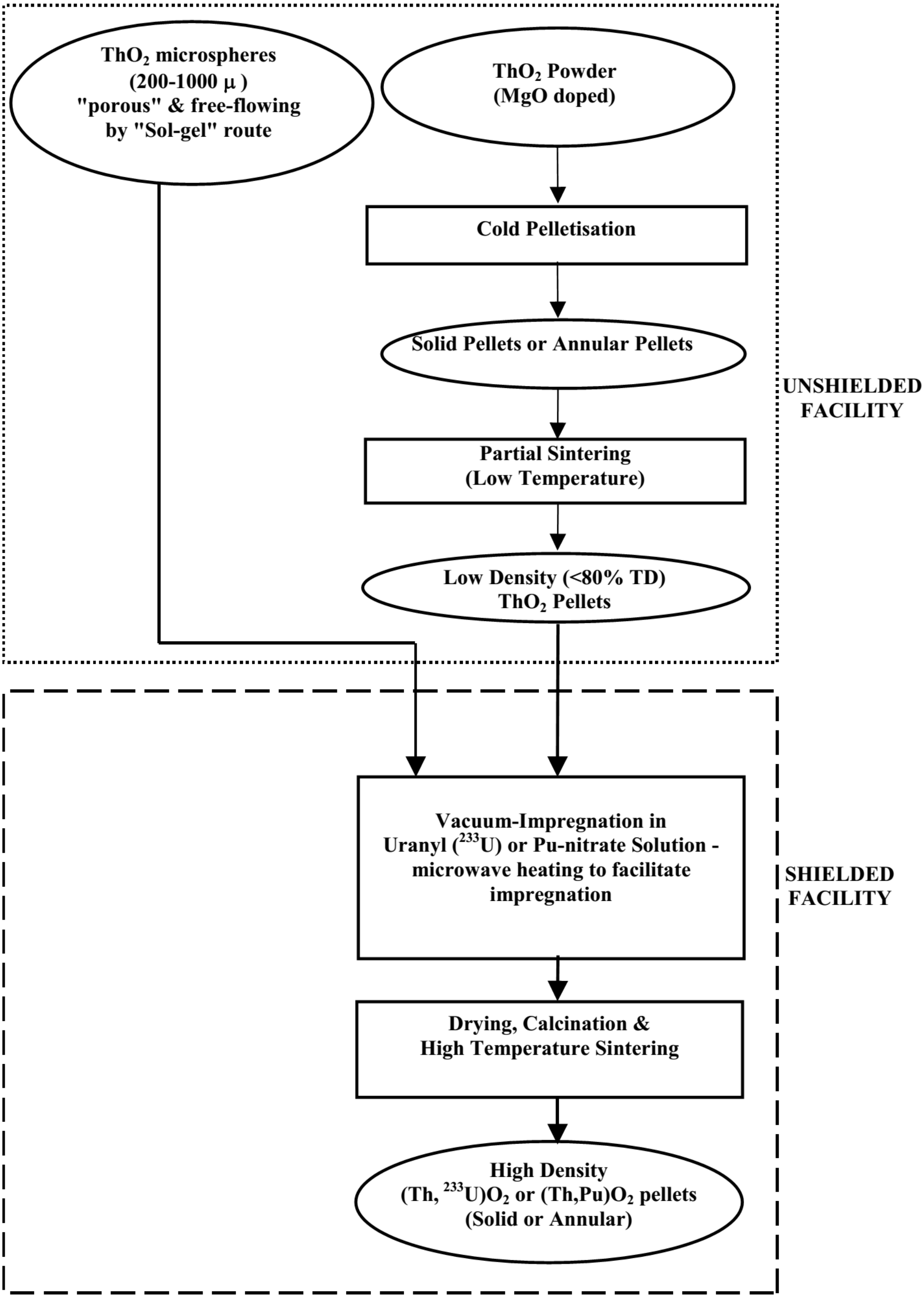


Figure 24.37. Process flowsheet based on "impregnation Technique" for manufacturing high density (Th $^{233}U)O_2$ and $(Th,Pu)O_2$ fuel pellets (Source IAEA 2005)

24.17 Fusion as a nuclear power generation technology

Nuclear fusion is a proposed next generation of nuclear energy generation technology. While it is at best several decades away for a viable and stable system to be commissioned, the potential is enormous. If fusion could be made to work, an almost inexhaustible source of energy and electrical power could be generated, with a very high fuel burn up rate. As a source of power, nuclear fusion is expected to have many advantages over fission. These include reduced radioactivity in operation and little high-level nuclear waste, and increased safety.

A nuclear fusion action is a reaction in which two or more atomic nuclei are combined once the short-range nuclear force between nucleons becomes larger than the electrostatic repulsive force between two positively charged nuclei. The outcome of this reaction is to form one or more different atomic nuclei and subatomic particles (neutrons or protons).

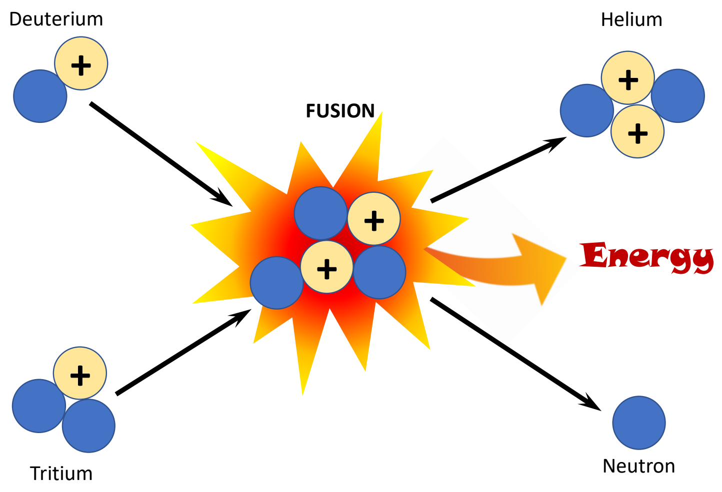


Figure 24.38. Nuclear Fusion reaction and release of energy
(Image: Simon Michaux)

The difference in mass between the reactants and products is manifested as either the release or the absorption of energy. This difference in mass arises due to the difference in atomic binding energy between the nuclei before and after the reaction. Fusion is the process that powers active or main sequence stars and other high-magnitude stars, where large amounts of energy are released.

This could happen if the protons involved either have large kinetic energies or if the protons are compressed by super large gravitational fields as observed in stars. Very high kinetic energies correspond to nucleus temperatures of several tens to hundred million degrees. Such high kinetic energies can be obtained for example in accelerators but only for small numbers. Larger amounts of fusion reactions can be obtained in special magnetic field arrangements.

The fundamental engineering challenges is to generate a rate of heat application by a fusion plasma that exceeds the rate of energy injected into the plasma. The engineering required to contain a fusion atomic reaction involve a high enough temperature, pressure, and confinement of fuel to create a stable plasma.

Proposed fusion reactors generally use hydrogen isotopes such as deuterium and tritium (and especially a mixture of the two), which react more easily than hydrogen to allow them to reach the Lawson power system criterion requirements with less extreme conditions. Most designs aim to heat their fuel to tens of millions of degrees, which presents a major challenge in producing a successful design. Currently, the most promising systems are based around tokamak reactors and stellarators which confine a deuterium-tritium plasma magnetically.

The necessary combination of temperature, pressure, and duration has proven to be difficult to produce in a practical engineering context, let alone an economic viability context. Research into fusion reactors began in the 1940s, as of 2020, no design has produced more power output than the electrical power input, resulting in a negative ERoEI ratio.

There are several technological barriers for fusion development to overcome (IAEA 2012).

- Commercial energy production requires steady state fusion conditions for a deuterium-tritium plasma on a scale comparable to that of today's standard nuclear fission reactors with outputs of 1 GW (electric) and about 3 GW (thermal) power.

- The material that surrounds and contains the large volume of plasma in a full-scale fusion reactor must satisfy two requirements.
    1. it has to survive an extremely high neutron flux with energies of 14 MeV
    2. it must do this not for a few minutes but for many years.

- An estimation of the neutron flux in a full-scale fusion power plant could be at least 10-20 times larger than in a current state-of-the-art nuclear fission power plant.

- Managing neutrons that are released during the reaction, which over time degrade many common materials used within the reaction chamber

- The radioactive decay of even a few grams of tritium creates radiation dangerous to living organisms, such that those who work with it must take sophisticated protective measures.

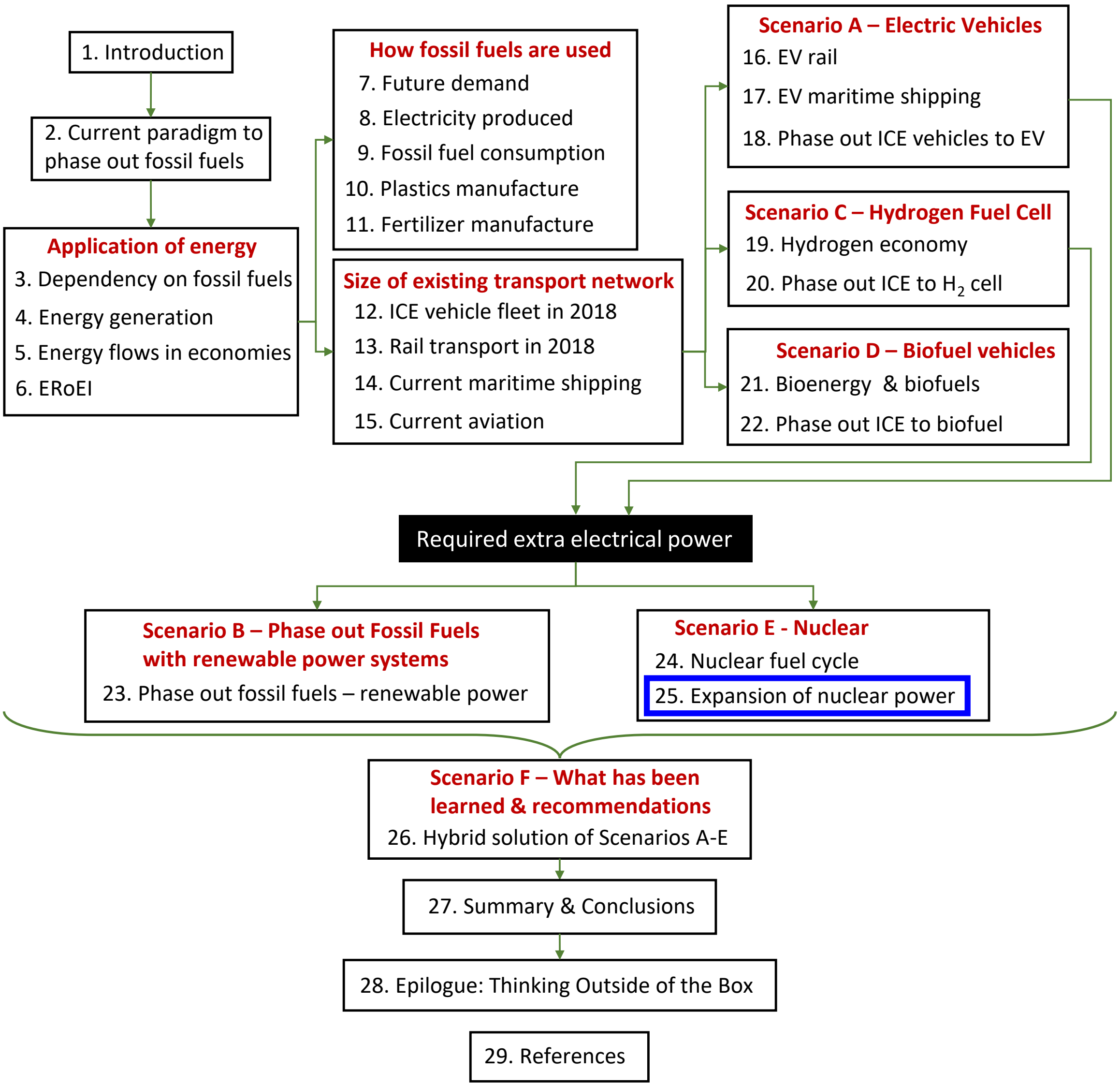
- Problems related to tritium supply and self-sufficient tritium breeding

- An efficient way must be found to extract the tritium quickly, and without loss, from this lithium blanket before it decays.

Nuclear fusion may well be the underlying technology of our industrial ecosystem one day in the future, but for now it is not feasible.

25 SCENARIO E – PHASE OUT FOSSIL FUELS COMPLETELY AND SUBSTITUTE WITH NUCLEAR POWER SOURCES

Scenario E was developed to address several questions related to using nuclear power as the primary future non-fossil fuel power generation system. Nuclear power is seen as the solution as it is the only non-fossil fuel system that is able to deliver large quantities of electrical power. Also, it can do this in any weather conditions and is not limited in the same way that solar, hydro or wind power systems are in context of geographical location. Just so, the rebuttal of any argument that solar power or wind power does not have a high enough ERoEI ratio is often with the suggestion that nuclear power is the clear solution. Can nuclear be expanded fast enough to be useful? Will the existing uranium resources last for a long enough time to justify the infrastructure construction? How big will the Spent Nuclear Fuel (SNF) stockpile be, and in what form? This Section is designed to put some numbers to that discussion.



Assessment of the Extra Capacity Required of Alternative Energy Electrical Power Systems to Completely Replace Fossil Fuels

The purpose of this simulation is to examine the proposed solution the expansion of the nuclear power plant fleet (and associated support systems) to deliver the extra non-fossil fuel power required to service the proposed post fossil fuel industrial ecosystem (Electric Vehicles/Hydrogen Fuel cell vehicles).

The existing nuclear power station fleet and its supporting value chain ecosystem are also not without their problems. Some of these issues are logistical, requiring more capital support and political will to resolve (for example, the commissioning of more spent fuel reprocessing plants, or the construction of more long-term storage facilities for spent fuel that cannot be recycled). Some of these issues have no technological solution. For example, the only current solution for the management of spent nuclear fuel (SNF) is long-term storage (with cycle times of tens of thousands of years). A large volume of SNF requires to be stored in powered cooling facilities underwater for 5-10 years. Not doing this has a very high risk of creating a spent fuel fire which would be a highly hazardous and impactful environmental disaster.

The following systems simulations were done and are presented in this chapter (the data output is shown in Appendix P).

1. Scenario E - Reference
   (nuclear power fleet stays as it is in scope of development, with 2 extra Generation III+ reactors connected to the grid every 10 years)
2. Scenario E – Generation III+ Technology
   (25 new Generation III+ reactors are connected to the grid each year, starting in 2025)
3. Scenario E – Generation II Technology
   (25 new Generation II reactors are connected to the grid each year, starting in 2025)
4. Scenario E – Generation IV Technology
   (10 new Generation III+ reactors are connected to the grid each year, between years 2025 and 2030 followed by 25 new Generation IV reactors are connected to the grid each year, starting in 2030)

With each of these systems simulations, the following questions will be examined:

- Can the nuclear fleet electricity generation be expanded fast enough to phase out fossil fuels?
- How long will uranium/thorium resources last before more exploration will be needed?
- What quantity of spent nuclear fuel will be generated?
- How much extra quantity of spent fuel will have to be stored and for how long?

The estimated extra power required from Scenario F (Section 26) will be plotted on the power generation charts in this chapter as a reference point, for which Scenario E must reach and sustain if it is to be viable. Scenario F was the combined learnings from this report, presenting a hybrid solution of EV and H_2-Cell transport, supported by a non-fossil fuel energy mix. The additional annual electrical power generation to phase out fossil fuel systems was calculated in Scenario F to be 37 670.6 TWh. So, the NPP fleet would have to expand in size to a total of **40 144.6 TWh** annual capacity (37 670.6 + 2474), where 2474 TWh was the annual electric power delivered to the global power grid by the global fleet of nuclear power stations in 2016. The year 2016 was used as the starting year for Scenario E simulations, as this was the year data was collected for all sectors of the nuclear fuel cycle.

Figure 25.1 shows the systems map order of calculations done for each year between 2021 and 2100.

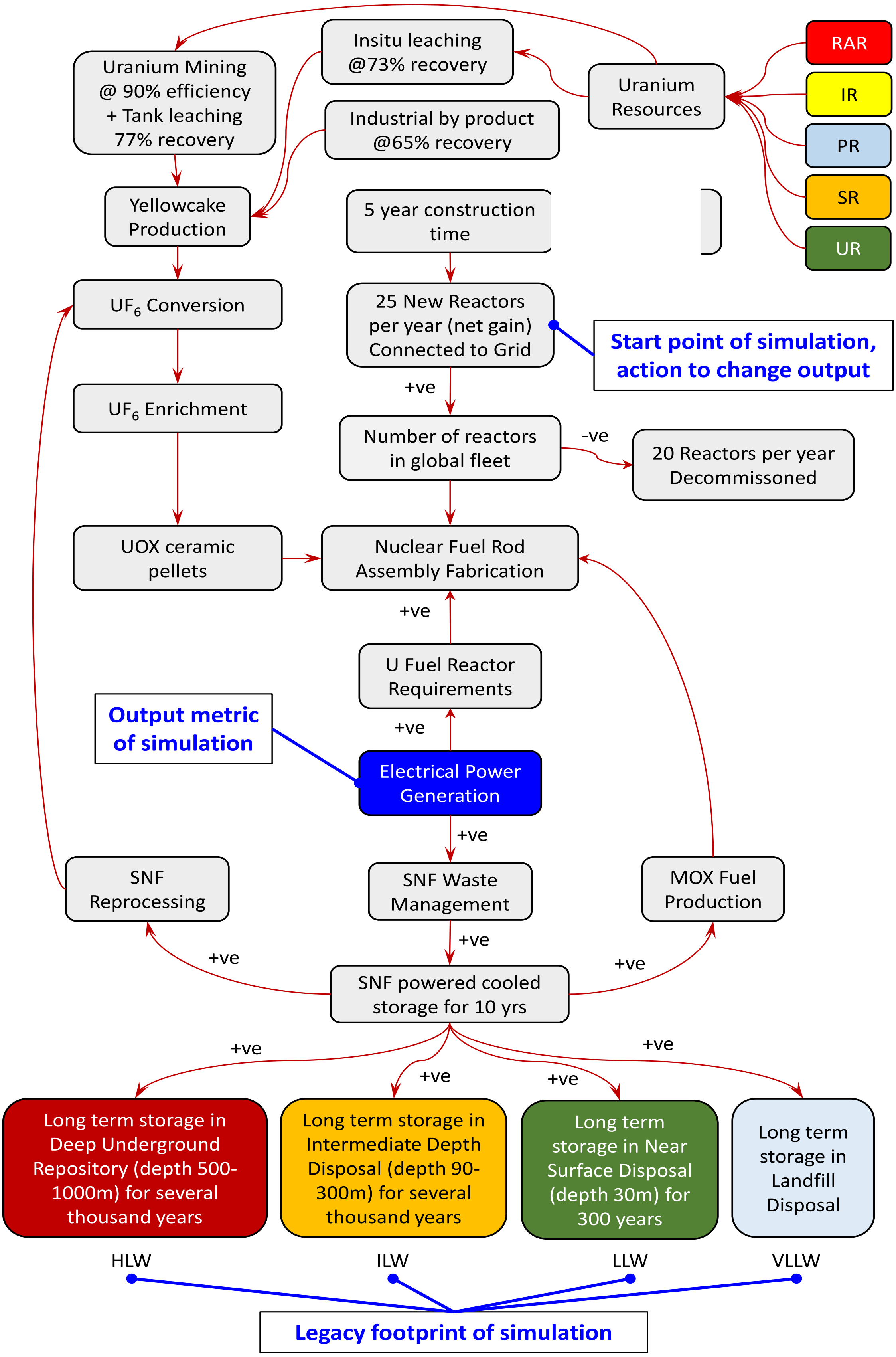


Figure 25.1. Systems map for Scenario E calculations
(Image: Simon Michaux)

25.1 Assumptions Made for Scenario E – Reference

This simulation was termed 'Reference'. In this simulation, the nuclear power plant fleet will stay as it has been for the last two decades. It will slowly increase in size (an increase of two new average sized Generation III+ power plants every 10 years. The electrical power output will slowly increase to reflect how the industry has been developed for the last 10 years projected into the future to year 2100. This simulation was to be a reference point for all other simulations.

The following assumptions were made in the Scenario E – Reference simulation:

Operation of nuclear power plants

- The quantity of nuclear powered electricity generation in 2016 was 2473 TWh (NEA/IEA 2019).
- The availability of each nuclear reactor was 91.5 %, or 334 days in a calendar year.
- The annual output of each average nuclear power plant was 11 221.6 GW.

The size of the nuclear power station fleet

- The number of operating nuclear reactors in 2016 was the global fleet was 441 (NEA/IEA 2019).
- Every ten years there is a net increase of 2 reactors connected to the power grid (accounting for stations being decommissioned).
- All new generators are assumed to be Generation III+ stations. For the purposes of this simulation, all new reactors are assumed to be an APR1400 pressurized water reactor, with an installed net capacity of 1400 MWe (KHNP 2011).

The Advanced Power Reactor 1400 MWe (APR1400) is a standard evolutionary advanced light water reactor (ALWR) in the Republic of Korea (South Korea) developed in 2002, designed by KEPCO and Korea Hydro & Nuclear Power Co., Ltd (KHNP 2011). The design is a development of the OPR1000, the Optimum Power Reactor 1000MWe, the first standard pressurized water reactor (PWR) plant in Korea. The APR1400 is an evolutionary ALWR for which the design is based on the current KSNP design with capacity evolution. It also incorporates a number of design modifications and improvements to meet the utility's needs for enhanced safety and economic goals and to address the new licensing issues such as mitigation of severe accidents (KHNP 2011).

APR1400 is a typical PWR plant using slightly enriched uranium and, hence, is not designed as a breeder or a high-converter reactor. However, the reactor core and other related systems are designed to use MOX fuel up to 1/3 of core. The spent fuel treatment plan is beyond the plant design scope. The APR1400 design has been optimized to achieve the high operation performance and to enhance the convenience of maintenance. The lifetime design goal of availability factor for APR1400 is above 92%. Tables 25.1 and 25.2 show the design specifications of this reactor.

So, if the APR1400 is able to deliver 11 221.6 GWh (1400 MW x 24 hours x 365 days, available 91.5% of the time) in a 365 day cycle, and consumes 29.9 tonnes of nuclear fuel assemblies, it would have an efficiency output of 375.3 GWh/tonne of fuel.

Construction of new infrastructure

- The number of new power plants being constructed will be a net gain of 2 each decade (10 years) (Assumption).

- New SNF tails powered cooled storage will be constructed in line with required global capacity to store new SNF generated (Assumption). In the U.S., approximately 70% of SNF is in powered cooled storage pools (National Research Council 2006), this ratio is projected to the global system. Current SNF long-term storage is at 80-90% of full saturation capacity.

Table 25.1. APR1400 design requirement for safety and performance (Source: KHNP 2011)

Type and capacity	Pressurized Water Reactor (PWR)
Advanced Power Reactor 1400 Mwe	APR1400
General Requirement	
Plant design life	60 Years
Plant availability target	>90%
Seismic design	SSE 0.3g
Primary coolant material	Light Water
Secondary coolant material	Light Water
Moderator material	Light Water
Thermodynamic cycle	Rankine
Type of cycle	Indirect
Safety Goals	
Core damage frequency < 1.0E-5/RY	
Containment failure frequency < 1.0E-6/RY	
Occupational radiation exposure < 1 ma -Sv/RY	
Unplanned trips	less than 0.8 per year
Output	
Reactor thermal output	3 983 MWth
Power plant output, gross	1 455 Mwe
Power plant output, net	1 400 Mwe
Power plant efficiency, net	35.10%
Mode of operation	Baseload and Load follow
Fuel	
Fuel element type	Fuel Rod
Enrichment of reload fuel at equilibrium core	4.09 Weight %
Average Discharge burnup of fuel	44.6 MWd/kg
Refueling interval	18 months or longer

Table 25.2. APR1400 fuel requirements (Source: Lamarsh & Baratta 2001, KHNP 2011, https://energycentral.com/c/ec/gen-3-nuclear-power-plants-minimal-fuel-use)

Input Parameter	APR1400 Reactor
Electric power output (MWe)	1400
Electric power output (GWe)	1.40
GWd/yr	467.57
GWd/t	44.60
Efficiency	35.1%
Fuel rod assemblies (t/yr)	29.87
% ^{235}U enrichment	4.09%

Global uranium resources of all classifications

- Uranium resources available are assumed as follows.

Table 25.3. Total global uranium resources
(Source: NEA/OECD Uranium 2018 Resources, Production and Demand) (Table G26 in Appendix G)

Uranium Resource	Acronym	Tonnes of U content
Reasonably Assured Resources	RAR	4 815 100
Inferred Resources	IR	3 173 000
Prognosticated Resources	PR	1 698 300
Speculative Resources	SR	5 832 300
Unconventional Resources	UR	8 116 900
	Total	23 635 600

Mining and mineral processing of U

- In 2016, the global mining of uranium in terms of Uranium content was 62 825 tonnes, at a variable grade (approximately 31.41 million tonnes of uranium ore) (Table 24.3 in Section 24).

- For each additional example Generation III+ nuclear reactor (size 1400 MWe installed capacity) that produces 11.2 TWh of electricity in a 365-day time period, this operation will require the mining of ore of various grades with 219.7 tonnes of uranium content, following the process flow sheet in Figure 24.24 (Calculation).

- The mining and mineral processing recovery of the production of Yellow Cake (U_3O_8) extraction efficiency was split into several sources. In situ leaching of uranium accounted for 57 % of annual supply of yellow cake U_3O_8 in 2016, which had a U recovery of 73 %. Conventional mining of uranium ore, which is then processed with tank leaching, accounted for 35.8% of 2016 annual supply of U_3O_8, had a U recovery of 77 %. Mining of the ore deposit was considered to by 90% efficient, leaving 10% of the U resource in the ground. Production of U_3O_8 as an industrial by-product accounted for 6.8% of annual supply, which had a U recovery of 65%. These proportional were used to estimate the needed amount of U supply form these sources, based on reactor requirements.

Conversion of Yellow Cake (U_3O_8) to uranium hexafluoride (UF_6)

- For each tonne of Yellow Cake (U_3O_8), 1.25 tonne of uranium hexafluoride (UF_6), 0.59 tonne solid waste, and 5.48 m^3 of liquid waste generated were produced (Figure 25.2) (Lamarsh & Baratta 2001, Glasstone & Sesonske 1994).

- The required mass of UF_6 from conversion is estimated from the annual nuclear reactor requirements of ceramic fuel pellets (accounting for the mass contributed by reprocessing of SNF fuel) (Assumption).

- A Generation III+ reactor producing 11.2 TWh, requires 29.9 tonne of nuclear fuel. If this fuel was sourced completely from yellow cake, then 198.83 tonnes of yellow cake would be converted to 248.11 tonnes of UF_6 (Lamarsh & Baratta 2001, Glasstone & Sesonske 1994).

Centrifuge enrichment of UF_6

- For each tonne of natural uranium hexafluoride (UF_6), 0.160 tonne (160kg) of enriched UF_6 is produced (to a content concentration of 4.09 %), and 0.840 tonne of depleted uranium (UF_6) generated was produced (Figure 25.2) (Lamarsh & Baratta 2001, Glasstone & Sesonske 1994).

- Annual enrichment of UF_6 globally in 2015 was 47 285 SWU (Table 24.14 in Section 24). For yearly Generation III+ reactor requirements in this simulation, 248.11 tonnes of converted UF_6 would then be enriched to 39.37 tonnes of enriched UF_6, at a grade of 4.09% ^{235}U.

The fabrication of UOX ceramic pellets

- The annual fabrication of nuclear UOX fuel ceramic pellets in 2016 was 13 913 tonnes (Table 24.15 in Section 24).

- For each additional tonne of enriched uranium hexafluoride (UF_6), 0,76 tonne (759 kg) of ceramic nuclear fuel pellets, 0.33 m^3 of solid waste and 6.02 m^3 of liquid waste were produced (Figure 25.2). The global quantity of UOX ceramic pellets required to service reactors is estimated based on overall reactor requirements, minus the quantity of MOX fuel produced in that year.

The fabrication of nuclear fuel rod assemblies

- The annual fabrication of Nuclear fuel assemblies is sourced from UOX pellets and MOX fuel that has been produced from SNF. In 2016, 15 276 tonnes of nuclear fuel rod assemblies were produced (Table 24.15 in Section 24).

- For each additional average sized Generation III+ nuclear reactor (size 1400 MWe installed capacity) that produces 11.222 TWh of electricity in a 365-day time period, this operation will require 29.9 tonnes of nuclear fuel rod assemblies (Figure 25.2, Table 25.2).

Mass of Spent Nuclear Fuel generated and put in powered underwater cooled storage

- Globally in 2010, there was 246 000 tonnes of Spent Nuclear Fuel (SNF) in storage facilities (IAEA 2018).

- In the U.S., approximately 70% of SNF is in powered cooled storage pools (National Research Council 2006), this ratio is projected to the global system. New SNF tails powered cooled storage and long-term storage facilities will be constructed in line with required global capacity to store new SNF generated. This means that in 2010, when globally there was 246 000 tonnes of SNF in storage, it is assumed that 172 000 tonnes is in power cooled storage and the rest is in dry storage (IAEA 2018).

- Globally 12 000 tonnes of Spent Nuclear Fuel (SNF) is generated each year (IAEA 2007). This assumed to continue as the existing nuclear power plant fleet will continue to operate. The additional SNF produced by the new Generation III+ plants will be calculated separately and added to this Reference.

- In this simulation, annual additional generated SNF will be added to the existing stockpile of 172 000 tonnes of SNF. This has been done to reflect what might happen if appropriate storage facilities of SNF are not constructed.

Reprocessing of Spent Nuclear Fuel (SNF)

- The global annual mass of reprocessed spent nuclear fuel was 1 080 tonnes. This rate remains static. In this simulation, the Generation III+ reactor, based on the APR1400, reprocessed nuclear fuel cannot be used as feed stock fuel.

Fabrication of MOX fuel from SNF

- The global fabrication of MOX fuel was 992 tonnes (Table 24.21 in Section 24). This rate remains static.

- In this simulation, the Generation III+ reactor, based on the APR1400, where MOX fuel can account for up to 1/3rd of the fuel mix. The MOX fuel stream is added to the UOX fuel stream to be merged and fabricated into nuclear fuel assemblies.

Mass of Spent Nuclear Fuel put in long-term storage after power cooled storage

- Current SNF long term storage is at 80-90% of full saturation capacity (WNWR 2019, IEA 2018).

- It is assumed that no new long-term storage facilities are built and all generated SNF is put into cooled storage. While this assumption is not sensible, it will provide a contrast to the proposed handling of SNF in the Generation II, Generation III+ and Generation IV simulations. The appropriate handling and storage of SNF in the back end of the nuclear fuel cycle is currently a limitation for scale up of the nuclear power plant fleet. This assumption, while not practical, will highlight the scale the task ahead and the need for early investment in adequate long-term storage of SNF.

Table 25.4. Proportions of types of Spent Nuclear waste and their method of storage (Source: IAEA 2018)

Spent Nuclear Fuel Generated	Proportion	Method of Storage
Low Level Waste (LLW)	69,2 %	Stable waste disposal in landfill
Very Low Level Waste (VLLW)	29,2 %	Long term storage of spent nuclear fuel in near surface depth facilities (30m)
Intermediate Level Waste (ILW)	1,6 %	Long term storage of spent nuclear fuel in intermediate depth facilities (90-300m)
High Level Waste (HLW)	0,06 %	Long term storage of spent nuclear fuel in deep underground geological repository facilities (500-1000m)

Global uranium resources of all classifications

- The resources available in this simulation are assumed to be the same as in Table 25.3.

Figure 25.2 shows the outcomes of a calculation of the inputs and outputs based on the assumptions listed. Figure 25.2 was developed by inputting the estimated needed nuclear fuel requirement of a Generation III+ reactor, then estimated the raw material streams to produce that nuclear fuel.

Figures 25.2 to 25.6 show the outcomes of this simulation. Appendix P shows the data results.

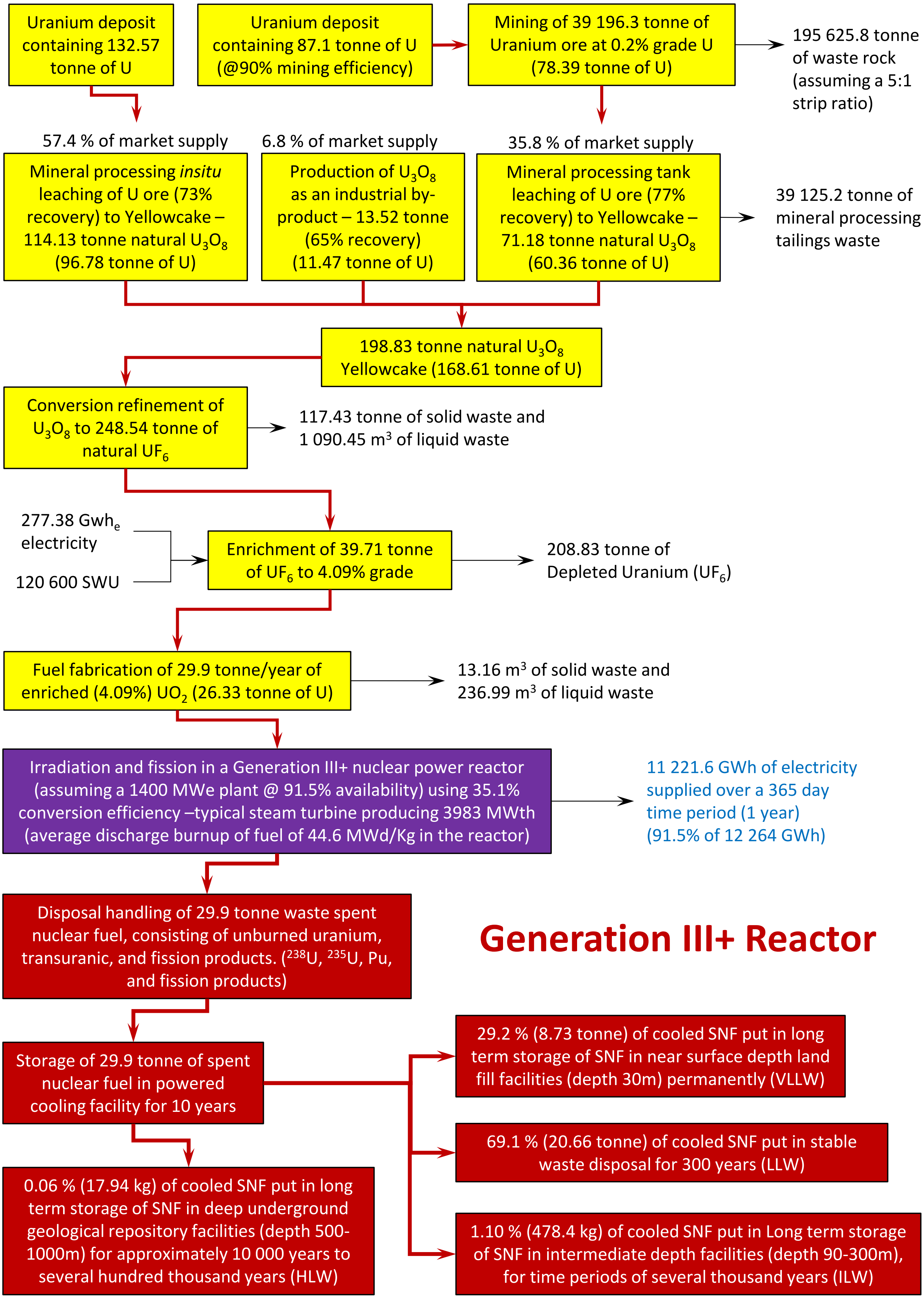


Figure 25.2. Calculation of uranium requirements in the nuclear fuel cycle in a Generation III+ reactor (Image: Simon Michaux)
(Source: data drawn from IAEA 2007, NEA/OECD Uranium 2011, Glasstone & Sesonske 1994, KHNP 2011)

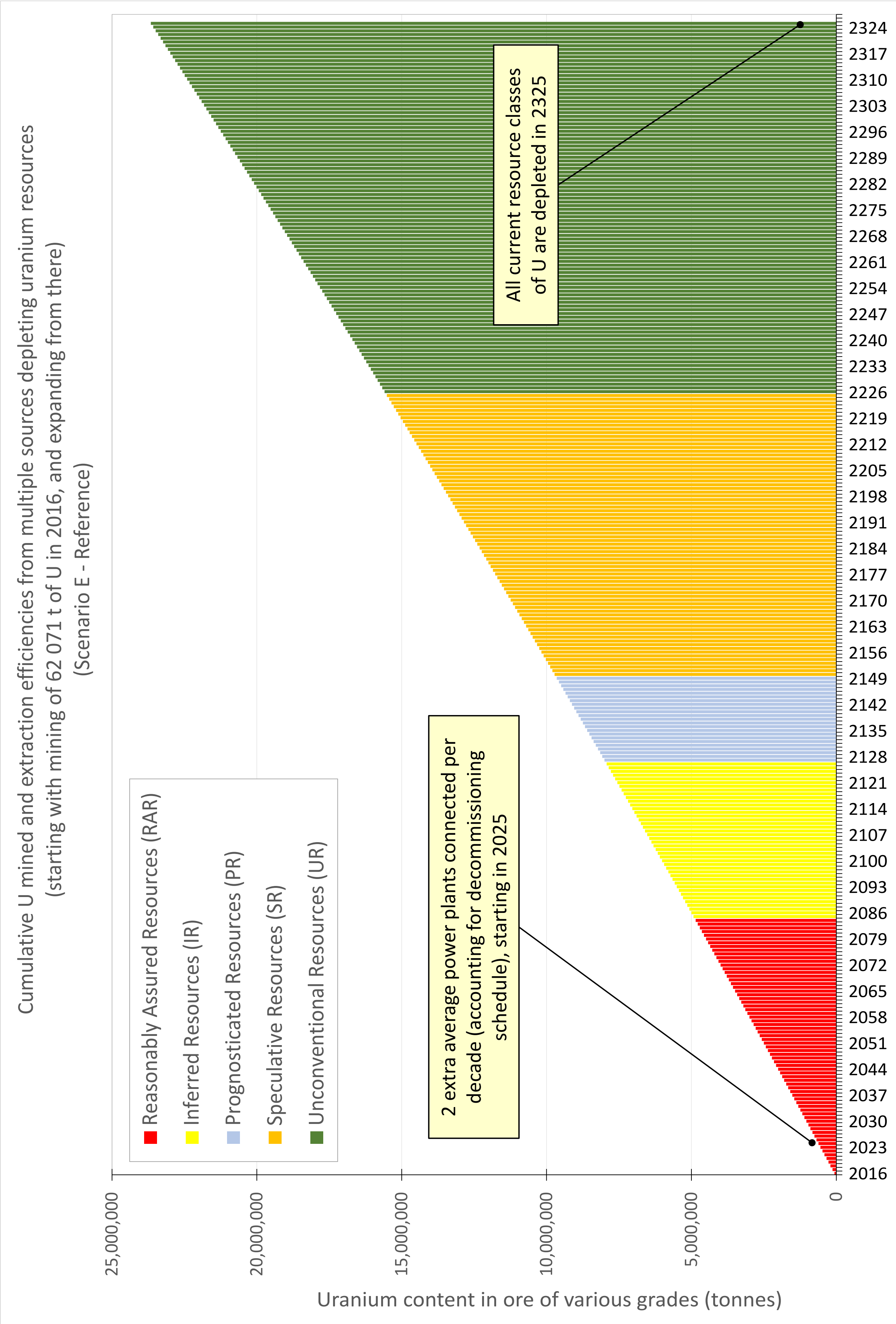


Figure 25.3. Cumulative uranium mined over time, extracting U from all resource classes in Scenario E - Reference

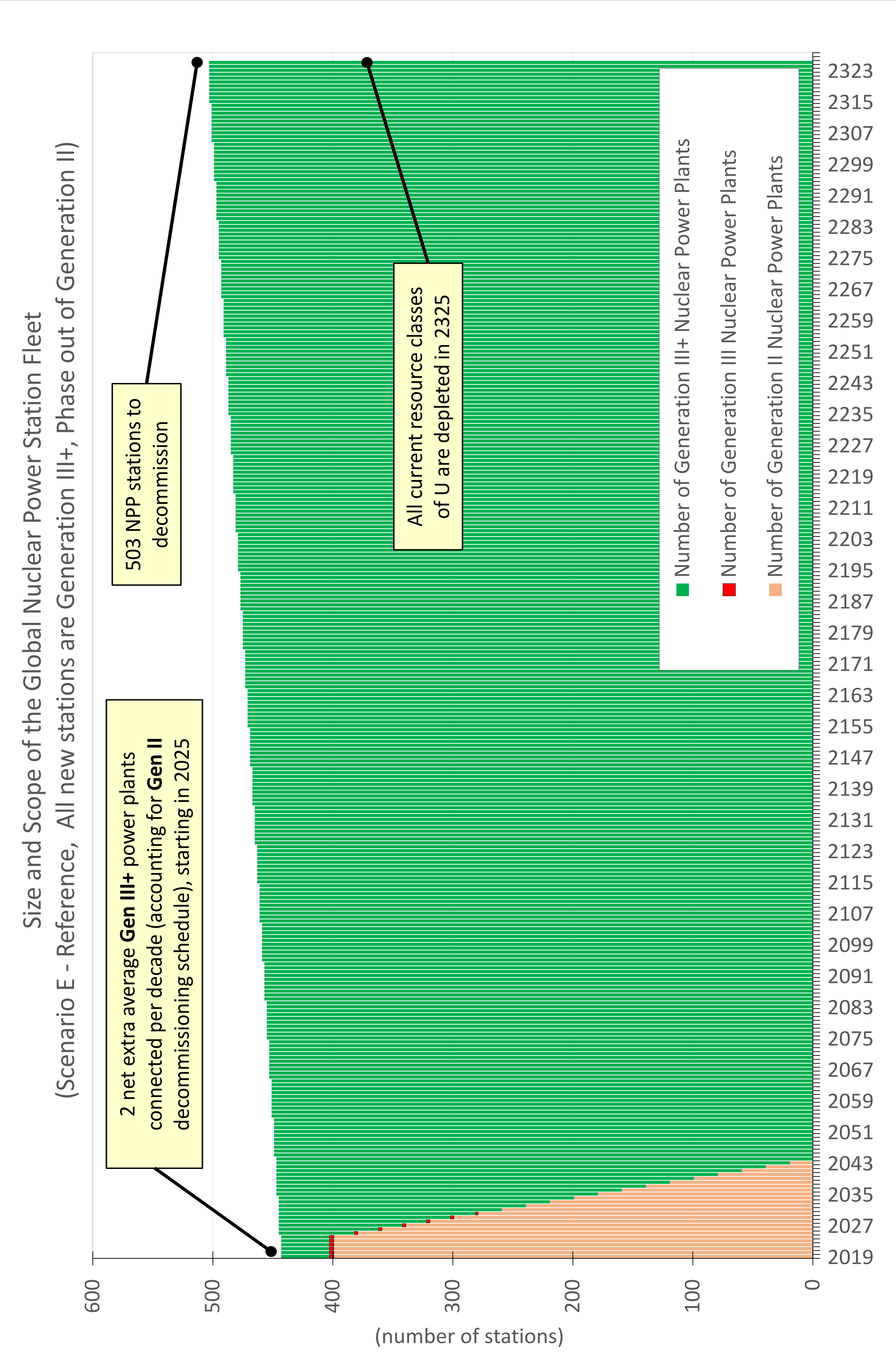


Figure 25.4. Number of nuclear power plants in the global fleet over time, Scenario E - Reference

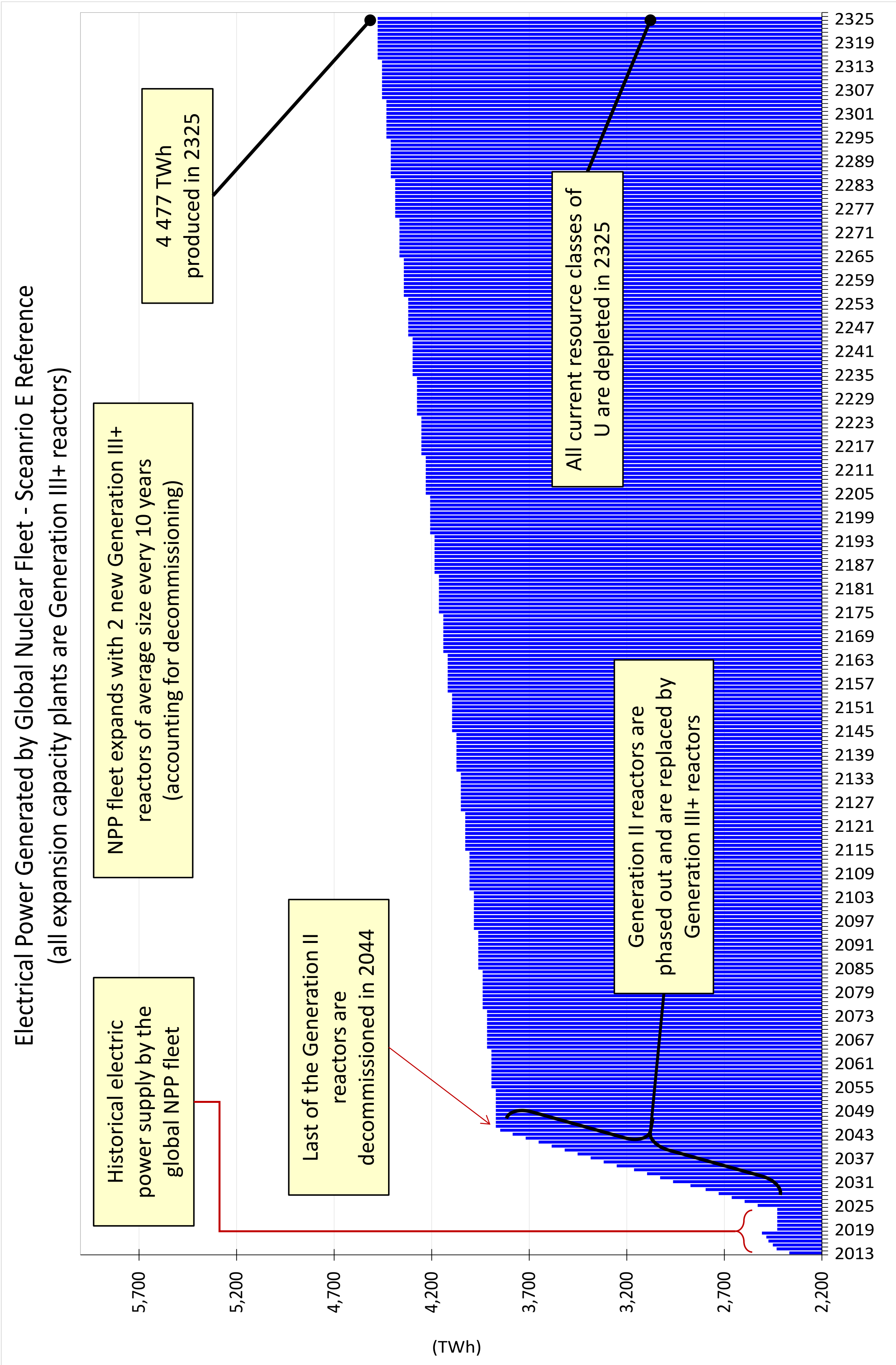


Figure 25.5. Global electrical power generated by nuclear power plants in Scenario E – Reference

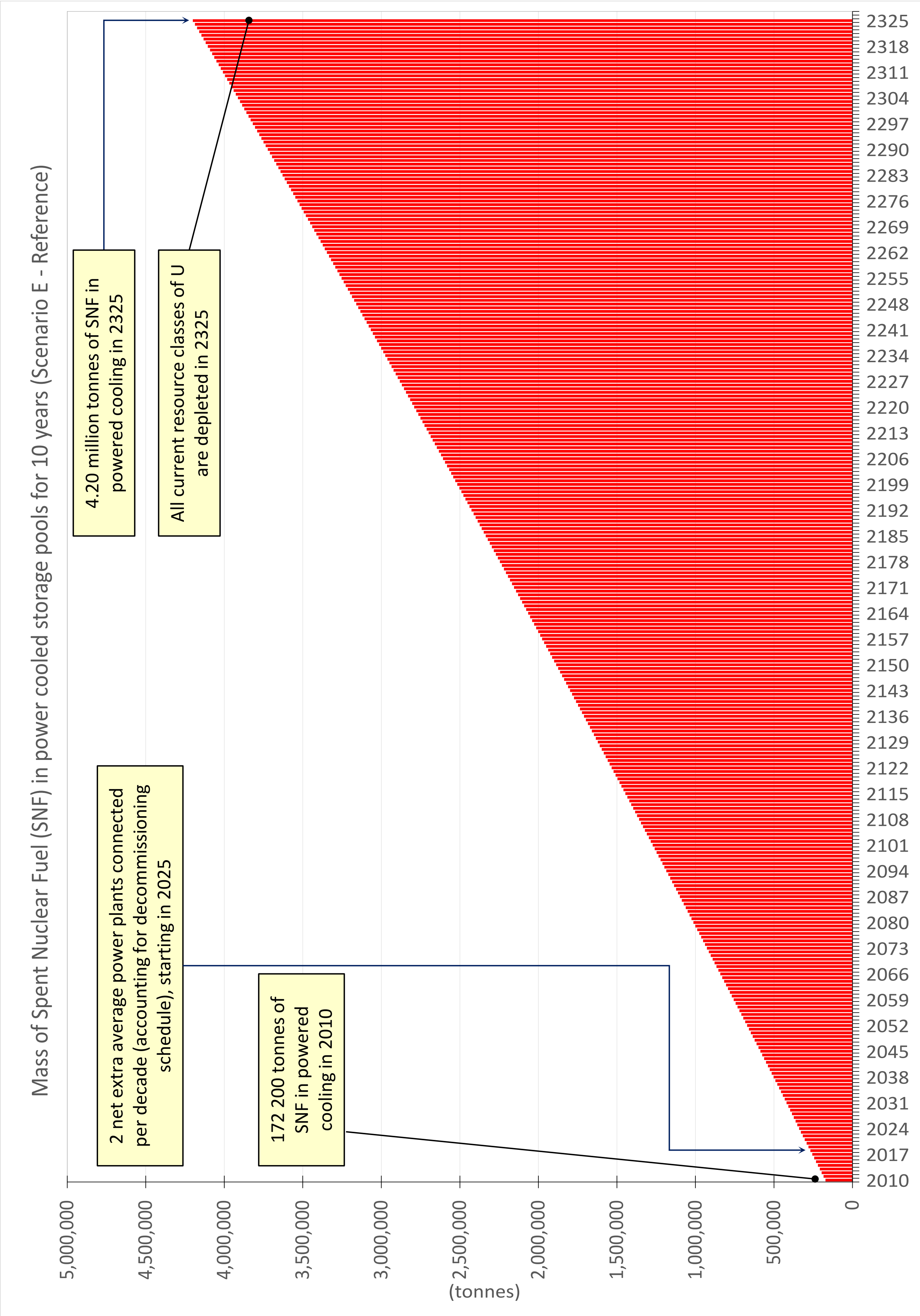


Figure 25.6. Spent nuclear fuel in power cooled storage for 10 years in Scenario E - Reference

25.1.1 Outcomes of Scenario E – Reference Simulation

The following learnings were gained from this simulation:

Table 25.5. Consumption of U resources in Scenario E – Reference Simulation

Resource Class	Quantity (tonnes)	Start of Consumption	Year of depletion
Reasonably Assured Resources (RAR)	4,815,100	2016	2084
Inferred Resources (IR)	3,173,000	2085	2126
Prognosticated Resources (PR)	1,698,300	2127	2149
Speculative Resources (SR)	5,832,300	2150	2225
Unconventional Resources (UR)	8,116,900	2226	2325

- In 2325, all current uranium resources had been consumed, which means the current NPP fleet could be supplied with uranium from mining for the next 304 years. The Reasonably Assured Resources (RAR) were sufficient in supply until the year 2084. Just so, there is ample uranium supply to produce fuel for the nuclear power plant fleet, if it stays on its current trajectory of development.

- The annual electrical power delivered by the global NPP fleet in 2050 was 3 871 TWh and 3 983 TWh in the year 2100. In 2325, the NPP fleet was delivering 4 477 TWh annually, where in the same year all current U resources are exhausted.

- When the current U resources are exhausted in the year 2325, 503 NPP stations would be required to be decommissioned.

- The total mass of Spent Nuclear Fuel (SNF) to be stored in powered cooling facilities in 2050 was 647 167 tonnes, a 265 % increase of the SNF stockpile in 2016. By 2100, that SNF stockpile was projected to be 1 259 629 tonnes. Uranium reserves are projected to be able to supply the NNP fleet till the year 2325, when an estimated 4 200 608 tonnes would be in power cooled storage. This 4.20 million tonnes would have to be stored in powered facilities when the nuclear power plant fleet, would no longer deliver power to the global electricity grid, and the required power to cool the SNF would have to be sourced from other non-fossil fuel powered systems like wind, solar or hydro.

- When the current U resources are exhausted in the year 2325, the estimated SNF in power cooled storage would be 17.2 times the 2016 SNF in power cooled storage. If more appropriate long-term storage facilities were constructed, this number would be lower. This outcome was done to be a contrast to proposed ambitious SNF handling regimes in Generation III+, Generation II and Generation IV simulations.

Table 25.6. Simulation outcome of Scenario E – Reference (Appendix P)

Year	Units	2016	2030	2050	2100	2150	2200	2250	2300	2325
Mining and mineral processing of U annually to meet reactor requirements	(tonnes)	62,071	62,510	63,389	65,586	67,782	69,979	72,176	74,373	75,251
Cumulative sum U extracted from resources with various methods from 2016	(tonnes)	62,071	1,030,549	2,430,407	6,015,479	9,722,591	13,551,741	17,502,930	21,576,158	23,657,682
UOX pelletization (converted UF_6)	(tonnes)	13,849	14,898	15,371	15,670	15,969	16,268	16,567	16,866	16,985
Rod/assembly fabrication (UOX +MOX)	(tonnes)	15,276	15,890	16,363	16,662	16,961	17,260	17,559	17,858	17,977
Number of nuclear power stations in global fleet	(number)	447	445	449	459	469	479	489	499	503
Number of Generation II Nuclear Power Plants	(number)		379	279	79					
Number of Generation III Nuclear Power Plants	(number)		3	2						
Number of Generation III+ Nuclear Power Plants	(number)		164	449	459	469	479	489	499	503
Electrical power generated by global nuclear fleet	(TWh)	2,474	2,873	3,871	3,983	4,095	4,208	4,320	4,432	4,477
Annual mass of Spent Nuclear Fuel generated and put in powered underwater cooled storage	(tonnes)	12,000	12,613	13,086	13,385	13,684	13,983	14,282	14,581	14,700
Fabrication of MOX fuel	(tonnes)	992	992	992	992	992	992	992	992	992
Mass of Spent Nuclear Fuel (SNF) in power cooled storage pools for 10 years	(tonnes)	244,200	351,268	647,167	1,259,629	1,887,041	2,529,402	3,186,714	3,858,976	4,200,608

25.2 Scenario E – Generation III+, all new reactors constructed are Generation III+ technology

In this simulation, all new reactors will be Generation III+, which is the current state of the art industrial engineering for nuclear technology that is considered reliable. The nuclear power fleet will be expanded as fast as possible to supply the needed electrical power required by Scenario A (Section 21), B (Section 22) and C (Section 23).

This is to examine the outcome if new technology was used due the clear efficiencies and safety advancements Generation III+ technology has over Generation II technology. The following assumptions were made in this systems simulation.

The APR1400 reactor is used (KHNP 2011) as an example in Scenario E – Generation III+, as shown in Section 25.1. Comparing the Generation III+ reactor (the APR1400), with its fuel efficiency of 375.3 GWh/tonnes of fuel, to the Generation II reactor (1000 MW), with its fuel efficiency of 215.7 GWh/tonne of fuel, it becomes apparent that technology has increased the power quantity output, fuel efficiency and reliability of service. The APR1400 not only has 40% greater power output but has increase of fuel efficiency of 74%. This is why Generation III+ reactors are more expensive and take longer to construct.

Uranium mining, UF_6 enrichment, and nuclear fuel rod assembly manufacture, were all estimated starting with the annual reactor requirements expanded number of nuclear power plants connected to the power grid. This simulation uses the same nuclear cycle profile as Figure 25.2. The following assumptions have been made in the Scenario E - Generation III+ simulation:

Construction of new infrastructure

- Construction time is optimized to be extremely efficient and is reduced to 5 years. Current construction cycle in 2020 for a nuclear reactor is 15-25 years due to variety of practical problems. The assumption is all of these are resolved. It is assumed a society wide emergency was declared and a ‘forced march’ pace of industrial production similar to what happened in the United Kingdom and the United States in World War II was undertaken. (Assumption)

- Construction of new nuclear power plants starts in 2021 and will be operating and connected to the grid 5 years later. So, the first group of new stations will be operating in 2026 (Assumption).

- The number of new power plants being constructed will be a net gain of 25 each year (Assumption).

- Each year construction of new stations will start in parallel to existing sites under construction. This means a massive increase in the capability to construct these sites (Assumption).

- New SNF tails powered cooled storage and long-term storage facilities will be constructed in line with required global capacity to store new SNF generated. In the U.S., approximately 70% of SNF is in powered cooled storage pools (National Research Council 2006), this ratio is projected to the global system. Current SNF long term storage is at 80-90% of full saturation capacity (Assumption).

The size of the nuclear power station fleet

- The number of operating nuclear reactors in 2016 was the global fleet was 441 (NEA/IEA 2019).

- All new nuclear power plants are assumed to be Generation III+ stations, using the APR1400 specifications (KHNP 2011).

- Starting in 2026, there is a net increase of 25 reactors connected to the power grid (accounting for stations being decommissioned) each year (Assumption).

- It is assumed that 20 Generation II reactors from the existing 2016 power plant fleet will decommission each year, starting in 2025, until 2047. All new reactors to meet demand and net increase the fleet size by 25, will be Generation III+ reactors. Construction of new sites will be done to meet the net gain of 25 new stations each year (Assumption).

Operation of nuclear power plants

- The quantity of nuclear powered electricity generation in 2016 was 2 473 TWhe (NEA/IEA 2019)

- The availability of each Generation III+ nuclear reactor was 91.5%, or 336 days in a calendar year (NEA/IEA 2019).

- The annual output of each average Generation III+ nuclear power plant was 11 221.6 GWhe (assuming 91.5% availability) (Calculation)

Global uranium resources of all classifications

- For this simulation, the available uranium resources are assumed to be the same as Table 25.5 shown in Section 25.1.

Mining and mineral processing of U

- In 2016, the global mining of uranium in terms of Uranium content was 62 825 tonnes, at a variable grade (approximately 31.41 million tonnes of uranium ore) (Table 24.16).

- The mining and mineral processing recovery of the production of Yellow Cake (U_3O_8) extraction efficiency was split into several sources. The numbers and proportions assembled for the Reference Scenario for mining and mineral processing were used in this simulation.

- For each additional average sized Generation III+ nuclear reactor (size 1400 MWe installed capacity) that produces 11.2 TWh of electricity in a 365-day time period, this operation will require the supply of 198.83 tonne of Yellow Cake U_3O_8. In situ leaching would supply 57.4% of this. Conventional mining would supply 35.8% of this and production of uranium as an industrial by-product would supply 6.8%.

- This means that U reserves would be depleted by 260 tonnes each year to supply a single Generation III+ reactor. This assumes a mining efficiency of 90%, leaving 10% of U in situ.

- This ore with 260 tonnes of U content would be subject to mineral processing to produce 245.1 tonnes of Yellow Cake U_3O_8.

- The mining and mineral processing recovery of the production of Yellow Cake (U_3O_8) extraction efficiency was split into several sources. The numbers and proportions assembled for the Reference Scenario for mining and mineral processing were used in this simulation.

Conversion of Yellow Cake (U_3O_8) to uranium hexafluoride (UF_6)

- For each tonne of Yellow Cake (U_3O_8), 1.25 tonne of uranium hexafluoride (UF_6), 0.59 tonne solid waste, and 5.48 m^3 of liquid waste generated was produced (Figure 25.2) (Lamarsh & Baratta 2001, Glasstone & Sesonske 1994).

- The required mass of UF_6 from conversion is estimated from the annual nuclear reactor requirements of ceramic fuel pellets (accounting for the mass contributed by reprocessing of SNF fuel) (Assumption).

- A Generation III+ reactor producing 11.2 TWh, requires 29.9 tonne of nuclear fuel. If this fuel was sourced completely from yellow cake, then 198.83 tonnes of yellow cake would be converted to 248.54 tonnes of UF_6 (Lamarsh & Baratta 2001, Glasstone & Sesonske 1994).

- The annual mass of reprocessed SNF fuel is added to the annual conversion UF_6 product mass as feed into the ceramic pellet production process (Assumption).

Centrifuge enrichment of UF_6

- For each tonne of natural uranium hexafluoride (UF_6), 0.160 tonne (160kg) of enriched UF_6 is produced (to a content concentration of 3.2%), and 0.875 tonne of depleted uranium (UF_6) generated were produced (Figure 25.2) (Lamarsh & Baratta 2001, Glasstone & Sesonske 1994).

- Annual enrichment of UF6 globally in 2015 was 47 285 SWU (Table 24.14).

- Additional UF_6 demand to fuel the new Generation III+ reactors are calculated based on nuclear fuel reactor requirements.

- For yearly Generation III+ reactor requirements in this simulation, 248.54 tonnes of converted UF_6 would then be enriched to 39.71 tonnes of enriched UF_6.

The fabrication of UOX ceramic pellets

- The annual fabrication of nuclear UOX fuel ceramic pellets in 2016 was 13 913 tonnes (Table 24.15 in Section 24).

- For each additional tonne of enriched uranium hexafluoride (UF_6), 0,76 tonne (760kg) of ceramic nuclear fuel pellets, 0.33 m^3 of solid waste and 6.02 m^3 of liquid waste were produced (Figure 25.2) (Lamarsh & Baratta 2001, Glasstone & Sesonske 1994).
- The global quantity of UOX ceramic pellets required to service reactors is estimated based on overall reactor requirements, minus the quantity of MOX fuel produced in that year.

The fabrication of nuclear fuel rod assemblies

- The annual fabrication of Nuclear fuel assemblies is sourced from UOX pellets and MOX fuel that has been produced from SNF. In 2016, 15 276 tonnes of nuclear fuel rod assemblies were produced (Table 24.15).

- For each additional average sized Generation III+ nuclear reactor (size 1400 MWe installed capacity) that produces 11.2 TWh (11 221.6 GWh) of electricity in a 365-day time period, this operation will require 29.9 tonnes of nuclear fuel rod assemblies (Figure 25.2, Table 25.2). This calculation is based on the fuel consumption rate of a Generation II reactor (29.9 tonnes of fuel rod assemblies), then adjusting availability time (where a Generation II reactor is available 71% of the time, compared to a Generation III+ availability of 91.5%).

<u>Mass of Spent Nuclear Fuel generated and put in powered underwater cooled storage</u>

- In this simulation, it is assumed that the stockpile of SNF in powered cooled storage in 2016 is the same as what was assumed in the Reference Scenario in Section 25.1.

- In this simulation, this stockpile of 172 000 tonnes of SNF will be slowly brought out of long-term storage and reprocessed or disposed of appropriately as new storage facilities are constructed, in the same fashion as simulation Generation II in Section 25.2. It is assumed that 10 000 tonnes of new capacity for SNF storage in the kinds of facilities show in Table 25.4 will be made operational each year. This schedule will start in 2025. This 10 000 tonnes of new capacity will be split up by the relative waste proportions shown in Table 25.4. It is in this fashion that the existing stockpile of Spent Nuclear Waste can be appropriately dealt with. This schedule will rehandle all the existing SNF stockpile into a long-term solution by the year 2042.

- Globally 12 000 tonnes of Spent Nuclear Fuel (SNF) is generated each year (IAEA 2007). This assumed to continue as the existing nuclear power plant fleet will continue to operate. The additional SNF produced by the new Generation III+ plants will be calculated separately and added to this Reference.

- Each average sized Generation III+ nuclear reactor will produce 29.9 tonnes each 1 year (365 day) time period (assumption).

- For every tonne of Spent Nuclear Fuel (SNF) generated, there is 1 tonne of SNF placed in powered cooled storage under water, where it will stay for 10 years. After 10 years it removed from power cooled storage and is split up into sub-streams and disposed of as per Table 25.4 Gen II. (Assumption)

<u>Reprocessing of Spent Nuclear Fuel (SNF)</u>

- The global mass of reprocessed spent nuclear fuel was 1080 tonnes (Table 24.20 in Section 24).

- In this simulation, the Generation III+ reactor, based on the APR1400, reprocessed nuclear fuel cannot be used as feed stock fuel.

<u>Fabrication of MOX fuel from SNF</u>

- The global fabrication of MOX fuel was 992 tonnes (Table 24.21).

- Global MOX fuel production from SNF capacity after cooled storage will increase by 500 tonnes each ten years, starting in 2026. It is assumed it will take 5 years to construct these new facilities. Construction is to start in 2021, and the first group will be operational in 2026 (thus in 2026, global MOX production capacity will be 1492 tonnes). From 2026 onwards, an extra 500 tonnes of MOX fuel production from SNF capacity will be constructed each 10 years. For example, an additional 500 tonnes of MOX fuel production from SNF will be operational in the year 2036 (thus in 2036, global capacity will be 1992 tonnes) (Assumption).

- The MOX fuel stream is added to the UOX fuel stream to be merged and fabricated into nuclear fuel assemblies.

- In this simulation, the Generation III+ reactor, based on the APR1400, where MOX fuel can account for up to 1/3rd of the fuel mix.

Mass of Spent Nuclear Fuel put in long term storage after power cooled storage

- Current SNF long term storage is at 80-90% of full saturation capacity (WNWR 2019, IEA 2018).

- For every tonne of Spent Nuclear Fuel that is brought out of cooled storage after 10 years, it is sub-divided according to the proportions shown in Table 25.4.

Figures 25.7 to 25.14 show the outcomes of this simulation. Appendix P shows the data results.

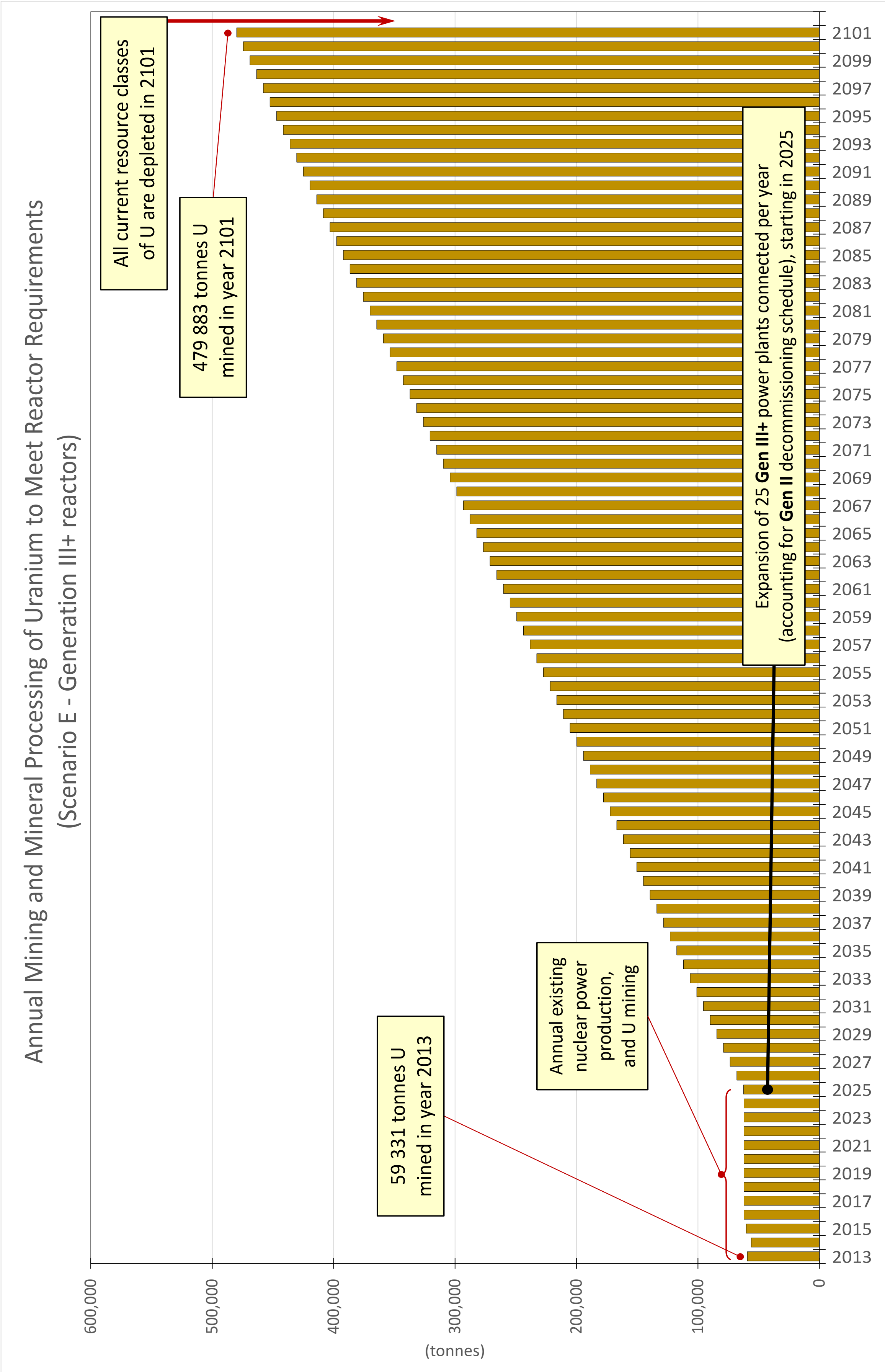


Figure 25.7. Annual uranium mined over time, extracting U from all resource classes in Scenario E-Generation III+

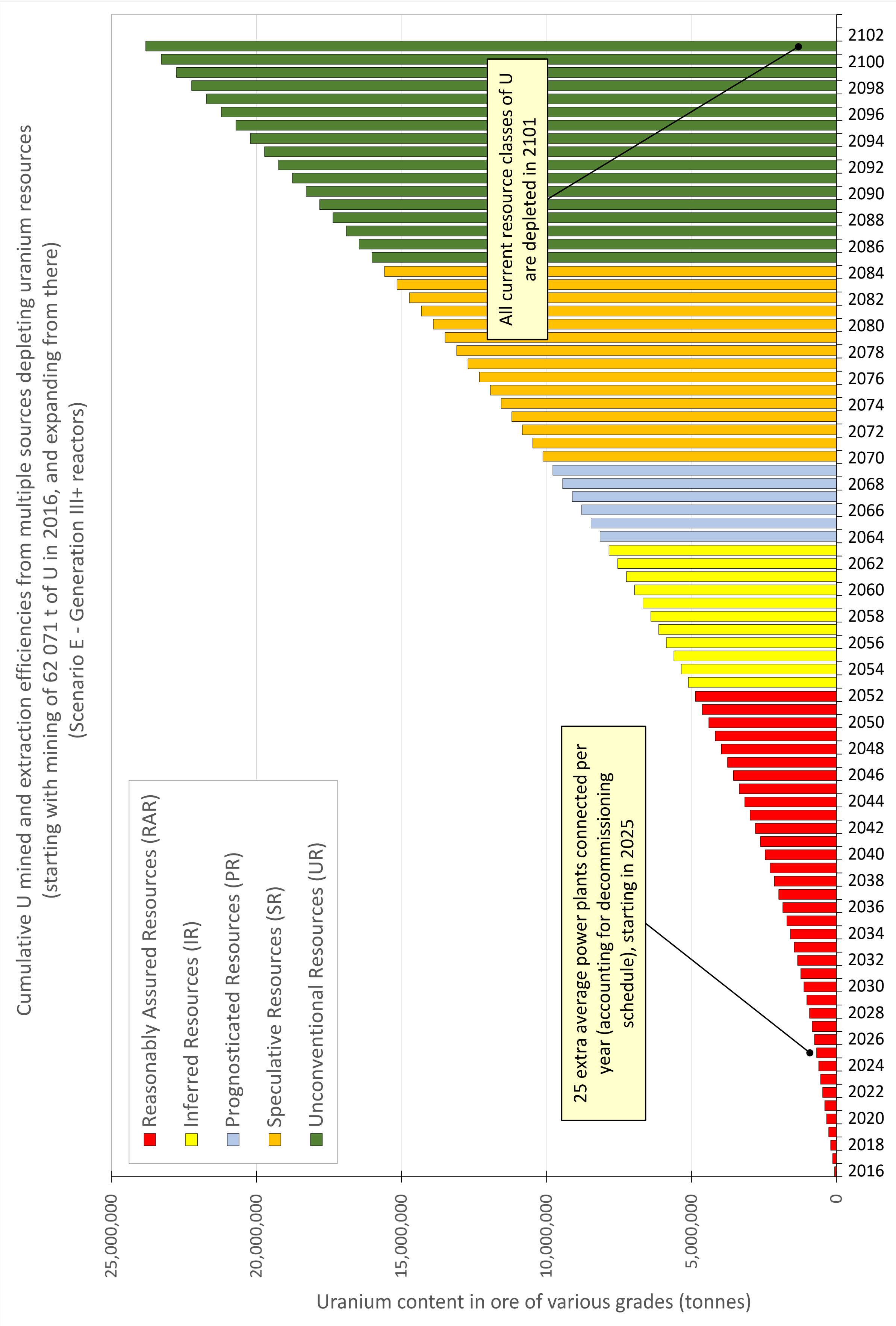


Figure 25.8. Cumulative uranium mined over time, extracting U from all resource classes in Scenario E-Generation III+

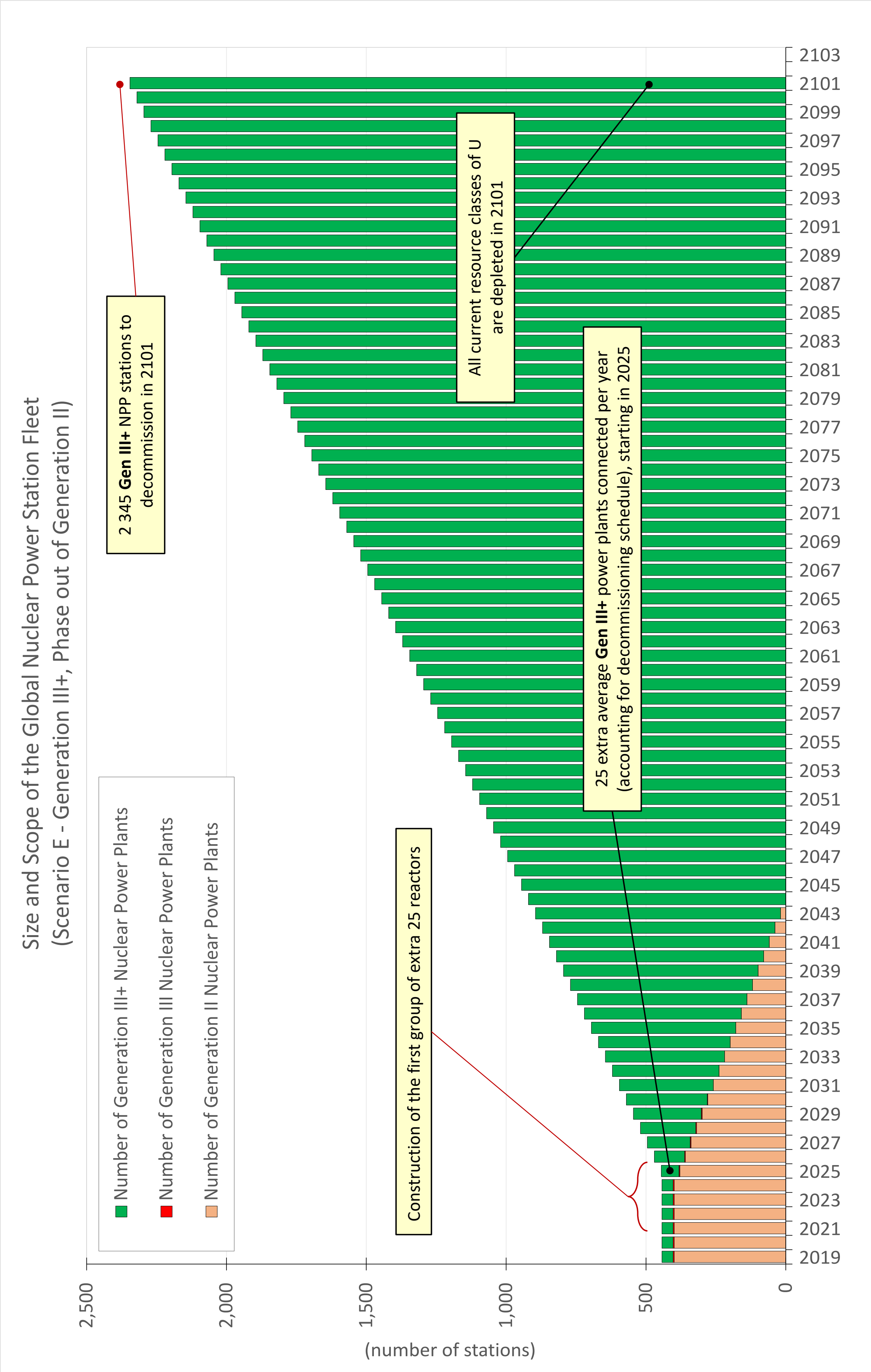


Figure 25.9. Number of nuclear power plants in the global fleet over time, Scenario E-Generation III+

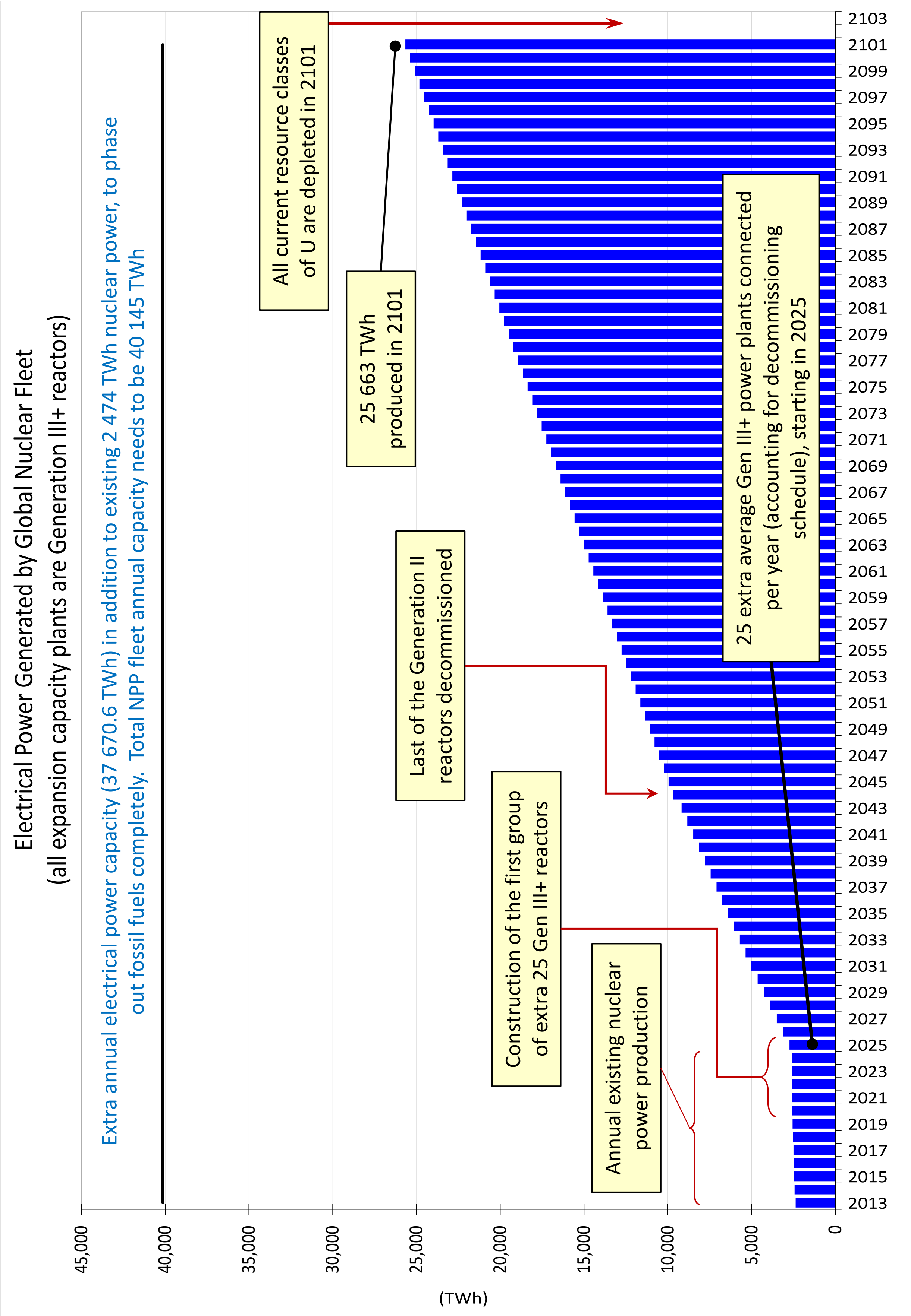


Figure 25.10. Global electrical power generated by nuclear power plants in Scenario E-Generation III+

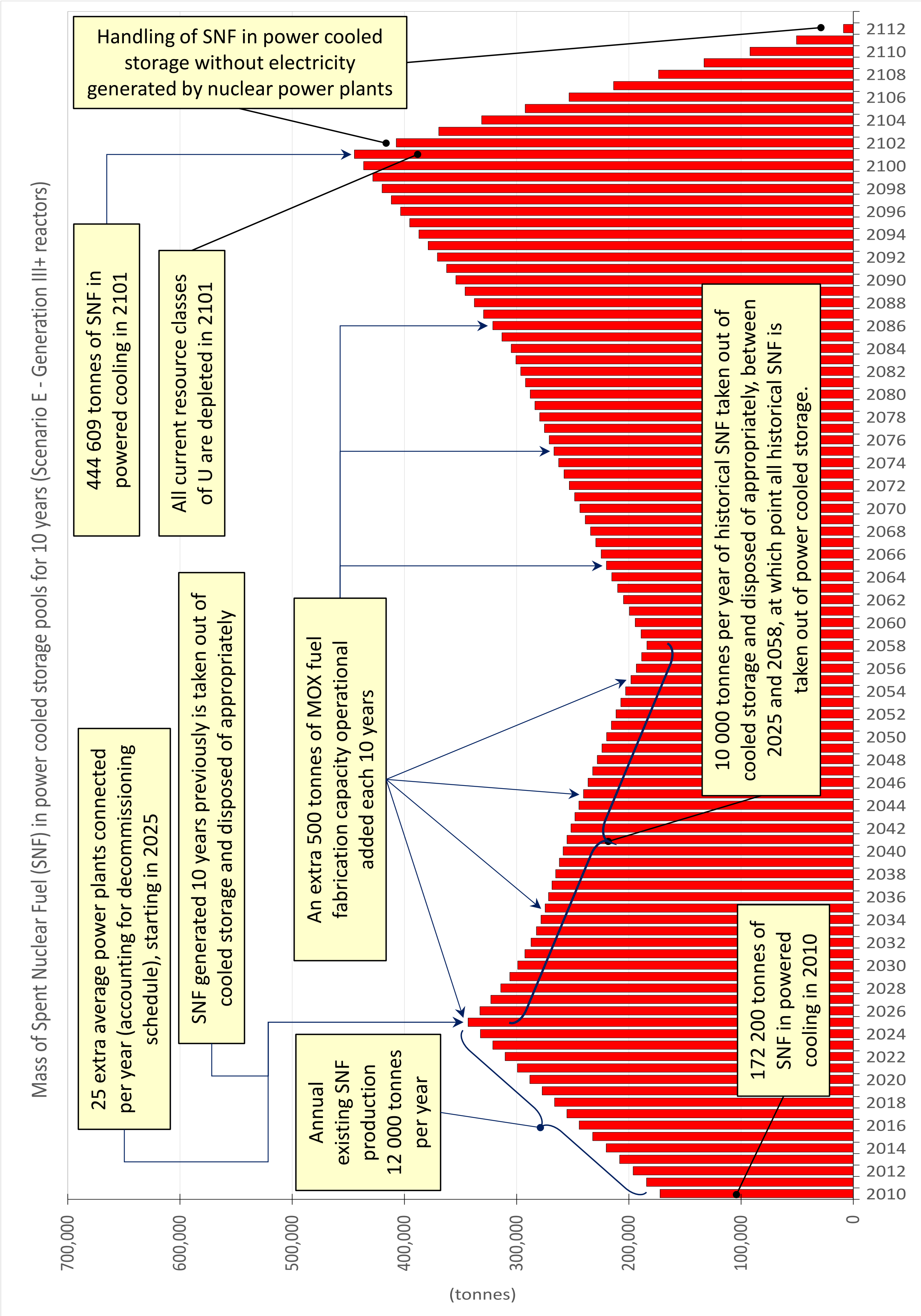


Figure 25.11. Spent nuclear fuel in power cooled storage for 10 years in Scenario E-Generation III+

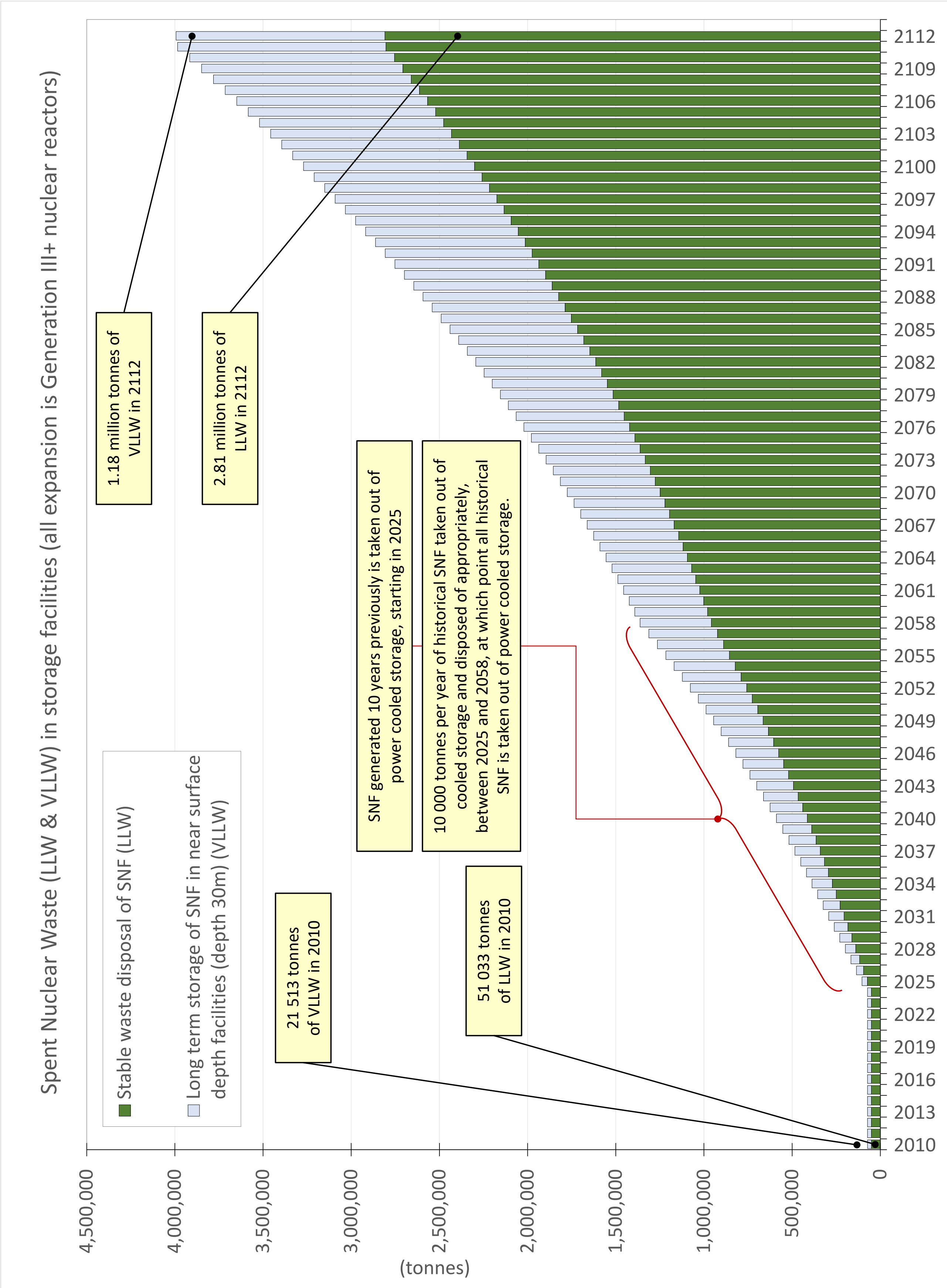


Figure 25.12. Cumulative long-term storage of ILW spent nuclear waste in intermediate depth (90 – 300m) Scenario E – Generation III+

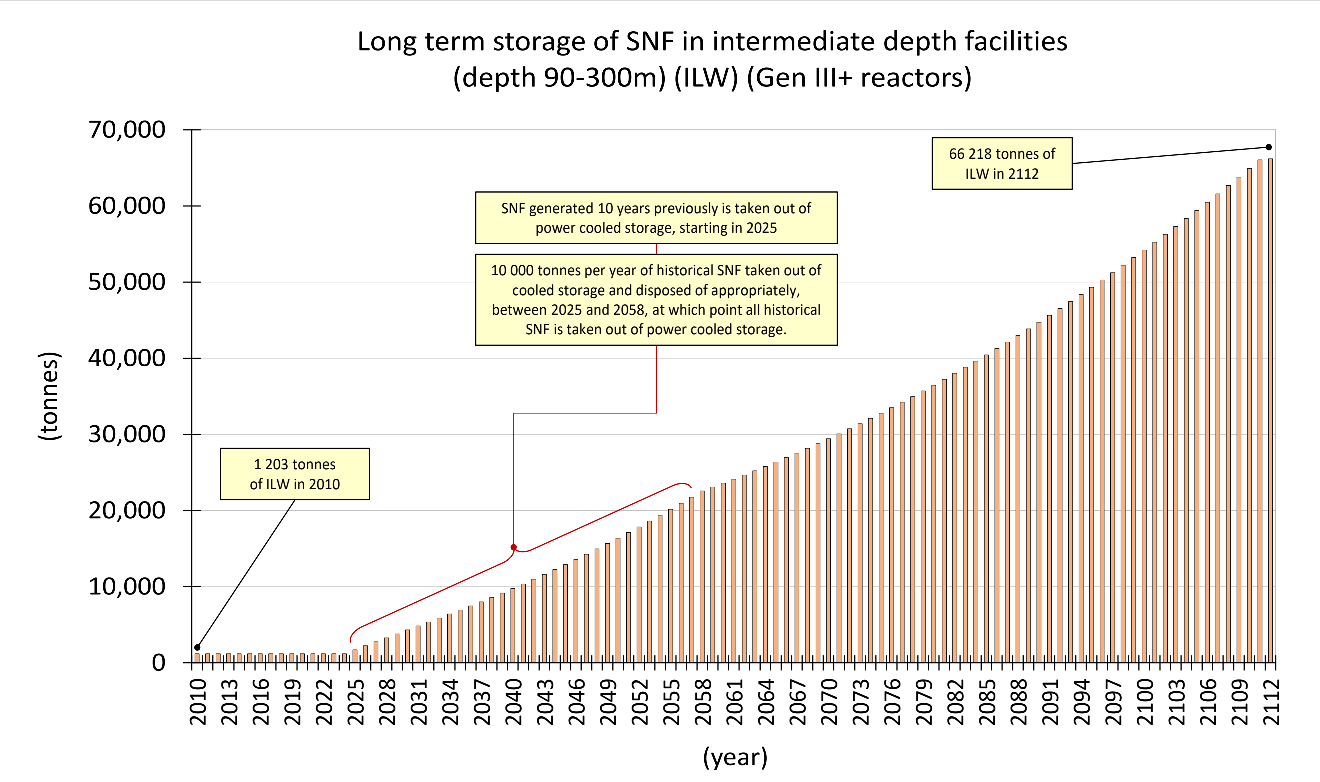


Figure 25.13. Cumulative long-term storage of ILW spent nuclear waste in intermediate depth (90 – 300m) Scenario E – Generation III+

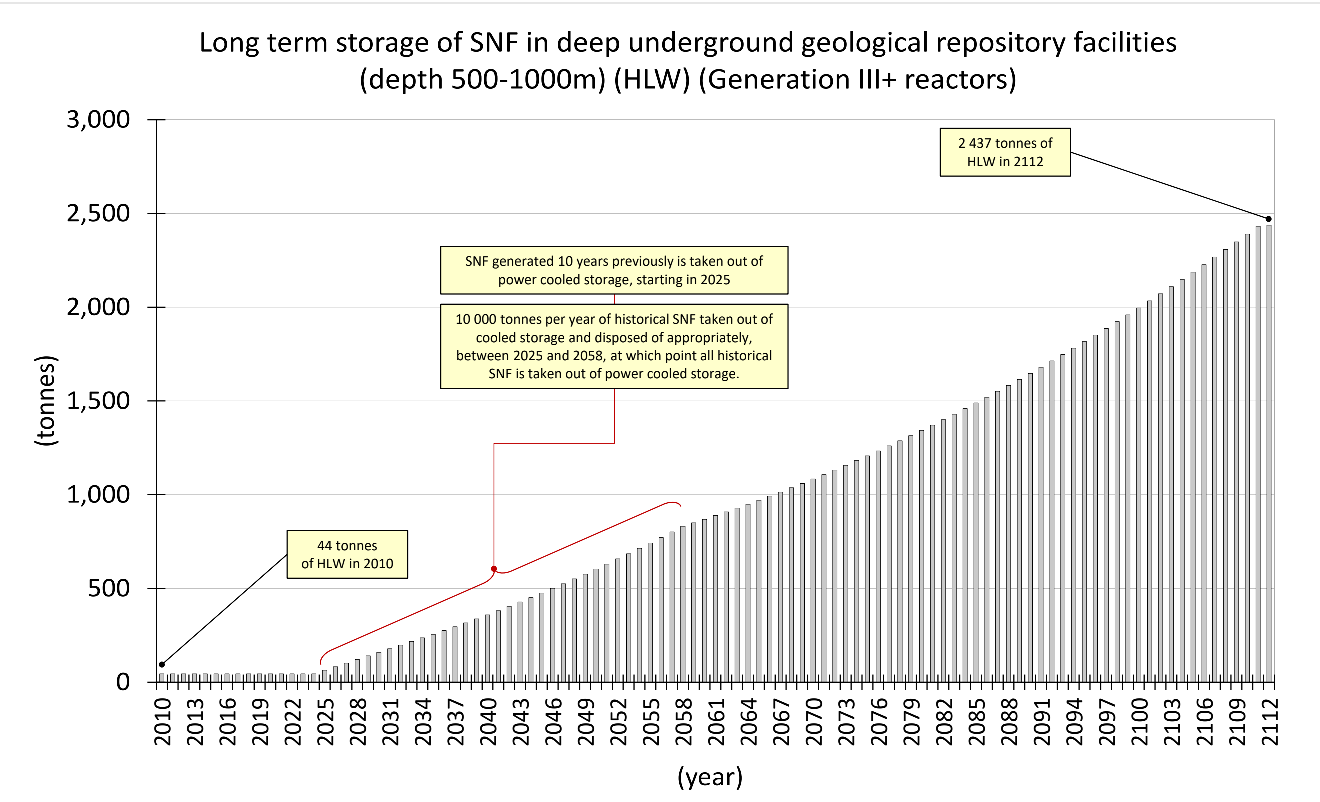


Figure 25.14. Cumulative long-term storage of HLW spent nuclear waste in intermediate depth (500 – 1000m) Scenario E – Generation III+

25.2.1 Outcomes of Scenario E – Generation III+ Simulation

The following learnings were gained from this simulation:

- All resource classes were fully consumed by 2101 in this simulation.

Table 25.7. Consumption of U resources in Scenario E – Generation III+ Simulation

Resource Class	Quantity (tonnes)	Start of Consumption	Year of depletion
Reasonably Assured Resources (RAR)	4,815,100	2016	2052
Inferred Resources (IR)	3,173,000	2053	2063
Prognosticated Resources (PR)	1,698,300	2064	2069
Speculative Resources (SR)	5,832,300	2070	2084
Unconventional Resources (UR)	8,116,900	2084	2101

- In 2101, all current uranium resources had been consumed, thus no more UOX fuel was made from mineral mining sources. This means that the large number of nuclear reactors operating at the time will have to shut down and the fleet of nuclear power stations will no longer deliver electrical power to the global power grid after 2101.

- The annual quantity of electrical power delivered by the global nuclear power plant fleet in 2101 was simulated to be 26 294 TWh. This was 104.1 % higher than what was produced at the peak of Scenario E – Generation II simulation in Section 25.2.

- This 25 633 TWh will only be 63.9 % of the required 40 145 TWh (37 670.6 + 2 474) of required power to service Scenario F (hybrid solution to phase out all fossil fuels completely). For nuclear power to be useful in phasing out fossil fuels, this kind of capacity needs to be available by 2040, with the 40 145 TWh 20 years later, and being delivered reliably for the following century. So there also is not enough time.

- This means that after decades of 'forced march' emergency industrialization, putting our faith in only the expansion of the nuclear power fleet using Generation III+ technology will not achieve long term energy supply security and is not viable. That being stated, this is a better outcome than what the simulation based on Generation II reactors showed.

- In 2101, nuclear power will no longer be fueled by mineral resources of uranium (based on current resources), there will still be 444 609 tonnes of SNF in powered cooled storage pools. This SNF will have to be cooled without electrical power being generated from the nuclear power plant network.

- In 2112, the final stockpile of SNF was as follows:

VLLW	1.18 million tonnes	landfill disposal
LLW	2.81 million tonnes	near surface storage (30m depth) for 300 years
ILW	66 218 tonnes	deep underground geological repositories
HLW	2 437 tonnes	deep underground geological repositories 100 000 years

- The combined mass of ILW and HLW was 68 656 tonnes (66 218 + 2 437), which needs to be stored for 100 000 years. This would require 11 Onkalo facilities (see Section 24.11.2).

Table 25.8. Simulation outcome of Scenario E – Generation III+ (Source: Appendix P)

Year	Units	2016	2025	2030	2040	2050	2060	2070	2080	2090	2101	2112
Mining and mineral processing of U annually to meet reactor requirements	(tonnes)	62,071	62,510	89,969	144,887	199,804	254,722	309,639	364,557	419,474	474,392	
Cumulative sum U extracted from resources with various methods from 2016	(tonnes)	62,071	683,269	1,122,078	2,457,341	4,402,799	6,958,452	10,124,299	13,900,340	18,286,576	23,283,006	
UOX pelletization (converted UF_6)	(tonnes)	13,849	14,345	18,136	25,380	32,438	39,413	46,388	53,363	60,338	67,313	
Rod/assembly fabrication (UOX +MOX)	(tonnes)	15,276	15,337	19,628	27,372	34,930	42,405	49,880	57,355	64,830	72,305	
Number of nuclear power stations in global fleet	(number)	447	445	570	820	1,070	1,320	1,570	1,820	2,070	2,320	
Number of Generation II Nuclear Power Plants	(number)		379	279	79							
Number of Generation III Nuclear Power Plants	(number)		3	2								
Number of Generation III+ Nuclear Power Plants	(number)		63	289	741	1,070	1,320	1,570	1,820	2,070	2,345	
Electrical power generated by global nuclear fleet	(TWh)	2,474	2,736	4,640	8,135	11,355	14,161	16,966	19,772	22,577	25,663	
Annual mass of Spent Nuclear Fuel generated and put in powered underwater cooled storage	(tonnes)	12,000	12,060	16,351	24,096	31,654	39,129	46,604	54,079	61,554	69,776	
Fabrication of MOX fuel	(tonnes)	992	992	1,492	1,992	2,492	2,992	3,492	3,992	4,492	4,992	
Total mass of Spent Nuclear Fuel (SNF) in power cooled storage pools for 10 years	(tonnes)	318,000	343,272	298,984	258,557	219,784	194,295	243,600	287,905	354,162	444,609	8,754.3
Annual mass of Spent Nuclear Fuel taken out of powered underwater cooled storage	(tonnes)	244,200	22,000	22,000	26,351	34,096	31,654	39,129	46,604	54,079	62,301	8,754.3
Total Stockpile mass of SNF to be disposed of into long term storage	(tonnes)	219,897	201,800	361,800	695,032	1,101,405	1,544,181	1,901,830	2,334,229	2,841,378	3,485,578	4,158,456.8
Stable waste disposal of SNF (LLW)	(tonnes)	92,856	73,161	183,801	414,230	695,238	1,001,417	1,248,732	1,547,736	1,898,429	2,343,894	2,809,188.9
Long term storage of SNF in near surface depth facilities (depth 30m) (VLLW)	(tonnes)	5,088	30,841	77,481	174,618	293,076	422,145	526,400	652,444	800,278	988,062	1,184,206.2
Long term storage of SNF in intermediate depth facilities (depth 90-300m) (ILW)	(tonnes)	191	1,725	4,333	9,764	16,388	23,605	29,435	36,483	44,750	55,250	66,218.0
Long term storage of SNF in deep underground geological repository facilities (depth 500-1000m) (HLW)	(tonnes)	44.0	63.5	159.5	359.4	603.2	868.9	1,083.5	1,342.9	1,647.2	2,033.7	2,437.5

25.3 Scenario E – Generation II, all new reactors constructed are Generation II technology

In this simulation, the nuclear power fleet will be expanded as fast as possible to supply the needed electrical power required by Scenario F (Section 26), which is a hybrid solution of all learnings in this report. In this simulation, all new reactors will be Generation II.

The purpose of this simulation is to examine the outcome if new technology was not used due to its cost and complexity (for example Generation III+ reactors) (NEA/IEA 2019) and the older Generation II technology was used due to cost savings. This simulation has been included because exactly this has been proposed to the author in one of the think tank discussion groups assembled to discuss long term energy security, by a senior European government official. While this was not an agreed upon policy, it was thought by a senior decision maker that cheaper nuclear reactors were considered to be better. This simulation was designed to provide a comparison to other options.

25.3.1 Estimation of uranium requirements and plant performance for a Generation II Reactor

To facilitate an estimate for future uranium requirements in context of electrical power generation, a simulation was done to calculate the mass of uranium consumed to generate 1 MW of electricity supplied to the power grid. In a study done in 2007, the IAEA estimated that an operating 1000 MWe (1 GW) light water reactor generates around 30-50 tonnes of spent nuclear fuel annually (IAEA 2007). The largest Generation II reactor is 0.9 GW (World Nuclear Association). A good example to use could be the Krško Nuclear Power Plant in Slovenia is a 0.7 GW power plant of type PWR (NEA/OECD Uranium 2018).

The following generic capability and consumption specifications of a 1000 MWe (3000 MWth) Generation II nuclear power plant reactor have been assembled for the operation of a 12 month cycle (IAEA 2007, Lamarsh & Baratta, US DoE 1993, and Glasstone & Sesonske).

- A typical Generation II reactor may contain about 165 tonnes of fuel (including structural material). A typical Generation II reactor may contain about 100 tonnes of enriched uranium (approximately 113 tonnes of uranium dioxide UO_2).
- This fuel is loaded within fuel rod assemblies. A typical load of 165 tonnes for example, would be 157 fuel assemblies composed of over 45,000 fuel rods.
- A standard fuel assembly design contains capacity to sustain the nuclear chain reaction for approximately 48 months of operation at full power.
- The removed fuel (spent nuclear fuel) still contains approximately 96% of reusable material (it must be removed due to decreasing kinf of an assembly).
- Annual natural uranium consumption of this reactor is approximately 250 tonnes of natural uranium (to produce of about 25 tonnes of enriched uranium).
- Annual enriched uranium consumption of this reactor is approximately 25 tonnes of enriched uranium.
- Annual fissile material consumption of this reactor is about 1 005 kg.
- Annual matter consumption of this reactor is about 1.051 kg.

So, the average Generation II reactor used in this simulation will deliver 7 888.5 GWh (1000 MW x 24 hours x 365 days, available 90% of the time) of electricity to the global power grid in a 365 day cycle and would consume 28.9 tonnes of nuclear fuel assemblies. This means this reactor would have an efficiency output of 273.3 GWh/tonne of fuel.

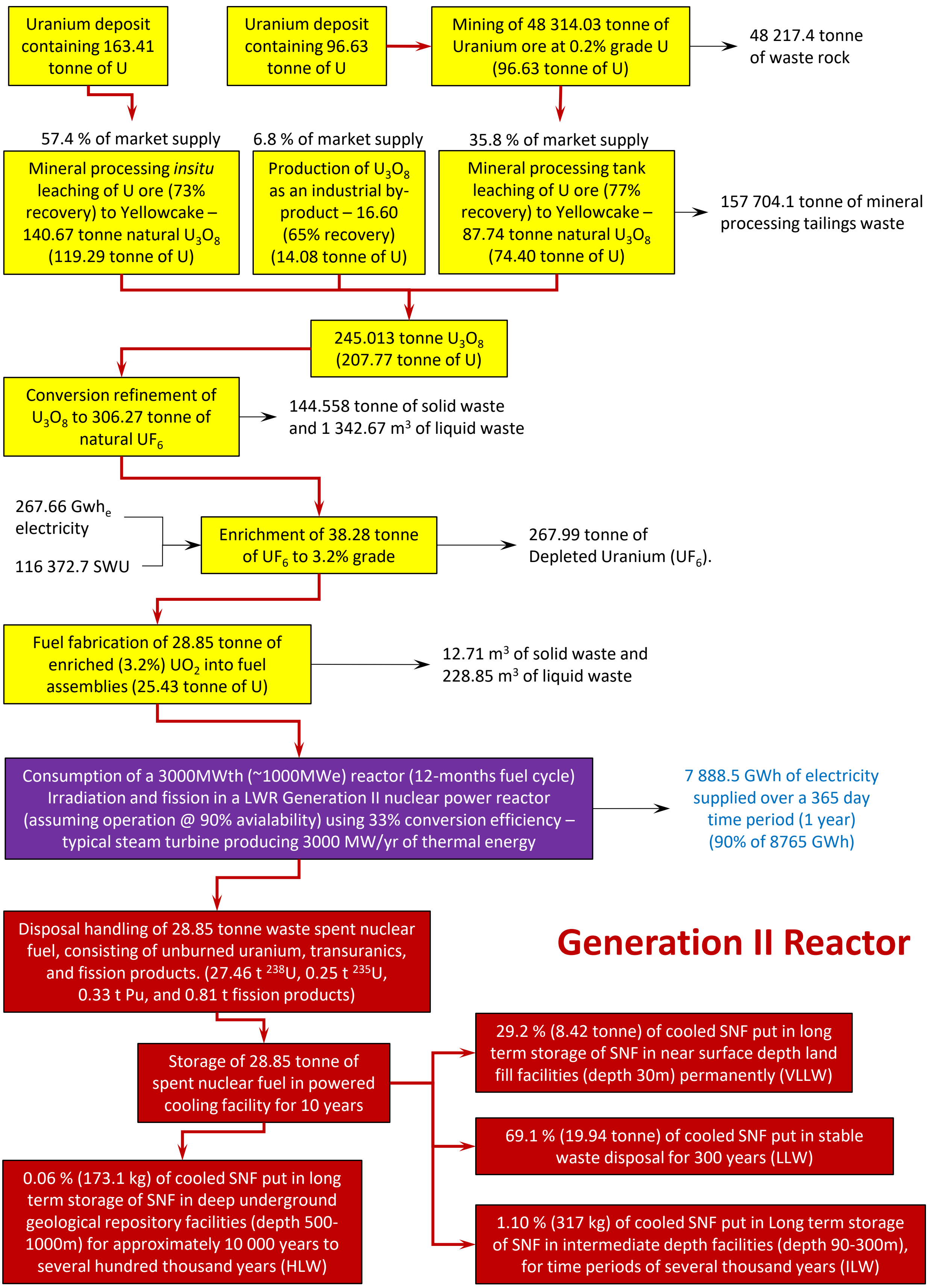


Figure 25.15. Calculation of uranium requirements in the nuclear fuel cycle in a Generation II reactor
(Image: Simon Michaux)
(Source: data drawn from IAEA 2007, NEA/OECD Uranium 2011, WISE Uranium Project)

Construction of new infrastructure

- Construction time is optimized to be extremely efficient and is reduced to 5 years. Current construction cycle in 2020 for a nuclear reactor is 15-25 years due to variety of practical problems. The assumption is all of these are resolved. It is assumed a society wide emergency was declared and a 'forced march' pace of industrial production similar to what happened in the United Kingdom and the United States in World War II was undertaken. (Assumption)

- Construction of new nuclear power plants starts in 2021 and will be operating and connected to the grid 5 years later. So, the first group of new stations will be operating in 2026. (Assumption)

- The number of new power plants being constructed will be a net fleet gain of 25 each year.

- Each year construction of new stations will start in parallel to existing sites under construction. This means a massive increase in the capability to construct these sites.

- New SNF tails powered cooled storage and long-term storage facilities will be constructed in line with required global capacity to store new SNF generated. In the U.S., approximately 70% of SNF is in powered cooled storage pools (National Research Council 2006), this ratio is projected to the global system. Current SNF long term storage is at 80-90% of full saturation capacity. (Assumption)

Operation of nuclear power plants

- The quantity of nuclear powered electricity generation in 2016 was 2 473 TWh (NEA/IEA 2019)

- Each new power plant constructed will be a Generation II reactor, which has a 1000 MWe capacity to generate electricity and deliver it to the power grid. Figure 25.15 shows the nuclear cycle of this unit.

- The availability of each nuclear reactor was 90%, or 328.5 days in a calendar year

- The annual output of each new Generation II nuclear power plant was 7 888.5 GWh (Figure 25.15)

The size of the nuclear power station fleet

- The number of operating nuclear reactors in 2018 was the global fleet was 441 (NEA/IEA 2019)

- The largest Generation II reactor found was 900 MWe (World Nuclear Association: World Nuclear Power Reactors). For this simulation, a 1000 MWe sized Generation II reactor is assumed.

- Starting in 2026, there is a net increase of 25 Generation II reactors connected to the power grid (accounting for stations being decommissioned) each year (Assumption).

Global uranium resources of all classifications

- The resources available in this simulation are assumed to be the same as in Table 25.3.

Mining and mineral processing of U

- In 2016, the global mining of uranium in terms of Uranium content was 62 825 tonnes, at a variable grade (approximately 31.41 million tonnes of uranium ore) (Table 24.6).

- For each additional average sized nuclear reactor (size 1000 MWe installed capacity) that produces 6.2 TWh of electricity in a 365-day time period, this operation will require the mining of ore of various grades with 260 tonnes of uranium content (Figure 25.15) (IAEA 2007).

- The mining and mineral processing recovery of the production of Yellow Cake (U_3O_8) extraction efficiency was split into several sources. The numbers and proportions assembled for the Reference Scenario for mining and mineral processing were used in this simulation. Annual production of Yellow Cake (U_3O_8) would be 245.0 tonnes (Figure 25.15).

Conversion of Yellow Cake (U_3O_8) to uranium hexafluoride (UF_6)

- For each tonne of Yellow Cake (U_3O_8), 1.25 tonne of uranium hexafluoride (UF_6), 0.59 tonne solid waste, and 5.48 m^3 of liquid waste generated was produced, as shown in Figure 25.15 (Lamarsh & Baratta 2001, Glasstone & Sesonske 1994).

- The required mass of UF_6 from conversion is estimated from the annual nuclear reactor requirements of ceramic fuel pellets (accounting for the mass contributed by reprocessing of SNF fuel) (Assumption).

- A Generation II reactor producing 6.2 TWh, requires 28.85 tonne of nuclear fuel (IAEA 2007). If this fuel was sourced completely from yellow cake, then 245.013 tonnes of yellow cake would be converted to 306.27 tonnes of UF_6 (IAEA 2007).

Centrifuge enrichment of UF_6

- For each tonne of natural uranium hexafluoride (UF_6), 0.125 tonne (125kg) of enriched UF_6 is produced (to a content concentration of 3.2%), and 0.875 tonne of depleted uranium (UF_6) generated was produced as shown in Figure 25.15 (Lamarsh & Baratta 2001, Glasstone & Sesonske 1994).

- Annual enrichment of UF_6 globally in 2015 was 47 285 SWU (Table 24.14).

- For yearly Generation II reactor requirements in this simulation, 306.27 tonnes of converted UF_6 would then be enriched to 38.28 tonnes of enriched UF_6, at a grade of 3.2% ^{235}U (IAEA 2007) (Figure 25.15)

The fabrication of UOX ceramic pellets

- The annual fabrication of nuclear UOX fuel ceramic pellets in 2016 was 13 913 tonnes (Table 24.15).

- For each additional tonne of enriched uranium hexafluoride (UF_6), 0.76 tonne (759 kg) of ceramic nuclear fuel pellets, 0.33 m^3 of solid waste and 6.02 m^3 of liquid waste were produced (Figure 25.15) (Lamarsh & Baratta 2001, Glasstone & Sesonske 1994).

The fabrication of nuclear fuel rod assemblies

- The annual fabrication of Nuclear fuel assemblies is sourced from UOX pellets and MOX fuel that has been produced from SNF. In 2016, 15 276 tonnes of nuclear fuel rod assemblies were produced (Table 24.15).

- For each additional average sized Generation II nuclear reactor (size 1000 MW installed capacity) that produces 6.224 TWh of electricity in a 365-day time period, this operation will require 28.85 tonnes of nuclear fuel rod assemblies, as shown in Figure 25.15 (IAEA 2007).

Mass of Spent Nuclear Fuel generated and put in powered underwater cooled storage

- Globally in 2010, there was 246 000 tonnes of Spent Nuclear Fuel (SNF) in storage facilities (IAEA 2018).

- In the U.S., approximately 70% of SNF is in powered cooled storage pools (National Research Council 2006), this ratio is projected to the global system. New SNF tails powered cooled storage and long-term storage facilities will be constructed in line with required global capacity to store new SNF generated. This means that in 2010, when globally there was 246 000 tonnes of SNF in storage, it is assumed that 172 000 tonnes is in power cooled storage and the rest is in dry storage (IAEA 2018).

- In this simulation, this stockpile of 172 000 tonnes of SNF will be slowly brought out of long-term storage and reprocessed or disposed of appropriately as new storage facilities are constructed. It is assumed that 10 000 tonnes of new capacity for SNF storage in the kinds of facilities show in Table 25.4 will be made operational each year. This schedule will start in 2025. This 10 000 tonnes of new capacity will be split up by the relative waste proportions shown in Table 25.4. It is in this fashion that the existing stockpile of Spent Nuclear Waste can be appropriately dealt with. This schedule will rehandle all the existing historical SNF stockpile into a long-term solution by the year 2042.

- Globally 12 000 tonnes of Spent Nuclear Fuel (SNF) is generated each year (IAEA 2007). This assumed to continue as the existing nuclear power plant fleet will continue to operate. The additional SNF produced by the new Generation III+ plants will be calculated separately and added to this Reference.

- For every tonne of Spent Nuclear Fuel (SNF) generated, there is 1 tonne of SNF placed in powered cooled storage under water, where it will stay for 10 years. After 10 years it is removed from power cooled storage and is split up into sub-streams and disposed of as per Table 25.4. (Assumption)

Reprocessing of Spent Nuclear Fuel (SNF)

- The global mass of reprocessed spent nuclear fuel was 1 080 tonnes (Table 24.20). Global SNF reprocessing capacity after cooled storage will increase by 500 tonnes each ten years, starting in 2025. It is assumed it will take 5 years to construct these new facilities. Construction is to start in 2021, and the first group will be operational in 2025. From 2025 onwards, an extra 500 tonnes of reprocessing capacity will be constructed each 10 years. For example, an additional 500 tonnes of SNF reprocessing will be operation in the year 2036 (Assumption).

- The reprocessed SNF stream is added to the conversion step (adjusting U_3O_8 feed in line with reactor requirements of finished nuclear fuel assemblies).

Fabrication of MOX fuel from SNF

- The global fabrication of MOX fuel was 992 tonnes (Table 24.21).

- Global MOX fuel production from SNF capacity after cooled storage will increase by 500 tonnes each ten years, starting in 2025. It is assumed it will take 5 years to construct these new facilities. Construction is to start in 2021, and the first group will be operational in 2025. From 2026 onwards, an extra 500 tonnes of MOX fuel production from SNF capacity will be constructed each 10 years. For example, an additional 500 tonnes of MOX fuel production from SNF will be operational in the year 2036 (Assumption).

- The MOX fuel stream is added to the UOX fuel stream to be merged and fabricated into nuclear fuel assemblies.

Figures 25.16 to 25.21 show the outcomes of this simulation. Appendix P shows the data results.

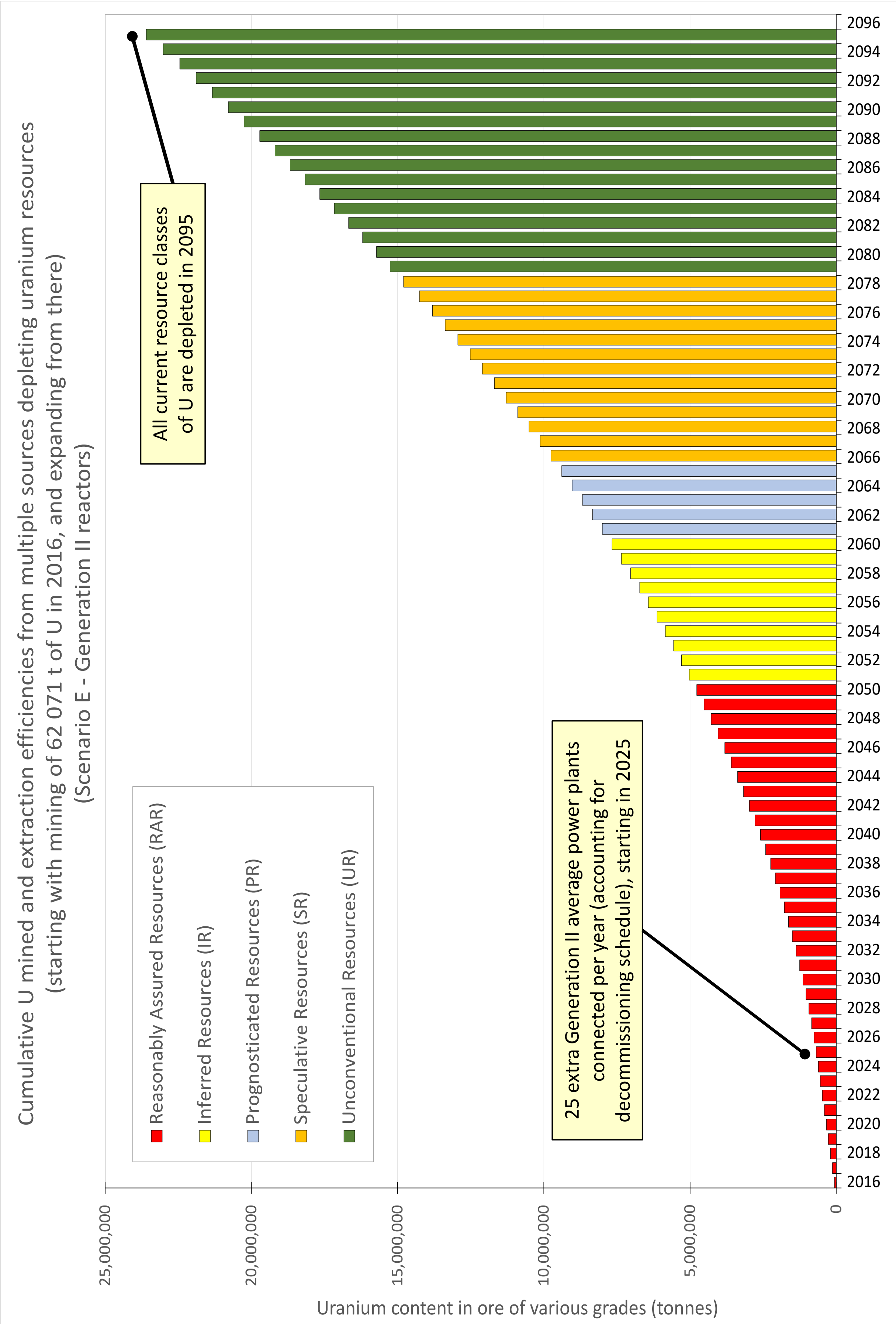


Figure 25.16. Cumulative uranium mined over time, extracting U from all resource classes in Scenario E-Generation II

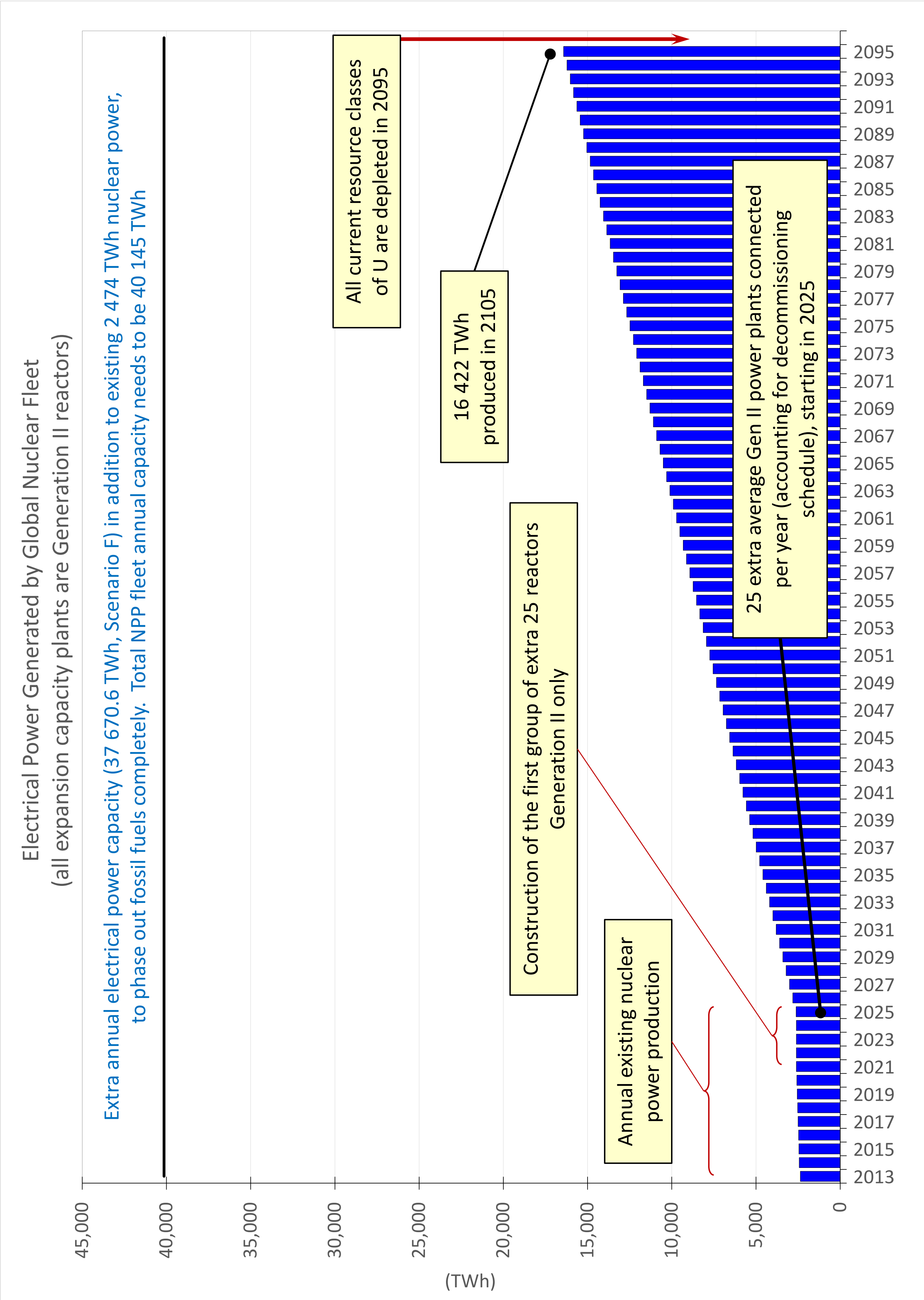


Figure 25.17. Global electrical power generated by nuclear power plants in Scenario E-Generation II

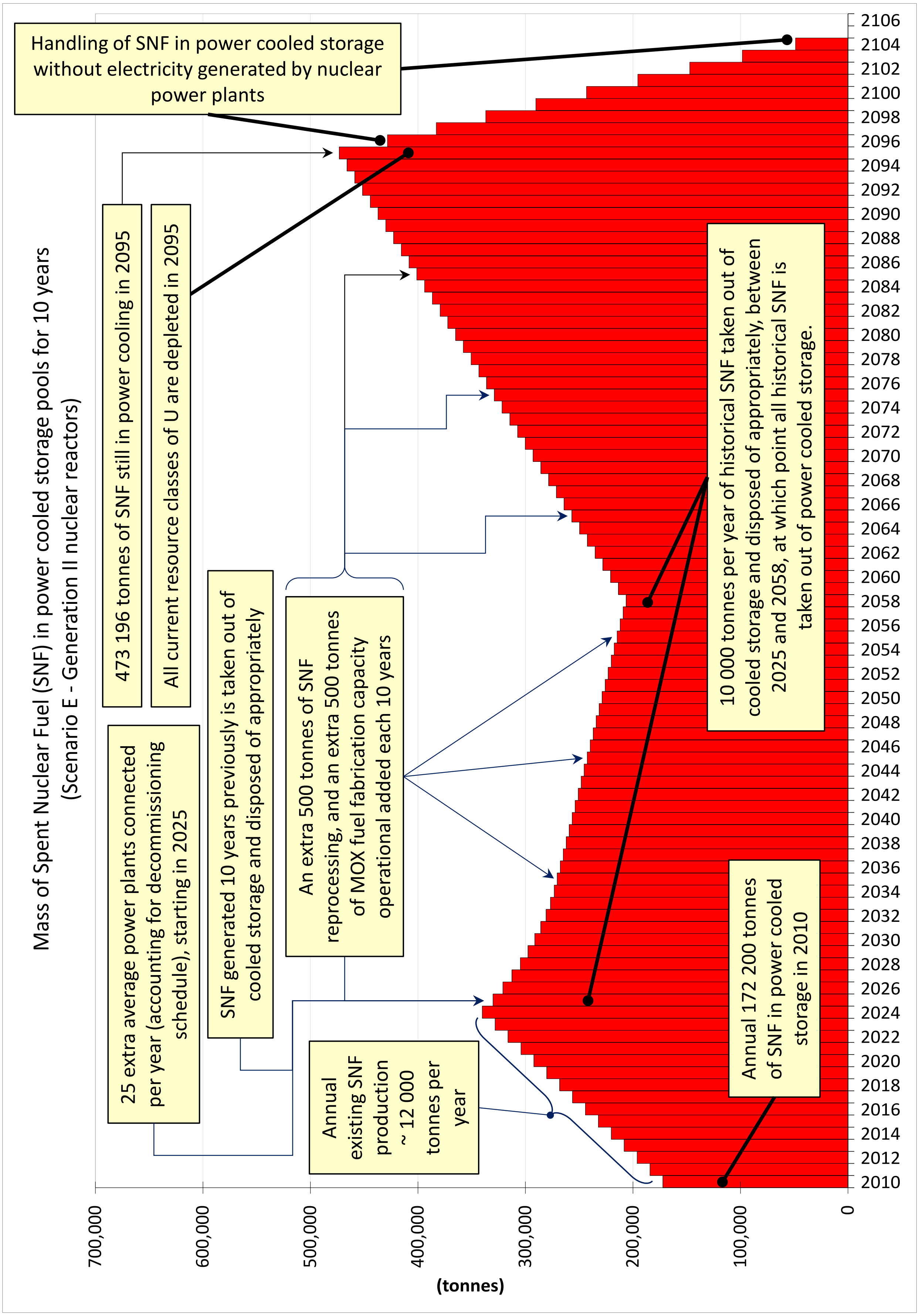


Figure 25.18. Spent nuclear fuel in power cooled storage for 10 years in Scenario E-Generation II

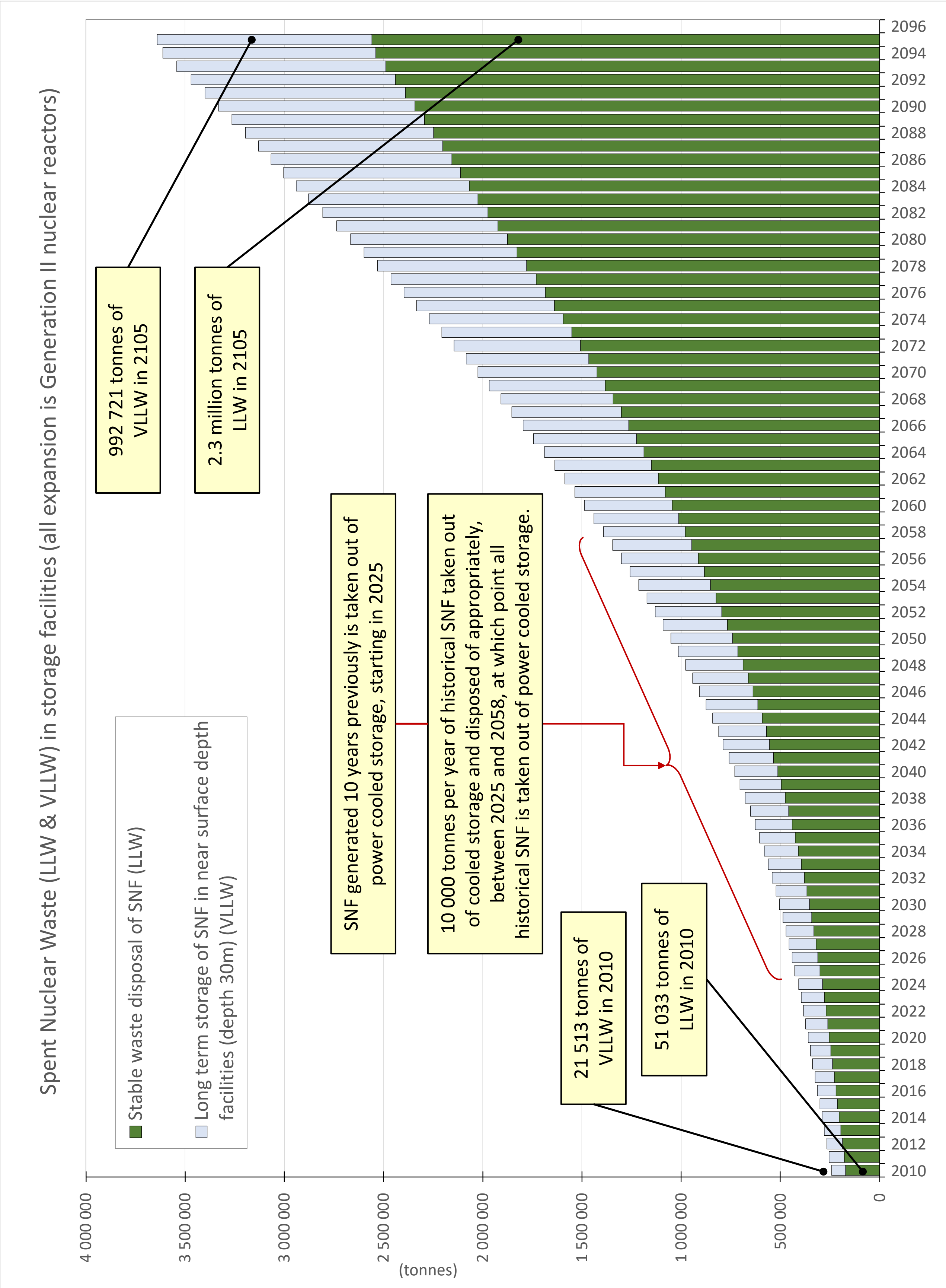


Figure 25.19. Cumulative long-term storage of ILW spent nuclear waste in intermediate depth (90 – 300m) Scenario E – Generation II

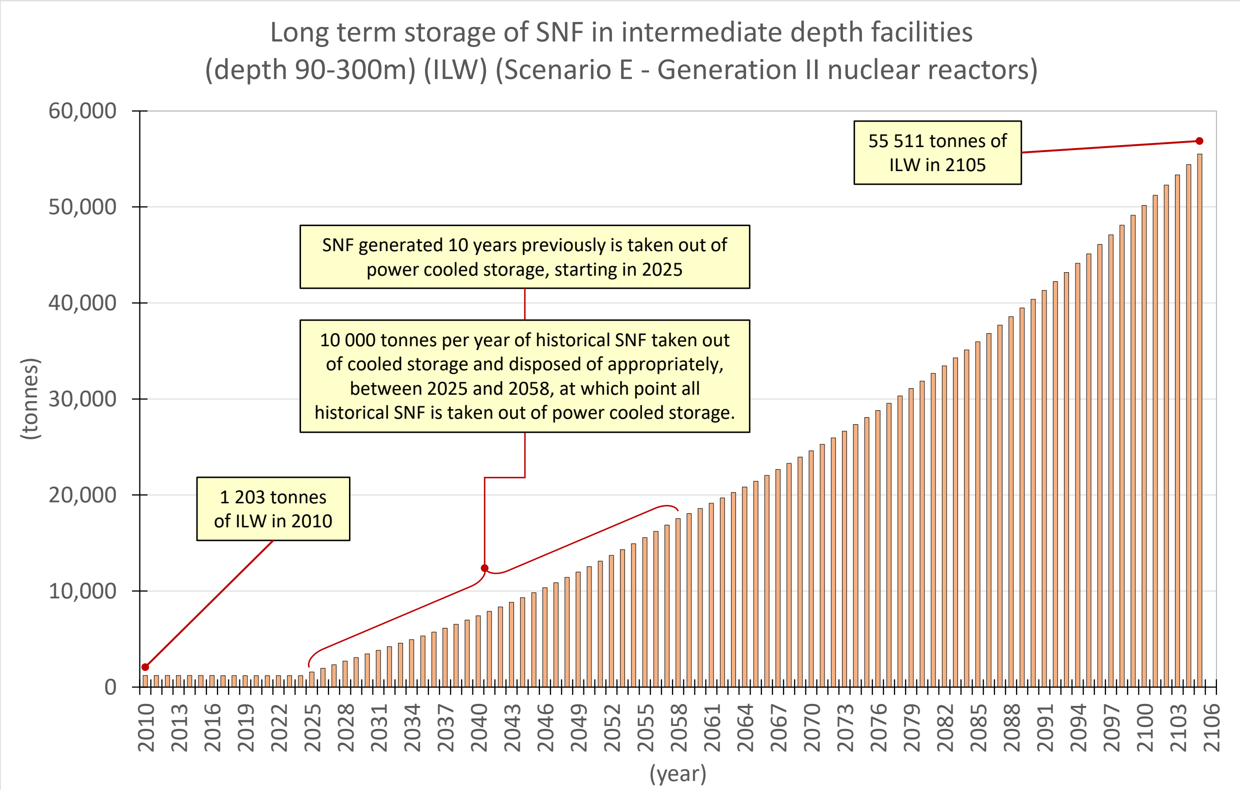


Figure 25.20. Cumulative long-term storage of ILW spent nuclear waste in intermediate depth (90 – 300m) Scenario E – Generation II

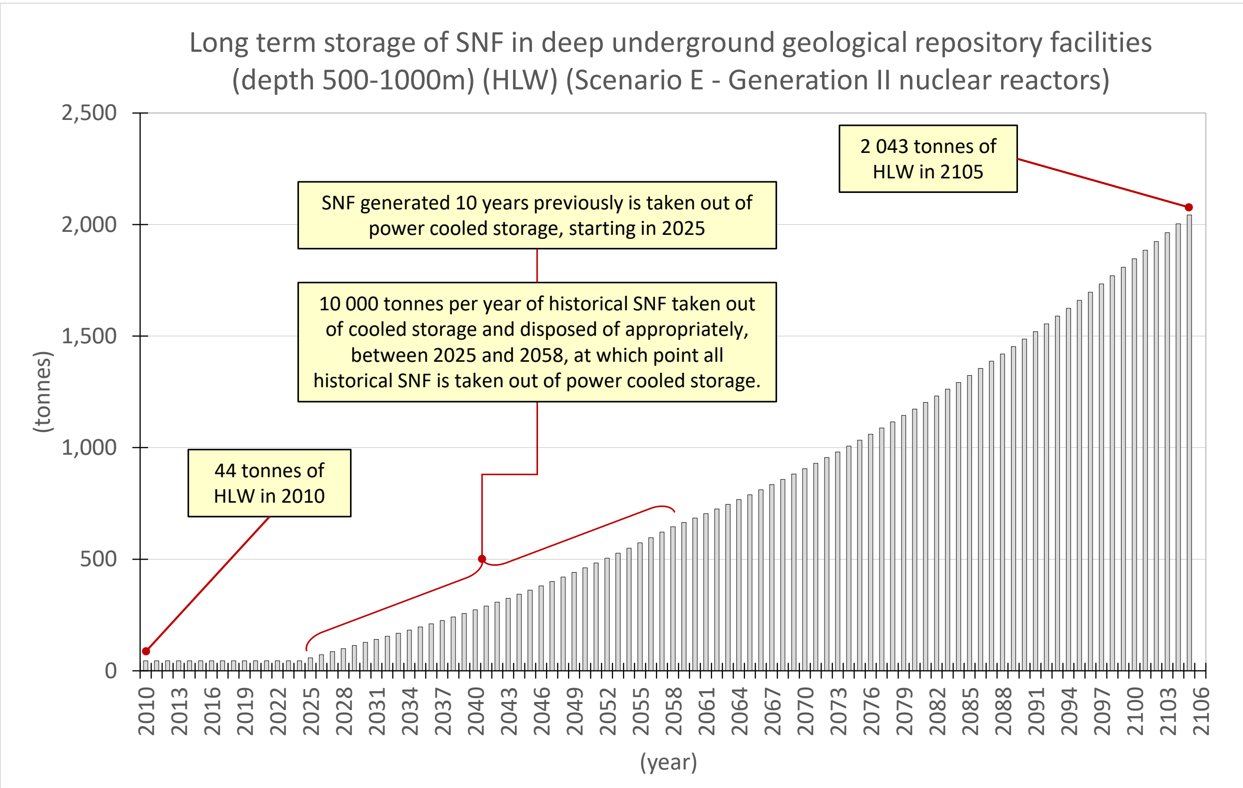


Figure 25.21. Cumulative long-term storage of HLW spent nuclear waste in intermediate depth (500 – 1000m) Scenario E – Generation II

25.3.2 Outcomes of Scenario E – Generation II Simulation

The following learnings were gained from this simulation:

- All resource classes were fully consumed by 2095 in this simulation.

Table 25.9. Consumption of U resources in Scenario E – Generation II Simulation

Resource Class	Quantity (tonnes)	Start of Consumption	Year of depletion
Reasonably Assured Resources (RAR)	4,815,100	2016	2050
Inferred Resources (IR)	3,173,000	2051	2060
Prognosticated Resources (PR)	1,698,300	2061	2065
Speculative Resources (SR)	5,832,300	2066	2078
Unconventional Resources (UR)	8,116,900	2079	2095

- In 2095, all current uranium resources had been consumed, thus no more UOX fuel was made from mineral mining sources. This means that the large number of nuclear reactors operating at the time will have to shut down and the fleet of nuclear power stations will no longer deliver electrical power to the global power grid, after 2095.

- This 16 422 TWh will only be 40.9 % of the required 40 145 TWh (37 670.6 + 2 474) of required power to service Scenario F (phase out all fossil fuels completely). For nuclear power to be useful in phasing out fossil fuels, this kind of capacity needs to be available by 2040. So there also is not enough time.

- This means that after decades of 'forced march' emergency industrialization, putting our faith in only the expansion of the nuclear power fleet using Generation II technology will not achieve long term energy supply security and is not viable.

- The peak annual power generation of the Generation II simulation of 16 422 TWh in 2095 is only 64.1 % of the peak annual power generation of the Generation III+ simulation of 25 663 TWh in 2101 (Section 25.2). This demonstrates the efficiency and value of the Generation III+ technological advancements compared to the Generation II technology.

- In 2095, electrical power will no longer be fueled by mineral resources of uranium (based on current resources), there will still be 473 196 tonnes of SNF in powered cooled storage pools. This mass of SNF could be managed appropriately (an assumption) and will have a portion of it taken out each year for long term storage and reprocessing, until 2105. This powered cooling capability will require electrical power. Failure to do this has a high risk of an SNF stockpile fuel fire, resulting in a large scale environmental hazard. To supply the needed power, it must be serviced by the last of the operating nuclear reactors, as all fossil fuels will be depleted by then. Renewable power sources like wind, solar and hydroelectricity will struggle to service the existing power requirement of society.

Table 25.10. Simulation outcome of Scenario E – Generation II (Appendix P)

Year	Units	2016	2025	2030	2040	2050	2060	2070	2080	2090	2100
Mining and mineral processing of U annually to meet reactor requirements	(tonnes)	62,071.0	62,612.6	96,460.1	164,155.1	231,850.1	299,545.1	367,240.1	434,935.1	517,661.0	
Cumulative sum U extracted from resources with various methods from 2016	(tonnes)	62,071.0	683,382.7	1,144,055.3	2,629,525.4	4,867,162.2	7,856,965.6	11,598,935.7	16,378,516.2	23,592,013.8	
UOX pelletization (converted UF6 + reprocessed SNF)	(number)	13,848.5	13,261.7	15,868.0	22,080.5	28,293.0	34,505.5	40,718.0	46,930.5	56,749.2	
Rod/assembly fabrication (UOX + Recycled SNF+MOX)	(TWh)	15,276.0	15,333.7	18,940.0	26,152.5	33,365.0	40,577.5	47,790.0	55,002.5	65,821.2	
Number of nuclear power stations	(Number)	447	445	570	820	1,070	1,320	1,570	1,820	2,195.0	
Electrical power generated by global nuclear fleet	(TWh)	2,473.6	2,617.0	3,603.0	5,576.0	7,548.0	9,520.0	11,492.0	13,464.0	16,422.3	
Annual mass of Spent Nuclear Fuel generated and put in powered underwater cooled storage	(tonnes)	12,000.0	12,057.7	15,664.0	22,876.5	30,089.0	37,301.5	44,514.0	51,726.5	62,545.2	
Annual mass of Spent Nuclear Fuel taken out of powered underwater cooled storage	(tonnes)		12,000.0	12,000.0	15,664.0	22,876.5	30,089.0	37,301.5	44,514.0	55,332.7	62,545.2
Reprocessing of Spent Nuclear Fuel	(tonnes)	1,080.0	1,080.0	1,580.0	2,080.0	2,580.0	3,080.0	3,580.0	4,080.0	4,580.0	
Fabrication of MOX fuel	(tonnes)	992.0	992.0	1,492.0	1,992.0	2,492.0	2,992.0	3,492.0	3,992.0	4,492.0	
Total mass of Spent Nuclear Fuel (SNF) in power cooled storage pools for 10 years	(tonnes)	318,000.0	330,257.7	291,365.0	256,508.3	228,633.3	220,758.3	292,883.3	365,008.3	473,195.8	0.0
Total Stockpile mass of SNF to be disposed of in long term storage	(tonnes)	244,200.0	96,797.0	211,757.0	455,342.0	769,570.2	1,140,923.5	1,509,401.7	1,955,005.0	2,767,644.2	3,405,560.0
Stable waste disposal of SNF (LLW)	(tonnes)	219,897.0	66,935.1	146,430.0	314,869.0	532,157.8	788,948.6	1,043,751.3	1,351,885.9	1,913,826.0	2,354,944.7
Long term storage of SNF in near surface depth facilities (depth 30m) (VLLW)	(tonnes)	92,856.0	28,216.3	61,727.2	132,732.2	224,329.7	332,579.2	439,990.6	569,883.9	806,768.3	992,720.7
Long term storage of SNF in intermediate depth facilities (depth 90-300m) (ILW)	(tonnes)	5,088.0	1,577.8	3,451.6	7,422.1	12,544.0	18,597.1	24,603.2	31,866.6	45,112.6	55,510.6
Long term storage of SNF in deep underground geological repository facilities (depth 500-1000m) (HLW)	(tonnes)	190.8	58.1	127.1	273.2	461.7	684.6	905.6	1173.0	1660.6	2043.3

25.4 Scenario E – Generation IV reactor technology

In this simulation, the development and industrial scale rollout of Generation IV nuclear reactors will be used to expand the nuclear power plant fleet. This technology is still conceptual and has yet to be actually shown to be viable. Nevertheless, this simulation will be done to provide a possible outcome if the hoped for Generation IV technology becomes technically stable and industrially viable. If this happens, the nuclear fuel cycle could be revolutionized, and uranium resources would last much longer. Thus, a radical assumption was made, and this simulation was conducted. Each new Generation IV station was assumed to be a Travelling Wave Reactor (TWR) (Weaver *et al* 2009). It is also assumed that each new TWR is of the same installed power capacity as the example APR1400 used in the Generation III+ simulation (KHNP 2011).

The TWR reactor has often been referred to as the Nuclear Candle (Sekimoto et al 2001), which refers to the characteristic of the fission reactions are confined to a boundary zone in the reactor core, that slowly advances over time. The reactor would burn through its fuel like a 'candle'. TWRs could theoretically run self-sustained for decades without refueling or removing spent fuel.

A TWR reactor in theory would use a small amount of enriched uranium ^{235}U (or another fissile material) to initiate the start of the nuclear reaction (Weaver *et al* 2009). The remainder of the fuel could be natural or depleted uranium ^{238}U. In theory (a TWR has never been built as of 2020) has the capacity using unconventional fuels like depleted uranium, natural uranium, thorium, spent fuel removed from light water reactors, or some combination of these materials (Ellis *et al* 2010, Rusov *et al* 2011, Sekimoto et al 2001). While these concepts have yet to be proven, this potential has the capacity to reorganize the nuclear fuel cycle.

In principle, TWRs are capable of burning spent fuel (SNF) from LWRs, which is currently discarded as radioactive waste. TWRs are also capable, in principle, of reusing their own fuel. In any given cycle of operation, only 20 – 35% of the fuel gets converted to an unusable form. This means that in theory (not proven) a TWR Generation IV nuclear reactor would consume only 17 to 32% of fresh uranium sourced fuel, compared to what a conventional Generation III+ would consume to produce a similar quantity of electricity. For this simulation, it has been assumed that a TWR reactor would consume a fuel made up of only 25% of freshly sourced uranium fuel, and the remainder would be unprocessed SNF.

As this is new technology, a radical assumption is made that a TWR reactor is shown to be reliable and viable, then the construction and connection to the power grid of 10 new TWR stations, starting from the year 2030. It assumed that the logistics of the construction of a Generation IV TWR station will be much more complex than the construction of a Generation III+ nuclear power plant station. This is why, as it will be required to expand the nuclear power plant fleet immediately, all new reactors constructed and connected between 2025 and 2030 will be Generation III+ APR1400 stations, which are the current state of the art industrial engineering for nuclear technology that is considered to be reliable.

The nuclear power fleet will be expanded as fast as possible to supply the needed electrical power required by Scenario F (Section 26), which was 37 670.6 TWh.

Uranium mining, enrichment, conversion, UF_6, and nuclear fuel rod assembly manufacture, were all estimated starting with the annual reactor requirements expanded number of nuclear power plants connected to the power grid.

The following assumptions have been made in the Scenario E - Generation IV simulation:

<u>Construction of new infrastructure</u>

- Construction time is optimized to be extremely efficient and is reduced to 5 years. Current construction cycle in 2020 for a nuclear reactor is 15-25 years due to variety of practical problems. The assumption is all of these are resolved. It is assumed a society wide emergency was declared and a 'forced march' pace of industrial production similar to what happened in the United Kingdom and the United States in World War II was undertaken. (Assumption)

- Construction of new Generation III+ nuclear power plants starts in 2021 and will be operating and connected to the grid 5 years later. So, the first group of new stations will be operating in 2025 (Assumption). Generation IV nuclear power plants will be assumed to be not only viable, but the first plant will be commissioned in 2030. From 2030, 10 new Generation IV plants will be connected to the grid each year. Starting in the year 2050, 25 new Generation IV plants will be connected each year. Starting in year 2087, 50 new Generation IV plants will be connected each year.

- Each year construction of new stations will start in parallel to existing sites under construction. This means a massive increase in the capability to construct these sites (Assumption).

- New SNF tails powered cooled storage and long-term storage facilities will be constructed in line with required global capacity to store new SNF generated. In the U.S., approximately 70% of SNF is in powered cooled storage pools (National Research Council 2006), this ratio is projected to the global system. Current SNF long term storage is at 80-90% of full saturation capacity (Assumption).

<u>The size of the nuclear power station fleet</u>

- The number of operating nuclear reactors in 2016 was the global fleet was 441 (NEA/IEA 2019).

- The number of new power plants being constructed will be a net gain of 25 Generation III+ APR1400 stations, each year until the year 2029. Between 2030 and 2049, all new reactors will be a net gain of 10 Generation IV TWR stations only.

- From 2050 onwards, all new reactors will be a net gain of 25 Generation IV TWR stations only (Assumption).

- From 2087 onwards, all new reactors will be a net gain of 50 Generation IV TWR stations only (Assumption).

- It is assumed that 20 Generation II reactors from the existing 2016 power plant fleet will decommission each year, starting in 2025, until the last Generation II station is decommissioned in 2044. All new reactors to meet demand and net increase the fleet size by 25, will be Generation III+ reactors. Construction of new sites will be done to meet the net gain of 25 new stations each year (Assumption).

- It is assumed that 25 Generation III+ reactors from the NPP installed before 2030 will decommission each year, starting in 2086 (reflecting a 60 year plant life), until the last Generation III+ station is decommissioned in 2106.

<u>Operation of nuclear power plants</u>

- The quantity of nuclear powered electricity generation in 2016 was 2 473 TWhe (NEA/IEA 2019).
- The availability of each Generation III+ and each Generation IV nuclear reactor (assumed to be) was 91.5%, or 336 days in a calendar year (NEA/IEA 2019).
- The annual output of each average Generation III+ nuclear power plant was 11 221.6 GWhe (assuming 91.5% availability) (Calculation)
- The annual output of each average Generation IV nuclear power plant was 11 221.6 GWhe, assuming the same output as an APR1400 station (Calculation)
- The quantity of nuclear powered electricity generation in 2016 was 2 473 TWhe (NEA/IEA 2019)

Global uranium resources of all classifications

- For this simulation, the available uranium resources are assumed to be the same as Table 25.3 shown in Section 25.1.

Mining and mineral processing of U

- The extraction and refining of uranium are assumed to be in the same profile as shown in the Reference, Generation II and Generation III+ simulations.
- For each additional average sized Generation III+ station, assumed to be APR1400 nuclear reactor (size 1400 MWe installed capacity) that produces 11.2 TWh of electricity in a 365-day time period, this operation will require the mining of ore of various grades with 219.7 tonnes of uranium content (Calculation).
- For each additional average sized Generation IV station, assumed to be a Travelling Wave Reactor (TWR) (size 1400 MWe installed capacity) that produces 11.2 TWh of electricity in a 365-day time period, this operation will require the mining of ore of various grades with 61.53 tonnes of uranium content, which is 25% of the fuel requirements of a Generation III+ reactor of the same power output capacity (Calculation). It is assumed the TWR reactor can use a mix fuel, where only 25% is fresh UOX pellets sourced from mining of uranium, and the rest is a mix of MOX fuel and unprocessed SNF. (Assumption)

Conversion of Yellow Cake (U_3O_8) to uranium hexafluoride (UF_6)

- The required mass of UF_6 from conversion is estimated from the annual nuclear reactor requirements of ceramic fuel pellets (accounting for the mass contributed by reprocessing of SNF fuel) (Assumption).
- A Generation II reactor producing 7.9 TWh, requires 28.9 tonne of nuclear fuel. If this fuel was sourced completely from yellow cake, then 245 tonnes of yellow cake would be converted to 306.3 tonnes of UF_6 (calculation).

- A Generation III+ reactor producing 11.2 TWh, requires 29.9 tonne of nuclear fuel. If this fuel was sourced completely from yellow cake, then 198.8 tonnes of yellow cake would be converted to 248.5 tonnes of UF_6 (calculation).

- A Generation IIV reactor producing 11.2 TWh, requires 7.48 tonne of nuclear fuel. If this fuel was sourced completely from yellow cake, then 49.18 tonnes of yellow cake would be converted to 61.47 tonnes of UF_6 (Assumption).

Centrifuge enrichment of UF_6

- For each tonne of natural uranium hexafluoride (UF_6), 0.160 tonne (125kg) of enriched UF_6 is produced (to a content concentration of 4.09%), and 0.840 tonne of depleted uranium (UF_6) generated was produced (Figure 25.23).

- Additional UF_6 demand to fuel the new Generation III+ reactors are calculated based on nuclear fuel reactor requirements.

- Additional UF_6 demand to fuel the new Generation IV reactors are calculated based on nuclear fuel reactor requirements (which are 25% of an equivalent capacity Generation III+ reactor).

The fabrication of UOX ceramic pellets

- The annual fabrication of nuclear UOX fuel ceramic pellets in 2016 was 13 913 tonnes (Table 24.15 in Section 24).

- For each additional tonne of enriched uranium hexafluoride (UF_6), 0,76 tonne (760kg) of ceramic nuclear fuel pellets, 0.33 m^3 of solid waste and 6.02 m^3 of liquid waste were produced (Figure 25.23).

- The global quantity of UOX ceramic pellets required to service reactors is estimated based on overall reactor requirements, minus the quantity of MOX fuel produced in that year (Assumption).

- For Generation IV reactors, a proportion of unprocessed SNF fuel is used to manufacture these ceramic pellets (Figure 25.22). So, fuel proportions for a theoretical Gen IV reactor, would have a 25% proportion of U from freshly mined uranium ore, and the remaining 75% would be made up of unprocessed SNF, and MOX fuel (Assumption).

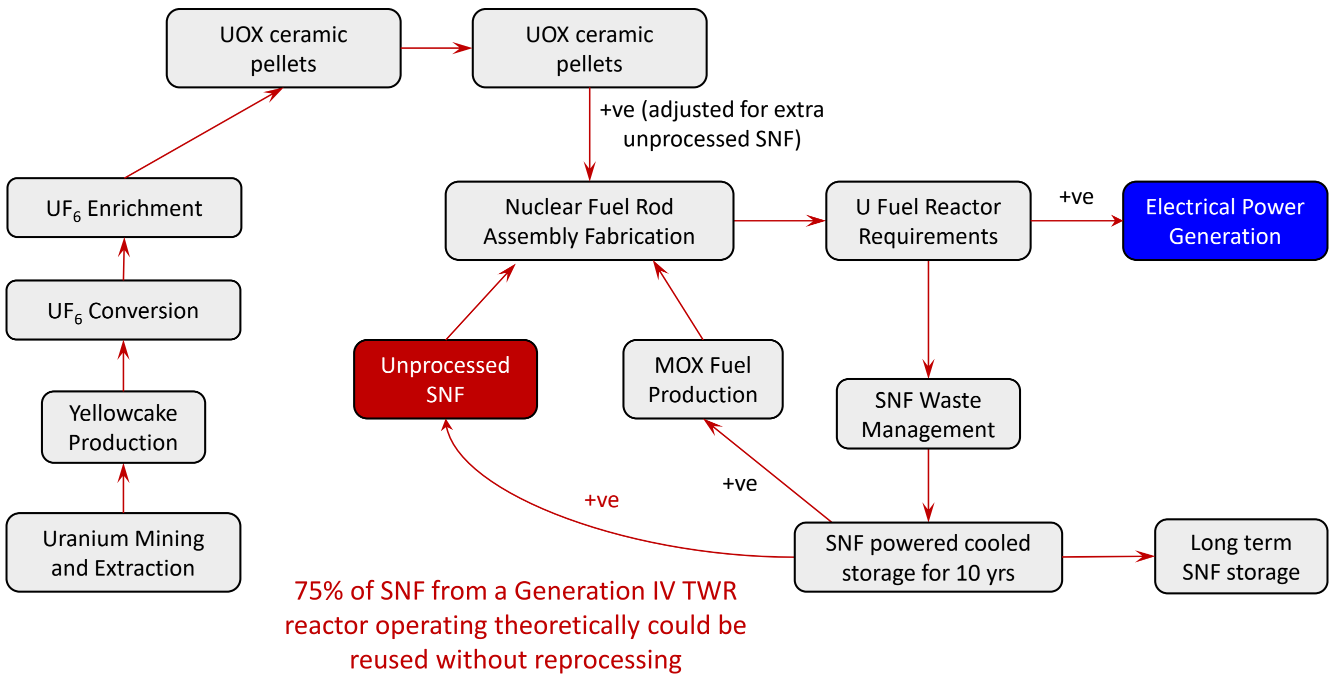


Figure 25.22. The reuse of SNF as a proportion of fuel rod assemblies to feed a TWR Generation IV reactor (Image: Simon Michaux)

<u>The fabrication of nuclear fuel rod assemblies</u>

- The annual fabrication of Nuclear fuel assemblies is sourced from UOX pellets and MOX fuel that has been produced from SNF. In 2016, 15 276 tonnes of nuclear fuel rod assemblies were produced (Table 24.15).

- For each existing average sized Generation II nuclear reactor (size 1000 MWe installed capacity) that produces 7.9 TWh (7 888.5 GWh) of electricity in a 365-day time period, this operation will require 28.9 tonnes of nuclear fuel rod assemblies (Figure 25.15).

- For each additional average sized Generation III+ nuclear reactor (size 1400 MWe installed capacity) that produces 11.2 TWh (11 221.6 GWh) of electricity in a 365-day time period, this operation will require 29.87 tonnes of nuclear fuel rod assemblies (Figure 25.23, Table 25.2).

- For each addition Generation IV reactor of the same size (1400 MWe installed capacity), that produces 11.2 TWh (11 221.6 GWh) of electricity in a 365-day time period, this operation will require 29.9 tonnes of nuclear fuel rod assemblies (Figure 25.23, Table 25.2). These fuel rod assemblies will be made up of a mix of ceramic pellets from freshly mined uranium (25%), ceramic pellets of MOX fuel and ceramic pellets made up of unprocessed SNF. This will mean that the annual reactor requirements for the TWR reactor would need 7.48 tonnes of freshly sourced UOX fuel.

<u>Mass of Spent Nuclear Fuel generated and put in powered underwater cooled storage</u>

- Globally in 2010, there was 246 000 tonnes of Spent Nuclear Fuel (SNF) in storage facilities (IAEA 2018).

- In the U.S., approximately 70% of SNF is in powered cooled storage pools (National Research Council 2006), this ratio is projected to the global system. New SNF tails powered cooled storage and long-term storage facilities will be constructed in line with required global capacity to store new SNF generated. This means that in 2010, when globally there was 246 000 tonnes of SNF in storage, it is assumed that 172 000 tonnes is in power cooled storage and the rest is in dry storage (IAEA 2018).

- In this simulation, this stockpile of 172 000 tonnes of SNF will be slowly brought out of long-term storage and reprocessed or disposed of appropriately as new storage facilities are constructed. It is assumed that 10 000 tonnes of new capacity for SNF storage in the kinds of facilities show in Table 25.4 will be made operational each year. This schedule will start in 2025. This 10 000 tonnes of new capacity will be split up by the relative waste proportions shown in Table 25.4. It is in this fashion that the existing stockpile of Spent Nuclear Waste can be appropriately dealt with. This schedule will rehandle all the existing SNF stockpile into a long-term solution by the year 2042.

- Globally 12 000 tonnes of Spent Nuclear Fuel (SNF) is generated each year (IAEA 2007). This assumed to continue as the existing nuclear power plant fleet will continue to operate. The additional SNF produced by the new Generation III+ plants and Generation IV plants will be calculated separately and added to this Reference.

- Each average sized Generation III+ nuclear reactor will produce 29.9 tonnes over each 1 year (365 days) time period (assumption).

- Each average sized Generation IV nuclear reactor will produce 29.9 tonnes each 1 year (365 days) time period (assumption).

- For every tonne of Spent Nuclear Fuel (SNF) generated, there is 1 tonne of SNF placed in powered cooled storage under water, where it will stay for 10 years. After 10 years it removed from power cooled storage and is split up into sub-streams and disposed of as per Table 25.4 (assumption).

Reuse of Unprocessed Spent Nuclear Fuel (SNF)

- A TWR reactor in theory would use a small amount of enriched uranium ^{235}U (or another fissile material) to initiate the start of the nuclear reaction (Weaver et al 2009). The remainder of the fuel could be natural or depleted uranium ^{238}U. In theory has the capacity using unconventional fuels like depleted uranium, natural uranium, thorium, spent fuel removed from light water reactors, or some combination of these materials (Ellis *et al* 2010, Rusov *et al* 2011, Sekimoto *et al* 2001).

- It is assumed that a proportion of fuel in nuclear fuel rod assemblies would be unprocessed SNF. This proportion is defined by Gen IV reactor requirements, and proportion of MOX fuel produced in that year.

Fabrication of MOX fuel from SNF

- The global fabrication of MOX fuel was 992 tonnes (Table 24.21).

- Global MOX fuel production from SNF capacity after cooled storage will increase by 500 tonnes each ten years, starting in 2026. It is assumed it will take 5 years to construct these new facilities. Construction is to start in 2021, and the first group will be operational in 2026 (thus in 2026, global MOX production capacity will be 1492 tonnes). From 2026 onwards, an extra 500 tonnes of MOX fuel production from SNF capacity will be constructed each 10 years. For example, an additional 500 tonnes of MOX fuel production from SNF will be operational in the year 2036 (thus in 2036, global capacity will be 1992 tonnes) (Assumption).

- The MOX fuel stream is added to the UOX fuel stream to be merged and fabricated into nuclear fuel assemblies.

Mass of Spent Nuclear Fuel put in long term storage after power cooled storage

- Current SNF long term storage is at 80-90% of full saturation capacity (WNWR 2019, IEA 2018).

- For every tonne of Spent Nuclear Fuel that is brought out of cooled storage after 10 years. It is sub-divided as shown in Table 25.4.

Figure 25.23 shows the outcomes of a calculation of the inputs and outputs based on the assumptions listed. Figure 25.23 was developed by inputting the estimated needed nuclear fuel requirement of a Generation IV reactor, then estimated the raw material streams to produce that nuclear fuel, using multiple references (IAEA 2007, NEA/OECD Uranium 2011, KHNP 2011, and Weaver *et al* 2009).

Figures 25.23 to 25.31 show the outcomes of this simulation. Appendix P shows the data results.

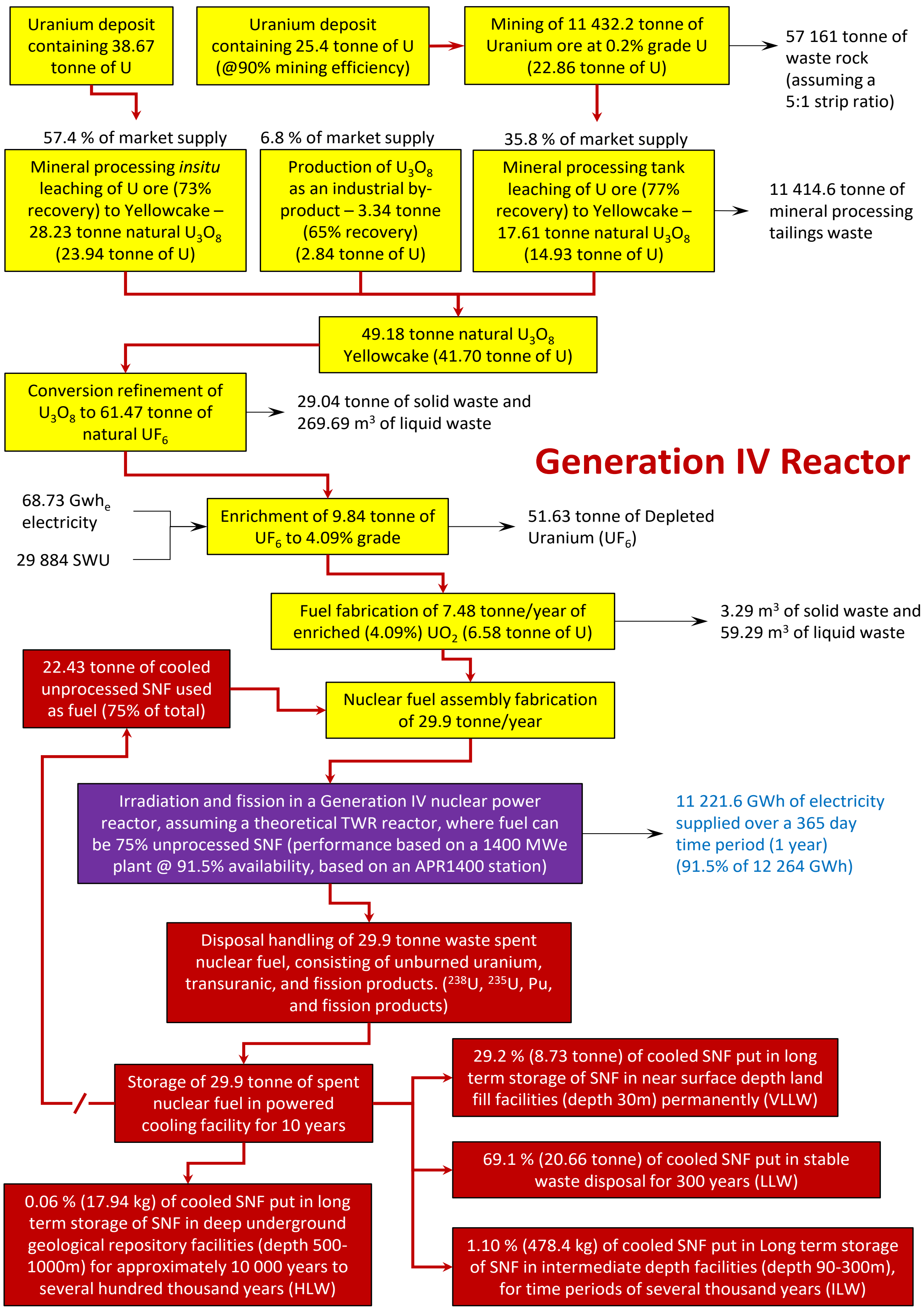


Figure 25.23. Calculation of uranium requirements in the nuclear fuel cycle in a Generation IV reactor (Image: Simon Michaux)
(Source: data drawn from IAEA 2007, NEA/OECD Uranium 2011, KHNP 2011, and Weaver et al 2009)

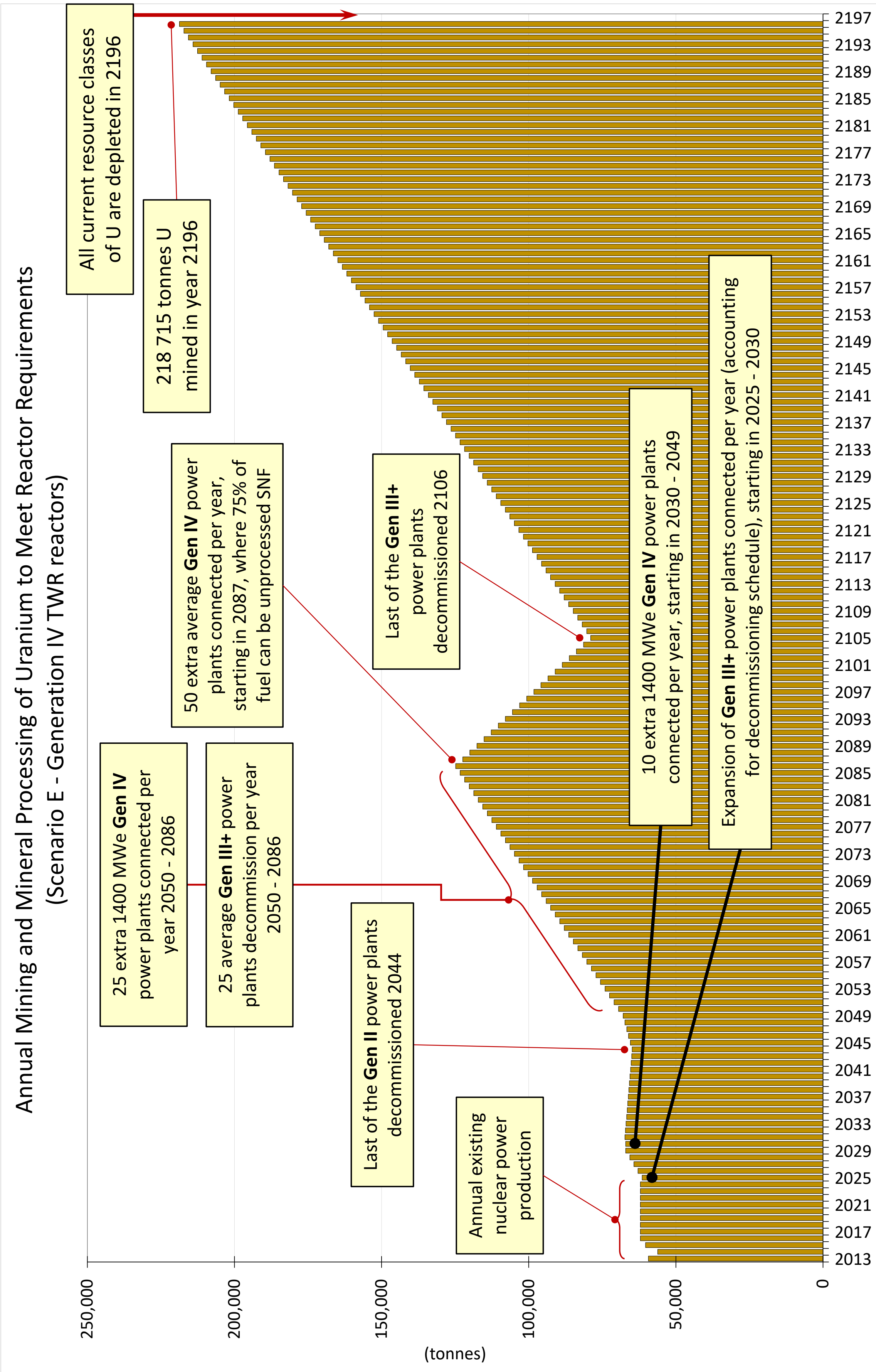


Figure 25.24. Annual uranium mined over time, extracting U from all resource classes in Scenario E-Generation IV

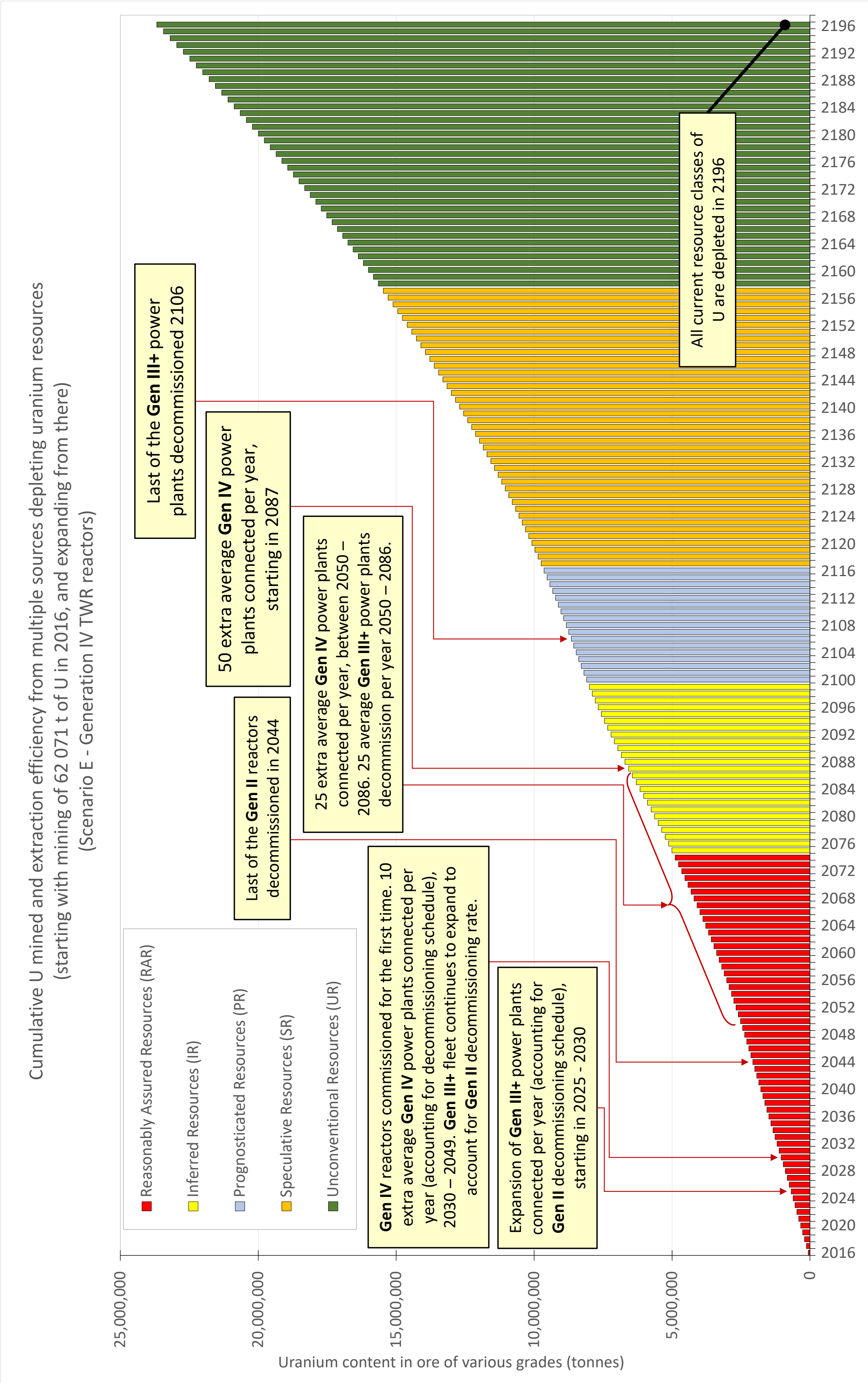


Figure 25.25. Cumulative uranium mined over time, extracting U from all resource classes in Scenario E-Generation IV

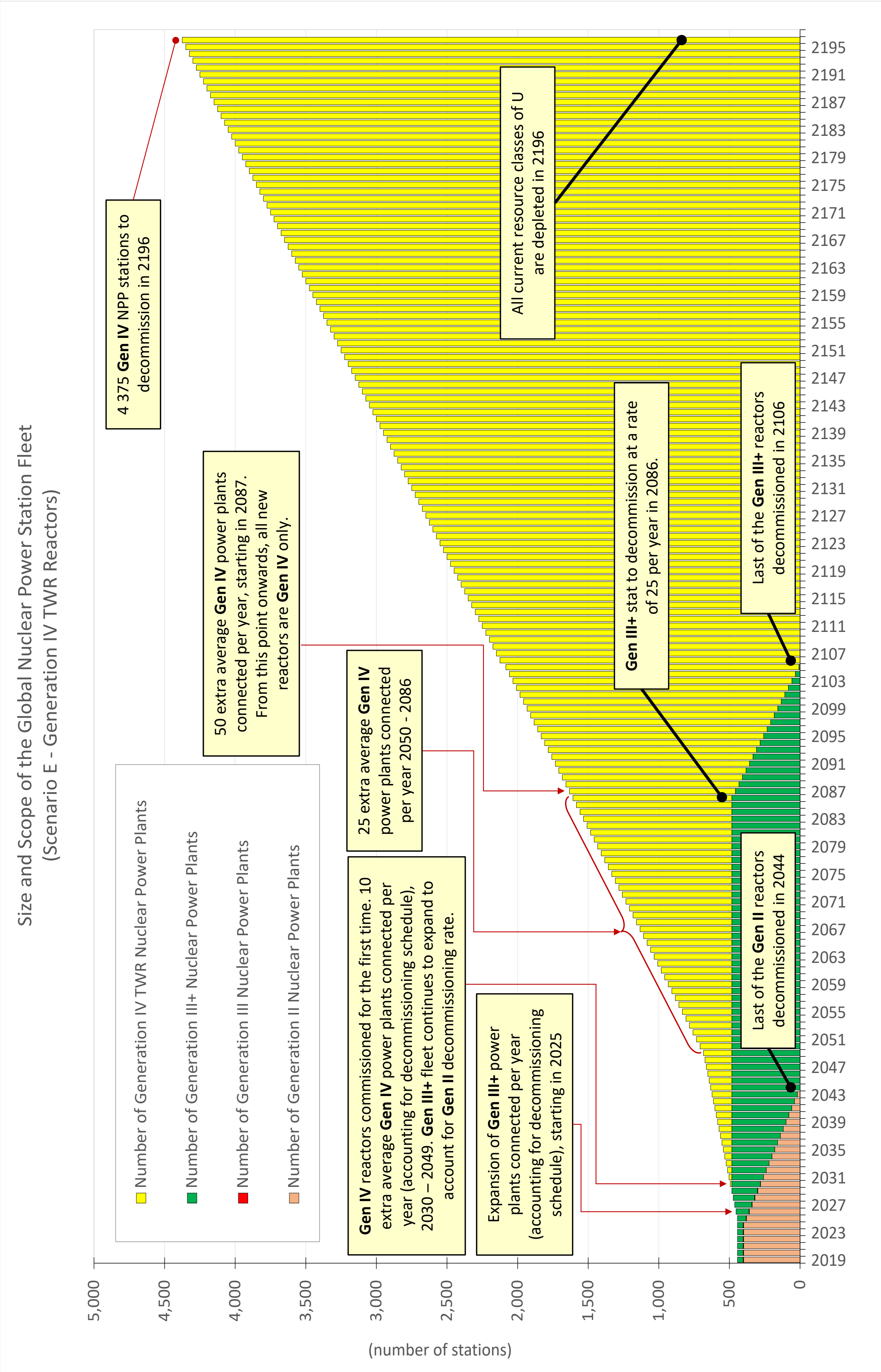


Figure 25.26. Number of nuclear power plants in the global fleet over time, Scenario E-Generation IV

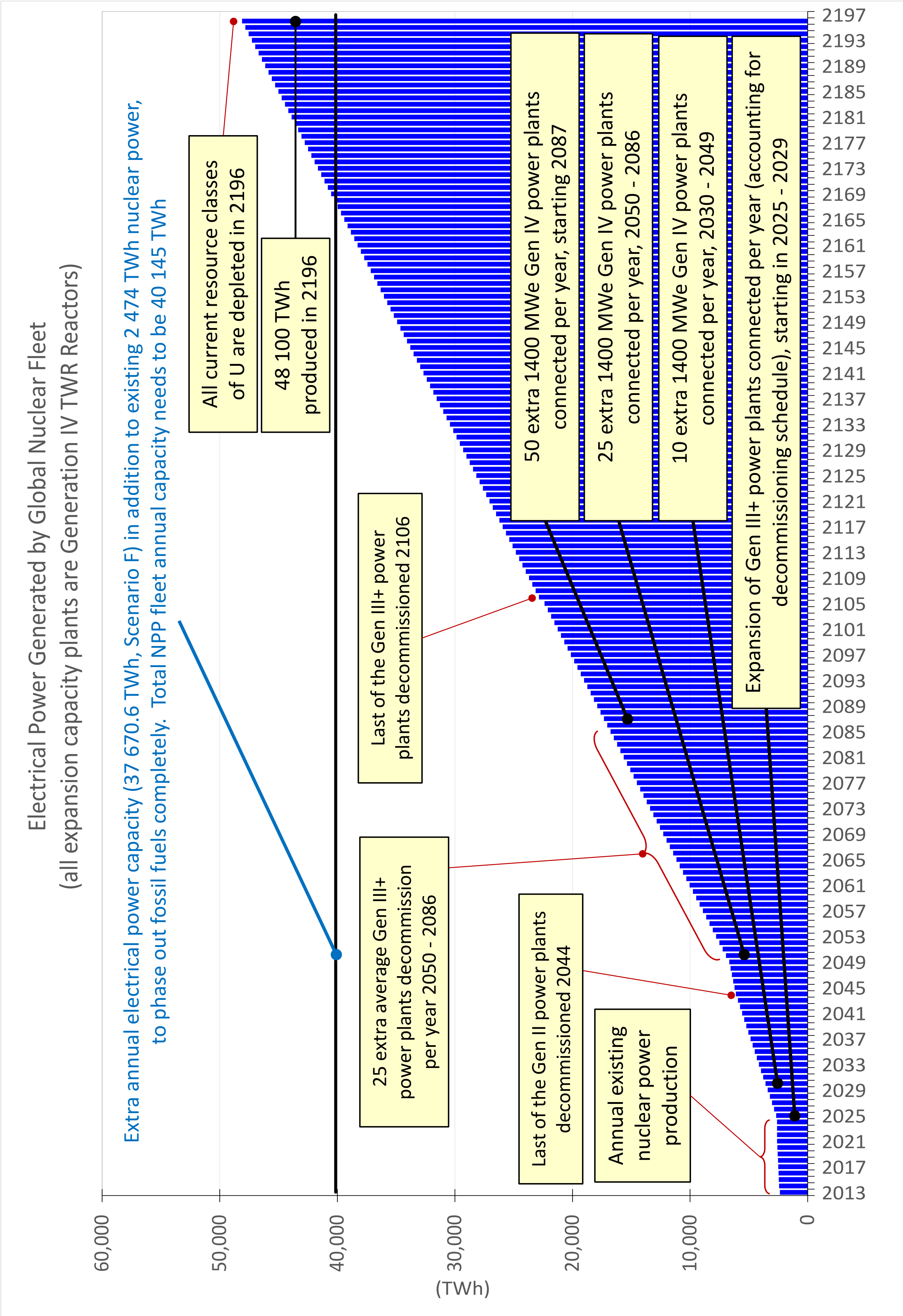


Figure 25.27. Global electrical power generated by nuclear power plants in Scenario E-Generation IV

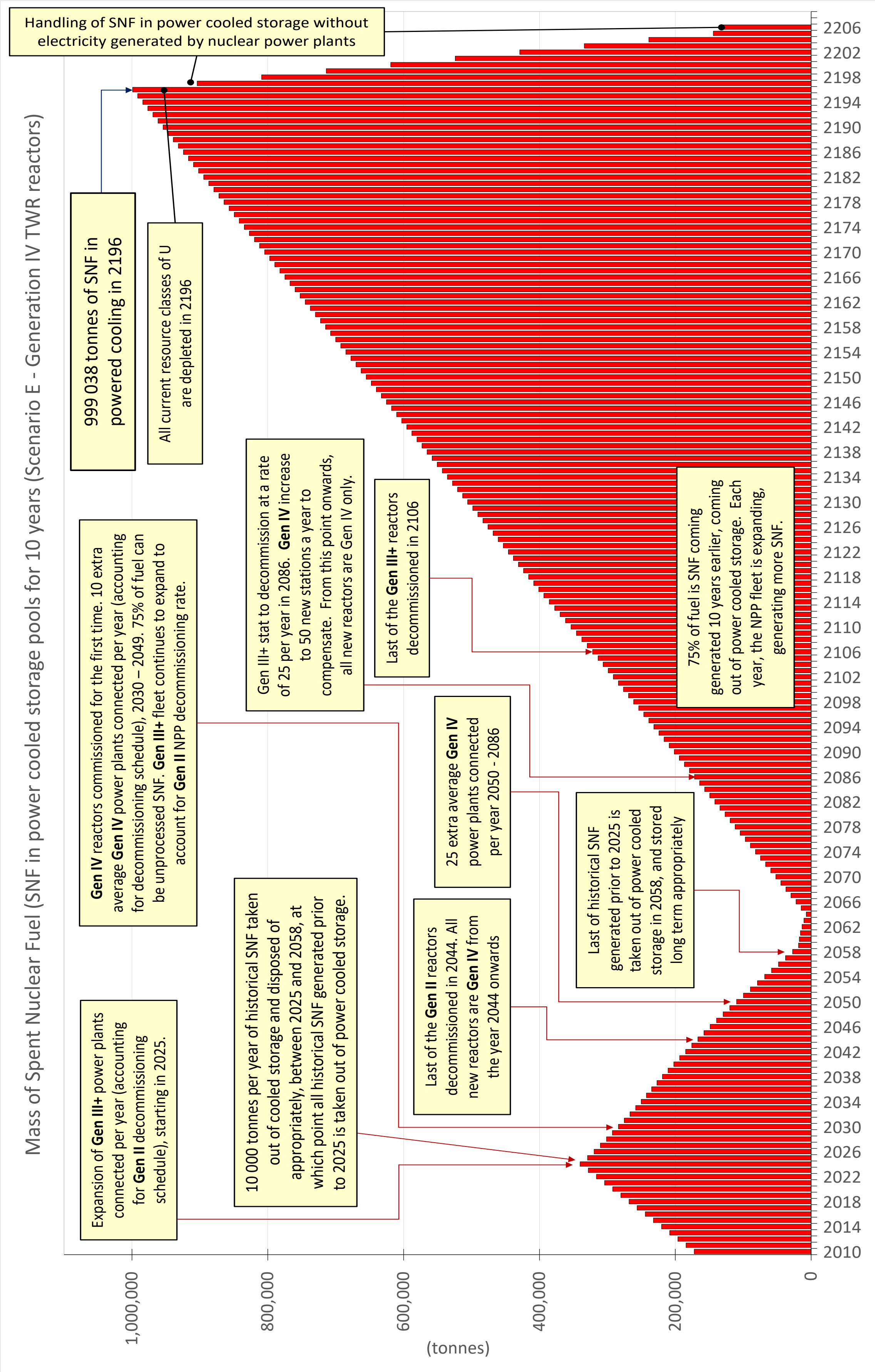


Figure 25.28. Spent nuclear fuel in power cooled storage for 10 years in Scenario E-Generation IV

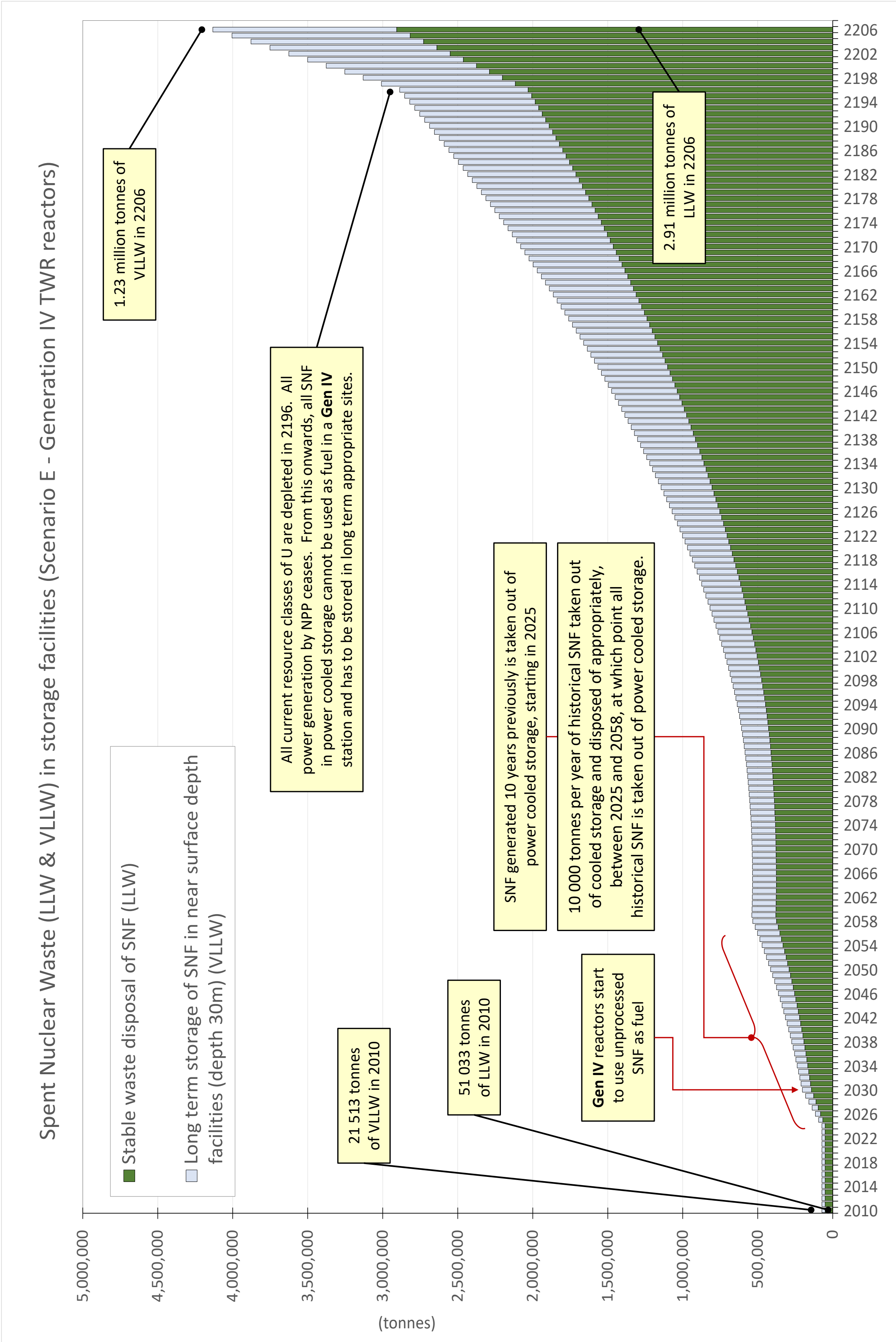


Figure 25.29. Cumulative long-term storage of ILW spent nuclear waste in intermediate depth (90 – 300m) Scenario E – Generation IV

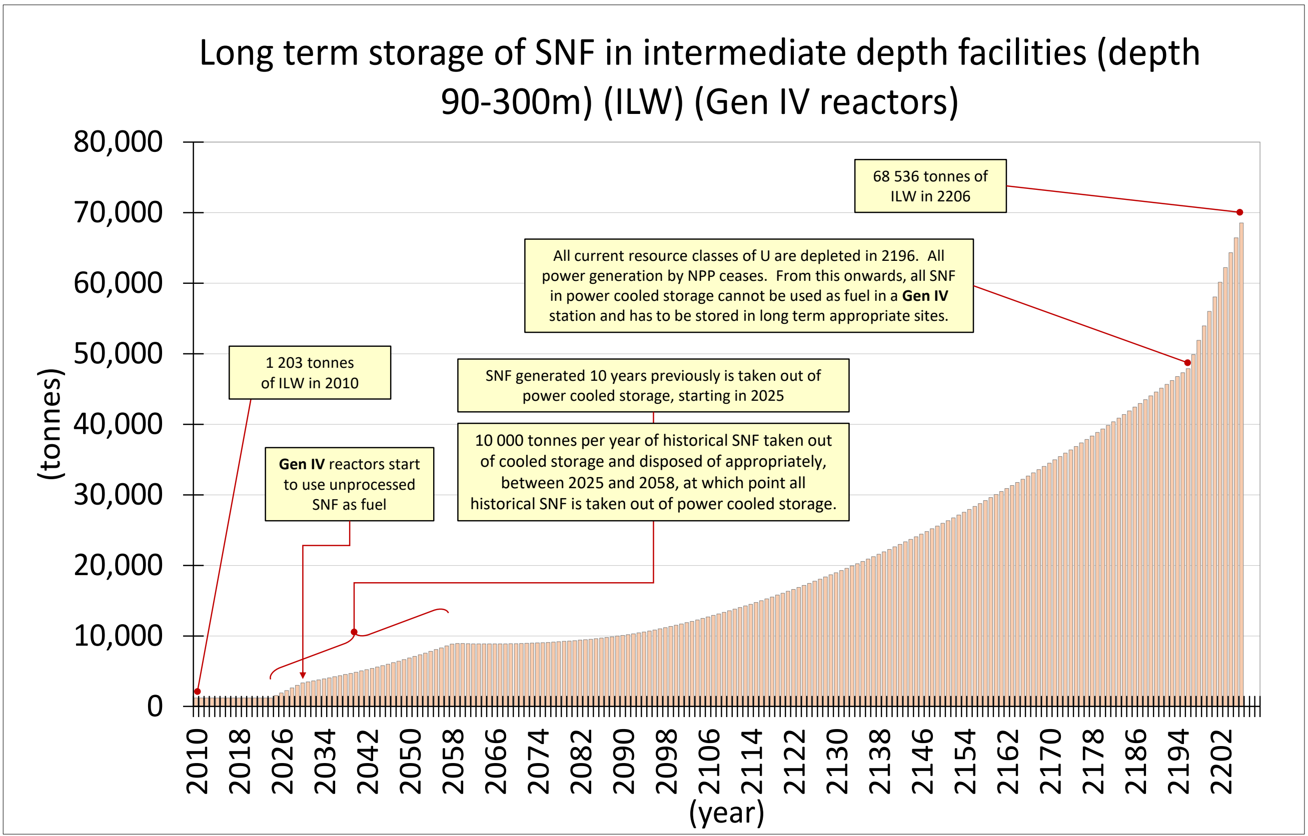


Figure 25.30. Cumulative long-term storage of ILW spent nuclear waste in intermediate depth (90 – 300m) Scenario E – Generation IV

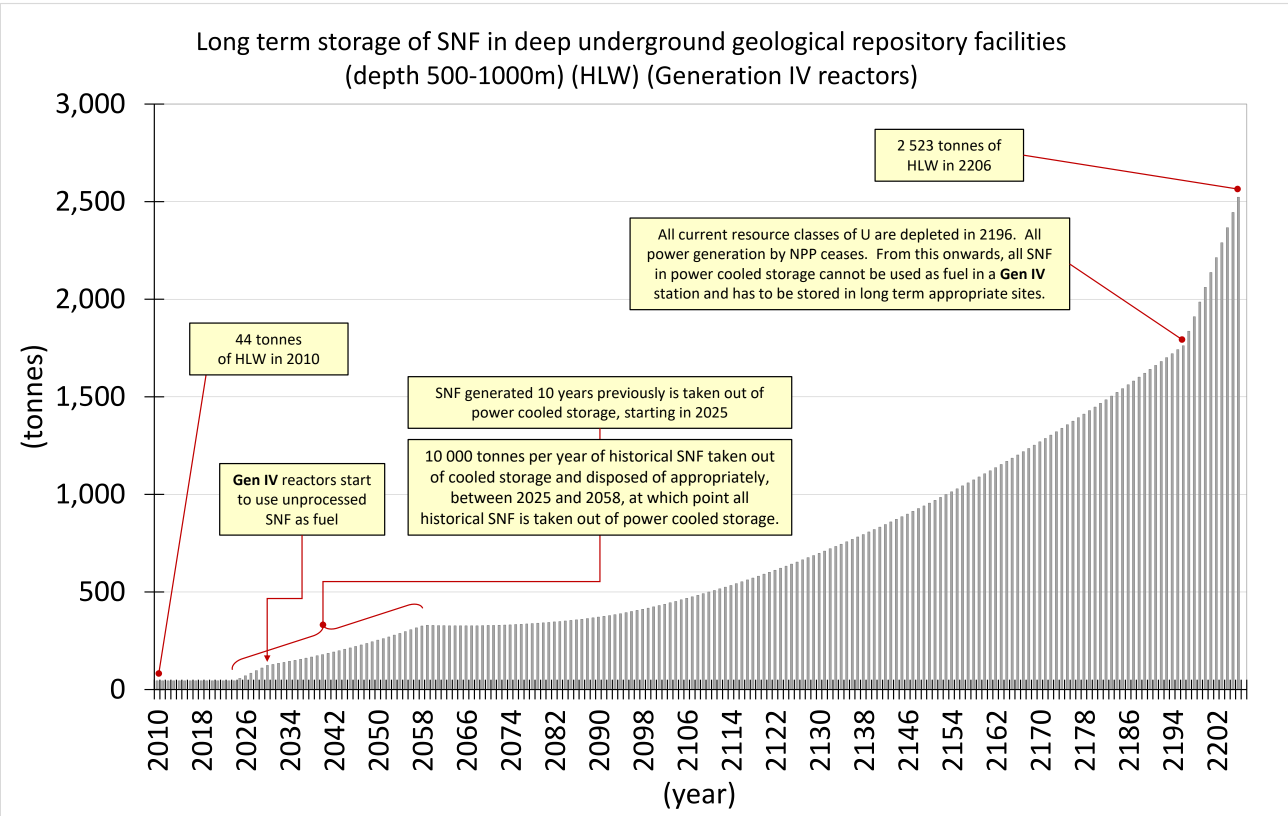


Figure 25.31. Cumulative long-term storage of HLW spent nuclear waste in intermediate depth (500 – 1000m) Scenario E – Generation IV

25.4.1 Outcomes of Scenario E – Generation IV Simulation

The following learnings were gained from this simulation:

Table 25.11. Consumption of U resources in Scenario E – Generation IV Simulation

Resource Class	Quantity (tonnes)	Start of Consumption	Year of depletion
Reasonably Assured Resources (RAR)	4,815,100	2016	2074
Inferred Resources (IR)	3,173,000	2075	2099
Prognosticated Resources (PR)	1,698,300	2100	2116
Speculative Resources (SR)	5,832,300	2117	2157
Unconventional Resources (UR)	8,116,900	2158	2196

- The uranium resources lasted much longer in the Generation IV simulation than either Generation II or Generation III+ simulations.

- In 2196, all current uranium resources had been consumed, giving 171 years of power supply service (starting in 2025). This means that the 4375 nuclear reactors operating in 2196 will have to decommissioned, and the fleet of nuclear power stations will no longer deliver electrical power to the global power grid after 2196.

- The annual quantity of electrical power delivered by the global nuclear power plant fleet in 2100 was simulated to be 20 977 TWh, with a peak production of 48 100 TWh in 2196.

- The additional annual power supply required to complete phase out fossil fuels (Scenario F, Section 26) was estimated 37 670.6 TWh, with a total capacity for the NPP fleet to be 40 145 TWh. This required annual power generation would not be reached until the year 2168, or 147 years from 2021. All current U resources would be exhausted 28 years later in 2196.

- This means that after decades of 'forced march' emergency industrialization, putting our faith in the expansion of the nuclear power fleet using Generation IV technology will not achieve the required annual power supply to completely phase out fossil fuels. A functional solution will need to be in place by a year similar to 2040 to 2060.

- This means that while nuclear power has its place, it will not be able to be the power source to phase out fossil fuels in time to meet climate change targets, nor risks of oil supply unreliability.

Table 25.12. Simulation outcome of Scenario E – Generation IV (Source: Appendix P)

Scenario E - Generation IV Reactors	Units	2016	2025	2030	2050	2070	2100	2150	2170	2196	2206
Mining and mineral processing of U annually to meet reactor requirements	(tonnes)	62,071.0	61,480.4	67,065.2	69,466.3	100,231.3	91,029.8	147,955.6	178,720.6	218,715.1	
Cumulative sum U extracted from resources with various methods from 2016	(tonnes)	62,071.0	682,124.8	1,045,324.6	2,520,749.7	4,423,369.3	8,097,932.1	14,269,106.4	17,915,934.7	23,678,893.2	
UOX pelletization of converted UF6	(tonnes)	13,848.5	14,659.4	14,018.1	16,815.3	20,552.8	28,775.3	39,240.3	42,977.8	47,836.5	
Required supply of unprocessed SNF from cooled storage to be used directly in Gen IV TWR reactors	(tonnes)			535.6	3,519.8	13,732.3	26,434.8	51,353.1	61,565.6	75,141.8	
Rod/assembly fabrication (UOX+MOX+SNF)	(tonnes)	15,276.0	15,276.8	16,045.7	22,827.1	37,777.1	60,202.1	98,085.4	113,035.4	132,470.4	
Number of nuclear power stations		447	443	493	708	1,208	1,958	3,225	3,725	4,375	
Number of Generation II Nuclear Power Plants	(number)		379	279							
Number of Generation III Nuclear Power Plants	(number)		3	2							
Number of Generation III+ Nuclear Power Plants	(number)		61	202	483	483	133				
Number of Generation IV TWR Nuclear Power Plants	(number)			10	225	725	1,825	3,225	3,725	4,375	
Electrical power generated by global nuclear fleet	(number)	2,473.6	2,679	3,585	6,950	12,561	20,977	35,195	40,806	48,100	
Annual mass of Spent Nuclear Fuel generated and put in powered underwater cooled storage	(TWh)	12,000.0	12,050.5	13,680.4	20,461.8	35,411.8	57,836.8	95,720.1	110,670.1	130,105.1	
Annual mass of Spent Nuclear Fuel taken out of powered underwater cooled storage	(tonnes)		22,000.0	22,535.6	30,460.0	27,936.8	50,361.8	88,245.1	103,195.1	122,630.1	
Total mass of Spent Nuclear Fuel (SNF) in power cooled storage pools for 10 year cycle	(tonnes)	244,200.0	329,258.5	283,805.3	109,836.3	52,105.2	276,355.2	655,188.2	804,688.2	999,038.2	
Annual mass of Spent Nuclear Fuel put into long term storage, adjusting for SNF fuel tasked for fuel recycling	(tonnes)			22,000.0	26,940.2	14,204.5	23,927.0	36,892.0	41,629.5	47,488.2	
Fabrication of MOX fuel	(tonnes)	992.0	992.0	1,492.0	2,492.0	3,492.0	4,992.0	7,492.0	8,492.0	9,492.0	
Total Stockpile mass of SNF to be disposed of	(tonnes)	73,800.0	95,800.0	205,800.0	421,335.1	546,747.3	706,500.1	1,592,790.5	2,116,273.7	2,937,253.0	4,204,666.1
Stable waste disposal of SNF (LLW)	(tonnes)	51,032.7	66,245.7	142,310.7	291,353.2	378,075.8	488,544.8	1,101,414.7	1,463,403.2	2,031,110.4	2,907,526.6
Long term storage of SNF in near surface depth facilities (depth 30m) (VLLW)	(tonnes)	21,512.7	27,925.7	59,990.7	122,819.2	159,376.8	205,944.8	464,298.4	616,893.8	856,209.2	1,225,660.2
Long term storage of SNF in intermediate depth facilities (depth 90-300m) (ILW)	(tonnes)	1,202.9	1,561.5	3,354.5	6,867.8	8,912.0	11,516.0	25,962.5	34,495.3	47,877.2	68,536.1
Long term storage of SNF in deep underground geological repository facilities (depth 500-1000m) (HLW)	(tonnes)	44.3	57.5	123.5	252.8	328.0	423.9	955.7	1,269.8	1,762.4	2,522.8

25.5 Scenario E Prognosis and Outcomes

The primary question these simulations were designed to answer was "can the nuclear fuel power plant (NPP) fleet be expanded to deliver enough extra power to phase out fossil fuels?" Tables 25.13 and 25.14 show a summary of all the simulations of how the nuclear power plant fleet could be expanded.

Table 25.13. Scenario E simulations comparison – duration, NPP fleet size, resource exhaustion

Senario E Simulation	Section	Years duration of simulation from 2016 to the last of SNF put into long term storage	Maximum size of NPP fleet	Peak production of Electricity (Twh)	Year of U resource exhaustion	Peak total mass of Spent Nuclear Fuel (SNF) in power cooled storage pools for a 10 year cycle in simulation (tonnes)
Reference	25.1	304	503	4,477	2325	4,200,608
Gen III+	25.2	91	2,345	25,663	2101	444,609
Gen II	25.3	84	2,195	16,422	2095	473,196
Gen IV	25.4	185	4,375	48,100	2196	999,038

The Reference simulation was designed to provide a reference point for the nuclear electrical power production, if the NPP fleet stayed on its current path of development. This simulation showed that U resources will last for 309 years, at which point more can be explored for. Just so, if the NPP fleet stays as it is, there is no resource shortage concerns. The Reference simulation was also to examine the back end of the nuclear fuel cycle. In 2013, 70% of Spent Nuclear Fuel (SNF) was in power cooled storage, with most storage facilities were 80-90% full (IAEA 2018). So, more storage facilities are required to be built. The combined mass of ILW and HLW was 68 656 tonnes (66 218 + 2 437), which needs to be stored for 100 000 years. This would require 11 Onkalo facilities (see Section 24.11.2).

In the Generation III+, Generation II and Generation IV simulations, an ambitious SNF handling regime has been proposed. To provide a contrast to this, the Reference simulation assumes no facilities are constructed, and all new SNF is kept in power cooled storage. Of course, this will not happen, and some facilities will be constructed. The purpose of the Reference simulation is to highlight the scale of the task ahead. Table 25.14 shows a simulation comparison for the back end of the nuclear cycle.

Table 25.14. Scenario E simulations comparison – Spent Nuclear Fuel

Senario E Simulation	Section	Total Stockpile mass of SNF to be disposed of into long term storage (tonnes)	Stable waste disposal of SNF (LLW) (tonnes)	Long term storage of SNF in near surface depth facilities (depth 30m) (VLLW) (tonnes)	Long term storage of SNF in intermediate depth facilities (depth 90-300m) (ILW) (tonnes)	Long term storage of SNF in deep underground geological repository facilities (depth 500-1000m) (HLW) (tonnes)
Reference	25.1	4,200,608	n/a	n/a	n/a	n/a
Gen III+	25.2	4,158,457	2,809,189	1,184,206	66,218	2,437
Gen II	25.3	3,405,560	2,354,945	992,721	55,511	2,043
Gen IV	25.4	4,204,666	2,907,527	1,225,660	68,536	2,523

A comparison of the Reference Scenario Simulation to the Generation II Scenario and the Generation III+ Scenario, shows an example of a Jevons Paradox. A Jevons paradox is an economic concept. The paradox occurs when technological development or government policy increases the efficiency with which a resource is used. The amount of needed resourced necessary for any one use is reduced, but the rate of consumption of that resource rises due to increasing demand (Bauer & Papp). The paradox is where the end result being the resource is consumed to depletion much faster as a consequence of an increase in efficiency. In 1865, the English economist William Stanley Jevons observed that technological improvements that increased the efficiency of coal-use led to the increased consumption of coal in a wide range of industries. He argued that, contrary to common intuition, technological progress could not be relied upon to reduce fuel consumption (Alcott 2005).

In Scenario F (Section 26) a hybrid solution of the learning of this report was estimated that an additional annual production of 37 670.6 TWh was required to phase out fossil fuels. This was added to the power generated by the existing NPP of 2 474 TWh, giving a total NPP global annual capacity of 40 145 TWh as a target to compare too. This power generation capacity target was put on the relevant charts in these simulations.

The following outcomes have been concluded from the Scenario E simulations:

- As previously shown in this report, nuclear power may be the only viable power source to supply heavy industry operations, that need concentrated amounts of consistently clean (sinusoidal) electricity in large quantities. Also, nuclear power could be the best option to supply energy for heating of building through winter. For this reason, nuclear power has its place and is absolutely necessary in the future energy mix.

- In all of the simulations, the Nuclear Power Plant fleet was not able to expand fast enough to be useful in annually delivering enough power to phase out fossil fuels (as per Scenario F, 37 670.6 TWh). Fossil fuels will need to be well on the way to being replaced by 2050. If the power required to do this is not in place soon enough with just nuclear, then other sources will be required.

- Only the Generation IV simulation was able to annually deliver more than 37 670.6 TWh. This required annual power generation would not be reached until the year 2141, or 120 years from 2021. All current U resources would be exhausted 55 years later in 2196. As Generation IV technology is still theoretical and not yet remotely viable, it can be concluded that nuclear power cannot be relied upon to completely substitute fossil fuel power generation.

- If the NPP fleet stayed on its current trajectory of development (Reference Simulation), then U resources will last for several centuries before more deposits need to be discovered. If the NPP was to be expanded to try and substitute fossil fuels power generation, U resources will last approximately 80 years (Generation III+ simulation). This duration could be extended by not expanding so quickly, but power generation would be proportionally less. In exchange for these 80 years of power delivery, 4.2 million tonnes of SNF would need to be stored appropriately for 100 000 years.

- The greatest challenge in the task to expand the NPP fleet is related to the volume of SNF in power cooled storage at the point if U resource exhaustion. For the Generation III+ simulation, at the point of U resource exhaustion in the year 2101, there will still be 444 609 tonnes of SNF in powered cooled storage pools. This SNF will have to be cooled without electrical power being generated from the nuclear power plant network. The electrical power required to operate these power cooled storage stations will have to come from another non-fossil fuel energy source, like solar, wind or hydro. Due to the industrial ecosystem energy requirements being applied to these non-fossil fuel energy generation systems, this is not a trivial task.

- The Generation III+, Generation II and Generation IV simulations require all of the current bottlenecks in the nuclear industry to be resolved. The industrial ecosystem collectively recognizes that an energy supply emergency is in progress and the entire ecosystem administration gets behind an aggressive expansion of the infrastructure supporting all sectors of the nuclear fuel cycle. All of societies industrial capability would be tasked to building new U extraction/refining/processing operations, new power plants and many newer SNF storage facilities. This will exhaust the industrial capability and exclude all other possible solutions. The outcome of these simulations shows that after decades of 'forced march' emergency industrialization, that nuclear power cannot be the supply solution on its own.

- The Generation III+ simulation is most likely as the current state of the art nuclear reactor technology is Generation III+. This provided the best performance with technology that is currently understood. This simulation also showcased the outcome of the propose SNF management and storage. This highlights the best base scenario for SNF handling for the duration of the nuclear fuel cycle as it consumes all resources.

- The purpose of the Generation II simulation is to test what would happen if the NPP was expanded using only Generation II reactors. This was done in response to the idea that Generation II reactors are preferable to the new Generation III+ reactors due to their lower cost of construction and the industry experience in managing these plants. This idea was proposed by a senior European bureaucrat in a sustainable energy development conference. The outcome of this simulation shows that Generation III+ technology should be favored over Generation II, in spite of the difference in cost.

- The difference in the volume of SNF to be handled for the duration of the Generation III+ and Generation II simulations needs to be explained as they both come from the same quantity of U resources. The Generation III+ total SNF stockpile was 1.32 times the Generation II total SNF stockpile. This was because in the Generation II simulation, the enrichment of ^{235}U was to a grade of 3.2%. In the Generation III+ simulation the enrichment of ^{235}U was to a grade of 4.09 %. This translated to 1.28 times extra available fuel.

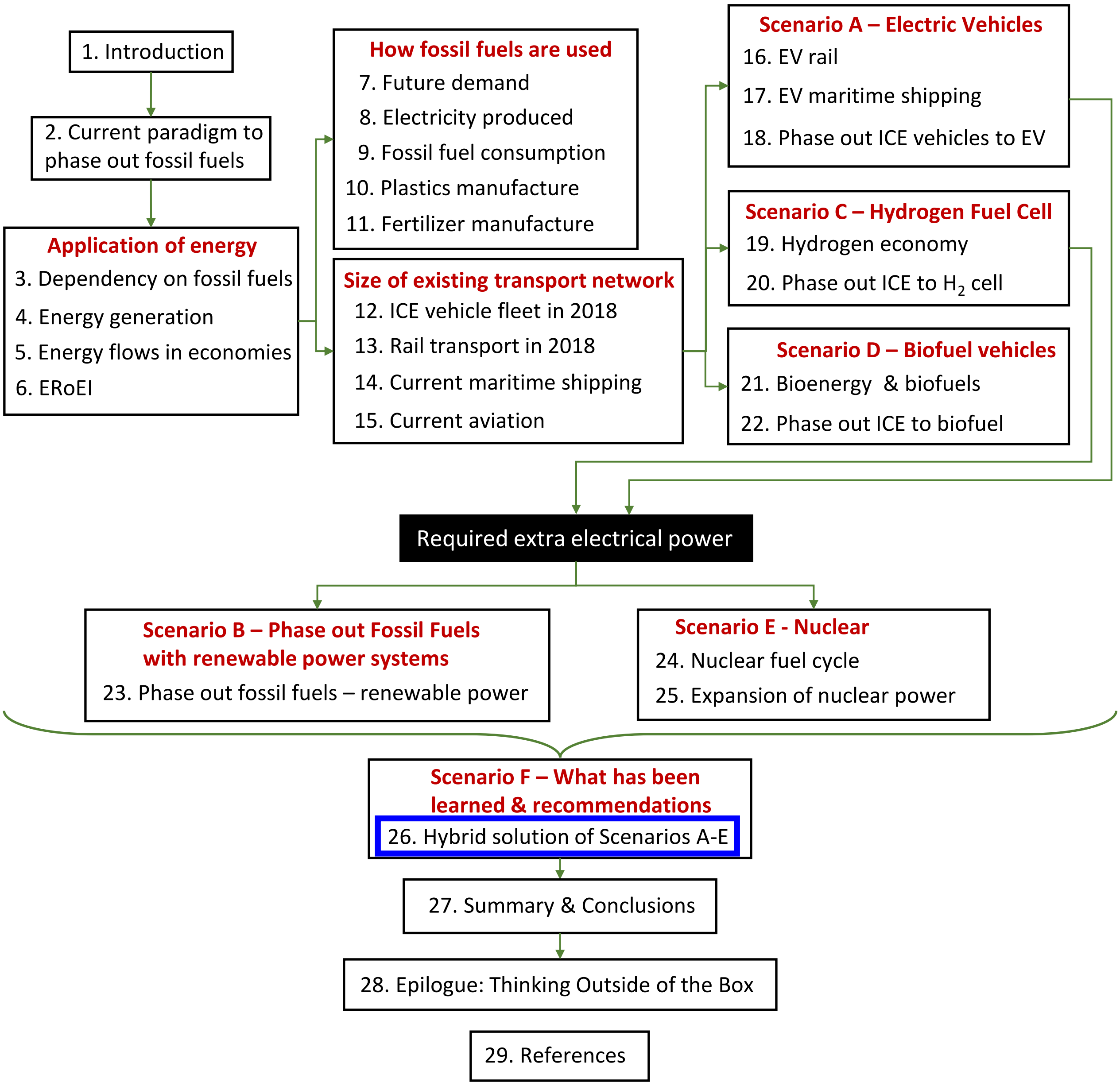
- Generation IV technology could revolutionize the nuclear fuel cycle and make it a viable fuel source and help manage the SNF management. The Generation IV simulation extended the duration of how long the U resources would last from 80 years to 180 years. In doing so, it also was able to manage historical SNF generated before 2025 in a much more appropriate manner. At the point of U resource exhaustion (2196), the SNF volume in power cooled storage was much larger (999 038 tonnes) as there were so many more reactors operating up to that point. In the Generation IV simulation, there was 4375 reactors operating in 2196, whereas there was 2345 Generation III+ reactors in 2101 in the Generation III+ simulation.

The following recommendations are made:

- Nuclear power is used to service heavy industry operations and heating requirements directly.
- Expansion of the fleet should be planned to a little bit larger in scope than reference scenario to make resources last.
- It is also recommended to develop a robust back end SNF handling system. The proposed storage of SNF and MOX fuel manufacture in the Generation III+ simulation is ambitious. It is recomended that a more practical version of this plan is developed.
- It is recomended to resource the development of Generation IV and thorium nuclear power technology.

26 SCENARIO F: HYBRID SOLUTION

The purpose of Scenario F is to assemble all the outcomes and learnings of Scenarios A, B, C, D and E and examine them collectively. There are clear advantages and disadvantages of each proposed energy system examined in this report. They all have their place. Scenario F is to assemble these learnings and propose a combination of Scenarios A to E, where all the respective advantages naturally overlap. A proposed plan to phase out fossil fuels is proposed, with the required number of Electric Vehicles (EVs), Li-Ion batteries, Hydrogen power cells, and biofuels is presented. The extra power capacity to support all this will be calculated and then required the number of different non-fossil fuel power stations is presented.



Assessment of the Extra Capacity Required of Alternative Energy Electrical Power Systems to Completely Replace Fossil Fuels

The purpose of this report is to provide some clarity, and hard numbers for the important task of phasing out fossil fuels. The approach for this report was developed in response to the lack of long-term data describing the scope of the task, and that there was no real understanding for how the different non-fossil fuel transport systems might interrelate.

In what circumstances would an EV be more appropriate than a Hydrogen cell powered vehicle? The current paradigm is that the free market will resolve these questions. The free market outcome is to continue to use fossil fueled Internal Combustion Engine (ICE) vehicles, with gas and coal powered electricity. Non-fossil fuel powered systems are not yet economically viable to overrun fossil fuel powered systems. When the market shifts and this trend reverses, there will be limited time for optimized industrial reform. Clarity of what the full global fossil fuel supported industrial ecosystem replacement would be useful before the market shifts.

Any system supported with oil and gas feedstock energy resources may soon become unreliable (Michaux 2019). The paradigm that "society can continue with fossil fuel based systems for decades if need be until renewable energy becomes viable", is unlikely to go smoothly. Then there are the climate change mitigation strategies that require fossil fuels to be phased out in the next few decades.

So, the after fossil fuels plan is needed now.

26.1 What was learned from Scenarios A to E

The following is a brief description of each Scenario and a summary of what was learned.

Scenario A was developed to examine the transformation of the global transport vehicle fleet from petroleum fueled ICE technology to **EV technology**. All passenger cars, trucks, commercial vans, rail locomotives and maritime shipping were replaced with EV's (using 2018 transport fleet scope). The size and scope of the transport system for the United States, Europe, China and for the Global system was estimated. The number of vehicles by class, size of batteries, the extra electrical power required to charge batteries, number of non-fossil fuel power stations and the number of power storage stations were estimated. This was compared to the existing non-fossil fuel power generation capability. It was proposed that EV powered aviation aircraft was not viable at this time, due to the required mass of the lithium ion battery. It was also proposed that EV maritime vessels were not viable for long range commodity and container shipping transport. This was due to the required mass of the battery banks.

Scenario B was developed to examine the logistics to **phase out all fossil fuels entirely**. All applications using oil, gas and coal were completely replaced with non-fossil fuel systems. The global transport fleet of ICE vehicles are substituted with Elective Vehicles, as per the outcomes of Scenario A. Fossil fuel fired electrical power generation capacity is replaced with nuclear, solar, wind, hydro, biomass, and geothermal electrical power generation systems in the same energy mix as in 2018. Heating applications (using gas) and steel manufacture (using coal) was substituted with electrical alternatives. The sum total was compared to the existing non-fossil fuel power generation capability. The number of new power stations for each respective power generation system was estimated.

Scenario C was developed to examine the transformation of the global transport vehicle fleet from petroleum fueled ICE technology to **Hydrogen Fuel Cell technology**. All passenger cars, trucks, commercial vans, rail locomotives and maritime shipping were replaced with hydrogen fuel cell powered vehicles (using 2018 transport fleet scope). The size and scope of the transport system for the United States, Europe, China and for the Global system developed in Scenario A was used. The total volume of hydrogen required to fuel H_2 cell vehicles (same number and class as 2018 fleet) to travel the same distance was calculated. A non-fossil fuel manufacture method to produce hydrogen (electrolysis) was used to estimate the additional electrical power that would be required to produce this volume of hydrogen.

The outcomes of Scenario C were compared to Scenario A, as they were to achieve the same thing, powering the global vehicle fleet without fossil fuels. There were three notable outcomes of this comparison.

1. The electrical power required to produce the required volume of hydrogen to fuel a hydrogen fuel cell powered vehicle to travel a given distance, was 2.5 times the electrical power required to charge an EV lithium ion battery, where both vehicles were the same size, class and travelled the same distance.

2. Comparing the two vehicles from point 1, the mass of the required lithium ion battery was 3.2 times the mass of the hydrogen fuel tank (assuming 700 bar gas pressure and a 5.7 wt.% storage density). This meant that the hydrogen fuel cell vehicle could have 3.2 times the range if the hydrogen fuel tank was the same mass as the lithium ion battery.

3. If the hydrogen fuel cell vehicle had a cryogenic liquid hydrogen fuel tank, the EV lithium ion battery would be 9.1 times the mass of the cryogenic tank (assuming 14 wt.% storage density).

This comparison showed the clear advantages that EV vehicles and H_2 cell vehicles had over each other. This difference in mass between lithium ion battery banks and hydrogen gas tanks show that hydrogen cell systems could be viable for maritime shipping (where EV maritime is not).

Scenario D was developed to examine the transformation of the global transport vehicle fleet from petroleum fueled ICE technology to **Biofuel fueled ICE technology**. The volume biofuels to be produced was based on 2018 global demand for petroleum products (gasoline petrol, diesel, marine bunker fuel oil, and jet fuel). Only the global system was examined.

Corn feedstock was used to produce ethanol in the same 2018 annual quantity to substitute for gasoline and jet fuel. Soybean feedstock was used to produce biodiesel in the same 2018 annual quantity to substitute for diesel and marine bunker fuel oil. The area of arable land required to do this was compared to 2017 planetary land use, where the required land area to grow biofuels far exceeded what was possible. The volume of fresh water required to irrigate the biofuel crops was compared to current global water withdraws by the global society. Again, this was shown to be impractical to even consider.

Biofuel produced from algae feedstock was also examined to produce all required biofuels. The most serious setback for this feedstock source was the negative Energy Returned on Energy Invested (ERoEI) ratio. Far more energy was required to produce the biofuel than was potentially contained in the orginal algae feedstock.

Biofuels as a complete solution were shown not to be viable. The technology works well on a small scale, but industrial production scale up has some seemingly insurmountable challenges.

That being stated, the biofuels solution has it place, as it has a capability that EV and H_2-cell technologies do not. Biofuels can be used to substitute jet fuel, where lithium ion battery EV systems and H_2-cell powered systems cannot. Biomass could also be used to substitute at least part of the plastics industry.

Scenario E was developed to examine whether the nuclear power plant (NPP) fleet could be expanded deliver the required electrical power to service the non-fossil fuel systems selected to support the power requirements proposed by Scenarios A, B and C. Nuclear power was proposed to be the primary energy source as it was perceived to have an ERoEI ratio too low to be useful. Renewable energy systems like wind and solar were considered to be too intermittent to be relied upon to service heavy industry.

The nuclear fuel cycle for several nuclear technologies were examined. Some assumptions were made where current social license to operate issues that are slowing productivity in the nuclear industry, are all resolved. The global industrial ecosystem recognizes it faces an energy emergency, and all industrial capability is tasked to aggressively expand the nuclear power plant fleet. This would be a similar industrialization push to what was seen in the United Kingdom and the United States during World War II. It was assumed that the incubation time to commission each nuclear power plant was reduced to 5 years, and each year 25 new stations were connected to the electrical power grid. These assumptions were ambitious and could be argued to be completely impractical. Their purpose was to assess whether it was possible for nuclear to be the primary energy source if all current limitations were removed.

It was found that the NPP fleet could not expand in capability fast enough to deliver sufficient electricity to service power requirements for Scenarios A, B or C. Also, the current global uranium resources would be exhausted in approximately 80 years during this aggressive expansion (where current U resources would last several hundred years if the NPP was maintained on its current development trajectory). The volume of Spent Nuclear Fuel generated during this time would have to be managed appropriately. When the last of the current U resources are exhausted, an unprecedented volume of SNF will need to be kept in power cooled storage for 10 years. These storage sites would have to be powered by some other electrical power generation source than nuclear.

Once again, the nuclear power solution has its place. It could be the most suitable non-fossil fuel power generation system to support industry, which needs large quantities of concentrated electrical power, and large quantities of high temperature heat. Nuclear also could deliver power to geographical areas where solar, hydro and wind were not viable, and could do so 365 days a year. Other renewable power systems were not able to function well during winter seasons.

26.2 Outcomes learned and the proposed hybrid solution - Scenario F

The following generic and approximate recommendations are made. Of course, if this was to be implemented then these recommendations would be stylized and optimized.

26.2.1 Electric Vehicles

All vehicles travelling a comparatively short range distance and/or operate within the boundaries of a city most of the time, should be an Electric Vehicle. This would include vehicle classes: passenger cars, motorcycles, buses, light trucks, commercial vans, and delivery trucks. Tables 26.1 to 26.4 show the Electric Vehicle fleet and the required electric power support to charge batteries for the United States, Europe, China, and the Global System.

Table 26.1. Size of the required electrical vehicle fleet in the United States – Scenario F

Vehicle Class	Number of Self Propelled Vehicles in 2018 U.S. Fleet (number)	Total km driven by class in 2018 U.S. Fleet (km)	Electrical power to be generated, assuming a 10% loss in transmission between power station and charging point (kWh)	Estimated Summed for Vehicle Class Battery Capacity to be Manufactured (kWh)	Total Mass of Li-Ion batteries (tonne)
Transit Bus	2,517,520	1.38E+11	2.74E+11	5.73E+08	2,490,156
Refuse Truck	1,850,465	7.45E+10	1.13E+11	3.81E+08	1,658,177
Paratransit Shuttle	1,678,668	6.13E+10	9.32E+10	3.82E+08	1,660,421
Delivery Truck	959,133	2.00E+10	2.47E+10	1.98E+08	859,466
School Bus	888,223	1.72E+10	3.41E+10	2.02E+08	878,569
Light Truck/Van	82,569,993	1.59E+12	5.52E+11	3.48E+09	15,129,284
Light-Duty Vehicle	79,237,170	1.47E+12	6.85E+11	1.22E+10	52,939,617
Passenger Car	78,293,789	1.43E+12	4.10E+11	3.66E+09	15,931,084
Motorcycle	16,223,409	6.15E+10	1.02E+10	3.49E+08	1,297,873
Total	264,218,370	4.87.E+12	2.20.E+12	2.14.E+10	9.28.E+07
	264 million vehicles	4.9 trillion km travelled in 2018	2 197.5 TWh power generated to charge batteries	21.4 TWh of Batteries	Total Li-Ion battery mass 92.8 million tonnes

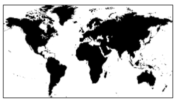
Table 26.2. Size of the required electrical vehicle fleet in Europe (EU-28) – Scenario F

Vehicle Class	Number of Self Propelled Vehicles in 2018 EU-28 Fleet (number)	Total km driven by class in 2018 EU-28 Fleet (km)	Electrical power to be generated, assuming a 10% loss in transmission between power station and charging point (kWh)	Estimated Summed for Vehicle Class Battery Capacity to be Manufactured (kWh)	Total Mass of Li-Ion batteries (tonne)
Bus	657,714	7.6E+09	1.50E+10	1.50E+08	650,565
Light Truck/Van	27,413,946	1.1E+11	3.85E+10	1.16E+09	5,023,052
Passenger Car	222,683,327	8.6E+11	2.48E+11	1.04E+10	45,311,216
Motorcycle	4,548,655	3.6E+09	6.00E+08	9.78E+07	363,892
Total	2.55E+08	9.78E+11	3.02E+11	1.18E+10	5.13E+07
	255 million vehicles	Travelled 977.97 billion km in 2018	301.8 TWh power generated to charge batteries	11.8 TWh of Batteries	Total Li-Ion battery mass 51.3 million tonnes

Table 26.3. Size of the required electrical vehicle fleet in China – Scenario F

Vehicle Class 	Number of Self Propelled Vehicles in 2018 Chinese Fleet (number)	Total km driven by class in 2018 Chinese Fleet (km)	Electrical power to be generated, assuming a 10% loss in transmission between power station and charging point (kWh)	Estimated Summed for Vehicle Class Battery Capacity to be Manufactured (kWh)	Total Mass of Li-Ion batteries (tonne)
Transit Bus + School Bus + Refuse Truck + Paratransit Shuttle + Delivery Truck	1,243,900	1.5E+10	2.98E+10	2.56E+08	1,114,643
Light Truck/Van + Light-Duty Vehicle + Other Vehicle Type	18,419,000	8.8E+10	3.06E+10	7.76E+08	3,374,910
Passenger Car	203,689,500	9.4E+11	2.70E+11	9.53E+09	41,446,385
Motorcycle	1,864,600	1.79E+09	2.97E+08	4.01E+07	149,168
Total	225,217,000	1.05.E+12	3.31.E+11	10,605,354,576	46,085,106
	225 million vehicles	Travelled 1.05 trillion km in 2018	330.9 TWh power generated to charge batteries	10.6 TWh of Batteries	Total Li-Ion battery mass 46.1 million tonnes

Table 26.4. Size of the required electrical vehicle fleet for the Global system – Scenario F (World Map Image by Clker-Free-Vector-Images from Pixabay)

Vehicle Class 	Number of Self Propelled Vehicles in 2018 Global Fleet (number)	Total km driven by class in 2018 Global Fleet (km)	Electrical power to be generated, assuming a 10% loss in transmission between power station and charging point (kWh)	Estimated Summed for Vehicle Class Battery Capacity to be Manufactured (kWh)	Total Mass of Li-Ion batteries (tonne)
Transit Bus + Refuse Truck + Paratransit Shuttle + Delivery Truck + School Bus	29,002,253	8.03E+11	1.60E+12	5.98E+09	25,988,541
Light Truck/Van + Light-Duty Vehicle	601,327,324	7.89E+12	2.99E+12	2.53E+10	110,181,094
Passenger Car	695,160,429	5.40E+12	1.55E+12	3.25E+10	141,450,035
Motorcycle	62,109,261	1.60E+11	2.65E+10	1.34E+09	4,968,741
Total	1,387,599,267	1.43E+13	6.1584E+12	6.5188E+10	2.83E+08
	1.39 billion vehicles	14.25 trillion km travelled in 2018	6 158.4 TWh power generated to charge batteries	65.19 TWh of Batteries	Total Li-Ion battery mass 282.6 million tonnes

26.2.2 Hydrogen Fuel Cell Vehicles

All vehicles travelling a comparatively long range distance and/or operate outside the boundaries of a city, should be a hydrogen cell powered vehicle. This would include vehicle classes: Class 8 HCV trucks, Rail locomotives, and all maritime shipping vessels. Table 26.5 shows the proposed footprint of the hydrogen cell Class 8 HCV Truck fleet. Table 26.6 shows the proposed hydrogen footprint of Class 8 HCV trucks, rail locomotives and maritime shipping vessels.

Table 26.5. Hydrogen cell Class 8 trucks in the United States, Europe, China, and Global systems (based on 2018 transport scope) (World Map Image by Clker-Free-Vector-Images from Pixabay)

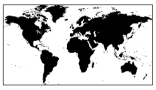
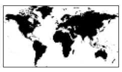
H_2 Cell Class 8 Trucks 	Number of Self Propelled Vehicles in 2018 Transport Fleet (number)	Total km driven by class in 2018 Transport Fleet (km)	Quantity of H_2 for all Class 8 HCV vehicles in that class to travel the same distance as was done in 2018 (tonnes)	Required electric power generation,a ssuming 10% grid transmission loss between power station and electrolysis unit (TWh)
United States	4,694,851	4.79E+11	3.84E+07	2,219.6
Europe (EU-28)	5,716,322	1.23E+11	9.83E+06	567.5
China	7,095,300	2.93E+11	2.35E+07	1,359.2
Global	28,929,348	1.62E+12	1.30E+08	7,503.7

Table 26.6. Global number of hydrogen cell vehicles and the volume of hydrogen to fuel them for one year (based on 2018 transport scope) (World Map Image by Clker-Free-Vector-Images from Pixabay)

Vehicle Class 	Number of Self Propelled Vehicles in 2018 Global Fleet (number)	Hydrogen Produced (million tonnes)	Required Electric power to manufacture H_2 with electrolysis (@ 50 kWh/kg) (kWh)	Required Electric power to compress H_2 into tanks at 700 barr pressure (@ 2.5 kWh/kg) (kWh)	Required annual electric power generation assuming 10 % grid transmission loss between power station and electrolysis unit and compression unit (kWh)
Class 8 Truck	28,929,348	129.9	6.50E+12	3.25E+11	7.50E+12
Rail Freight Locomotives	104,894	18.5	9.23E+11	4.62E+10	1.07E+12
Martime Shipping	101,105	51.7	2.58E+12	1.29E+11	2.98E+12
Total	29,135,347	200.1			1.16E+13

29.1 million H-Cell vehicles

11 553.6 TWh

26.2.3 Biofuels and Biomass

Fueling the aviation industry is an interesting challenge. An electric propulsion system powered by a battery may work for small aircraft, but the mass of the required battery bank to power an aircraft of the specifications of an Airbus A350 (carry 440 passengers + luggage 15 000 km) would be so large the aircraft could not take off.

The same aircraft, if powered by a hydrogen cell would have a hydrogen fuel tank 3.2 times smaller in mass than the battery bank, but due to the required geometry of the gas tank, it would have to be situated inside the cabin. A 700 bar pressure hydrogen fuel tank would not fit easily into the aircraft wing like jet fuel (or biofuel) does. To mitigate risk of leaking, conventional gas tanks are cylinders with rounded ends. A hydrogen tank large enough to propel an aircraft like an Airbus 350 would be so large that it would take up cabin space, reducing cargo capacity.

As discussed in Section 21.4.1, jet fuel can be manufactured as a biofuel from biomass feedstock. This solution should be managed carefully, however. In Scenario D, direct substitution for all petroleum products with biofuels would require arable land, fresh water and biomass that far exceeds the planet Earth's sustainable capacity. So, what is proposed here is biofuels are used to keep a small proportion only of the existing aviation industry operating.

Biomass could be used as a feedstock to manufacture plastic products. In doing so, a small proportion of the existing plastics industry could be maintained. Fossil fuels still should be used in very small quantities to make high performance plastics for very important applications.

Biomass as feedstock Combined Heat and Power (CHP) plants have the capability to continuously produce heat at a high enough temperature and in enough quantities to facilitate some manufacturing operations that no other renewable power source can. This would be a direct substitution for coal for some specialized applications.

The size and scope of the use of biomass, biowaste and/or biofuels is entirely dependent on how much the regional environment can sustainably support. A full systems analysis would be required accounting for a full mass flow balance in context of the planetary environment is required to determine the true sustainable scope of this action. Scenario D shows the outcome products will be much less than the current petroleum product global footprint.

26.2.4 Nuclear Power

The nuclear power plant (NPP) fleet cannot be expanded fast enough to be useful in delivering enough electricity to completely phase out fossil fuels. It was also found that all existing uranium resources would be exhausted well before even reaching the target annual power production. If the NPP was developed on its current trajectory, uranium resources would last something like 300 years. These were outcomes of Scenario E, where the target quantity of electrical power generation required to phase out fossil fuels was 30 853.9 TWh (an outcome of Scenario B).

However, nuclear power certainly does have its place in the future energy mix. Nuclear power has the capacity to generate concentrated volumes of electrical power at a steady continuous rate. It can do so in all weathers and all geographical locations. No other non-fossil fuel power generation system has these capabilities. Wind and solar are highly intermittent and vary in productivity with the yearly seasons.

Nuclear power should be used to support industrial actions like some manufacturing operations that require heavy current electrical supply that is stable and consistent. Nuclear power also should be tasked with supplying power for building heating applications in the winter in the Northern Hemisphere (a direct substitution for gas).

26.2.5 Fertilizer Production

As discussed in Section 11, industrial fertilizer is manufactured with the use of among other things, gas. There is no viable solution that can replace this action at an industrial scale (at this time). Industrial agriculture has a number of challenges to overcome. The degradation of arable land, and the overloading of the nitrogen cycle and phosphorus cycle in the planetary environment are the most pressing issues to be addressed.

It is recomended to consider the phasing out of large scale industrial agriculture, with its dependency on petrochemical fertilizers, pesticides, and herbicides. Food production could be reorganized to be supplied from a large number of local to consumption small scale organic farming operations.

The issue of land degradation should also be addressed in a proactive fashion on a global scale. Just so, it is recommended to consider the rehabilitation of formerly arable land that has been sterilized from the application of industrial agriculture (or any other industrial pollution). This could be done by first ensuring the mineral balance, and the sand/clay/gravel ratios in the soil are appropriate to manage the required water drainage. Then the organic humus content of the soil could be increased, where the soil food web of microbes, fungi and nutrients could be sustainably reestablished.

26.3 Number of electric vehicles, hydrogen cells and electrical power plants to be constructed for Scenario F

The additional (to existing non-fossil fuel power systems) annual quantity of electrical power to be generated can now be estimated for Scenario F. Table 26.7 shows the annual electrical power required to charge EV batteries and generate hydrogen for different vehicle classes. Table 26.8 shows the mass of lithium ion batteries needed for these EV's. Table 26.9 shows the annual electrical power required to phase out fossil fuel (gas and coal) power generation applications, heating applications and steel manufacture.

Table 26.7. Electrical power extra annual capacity required to support non fossil fuel vehicles in the Global fleet – Scenario F (World Map Image by Clker-Free-Vector-Images from Pixabay)

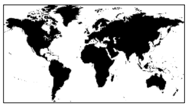
Vehicle 	Power required to charge Li-Ion batteries in EV vehicles (TWh)	Power required to manufacture hydrogen (TWh)
Class 8 Truck		7,503.7
Bus & Delivery Truck	1,597.5	
Light Truck & Van	2,988.6	
Passenger Car	1,545.9	
Motorcycle	26.5	
Maritime Shipping		2,983.4
Rail Transport		1,066.5
Total (TWh)	6,158.4	11,553.6

Table 26.8. Estimated number and mass of Li-Ion batteries for all self-propelled vehicles in the global fleet (World Map Image by Clker-Free-Vector-Images from Pixabay)

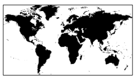
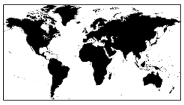
Vehicle Class 	Number of Self Propelled Vehicles in 2018 Global Fleet (number)	Battery Capacity (kWh)	Estimated Range (km)	Estimated Summed for Vehicle Class Battery Capacity to be Manufactured (kWh)	Energy Consumption of EV System (kWh/km)	Average Li-Ion Battery Mass @230Wh/kg in vehicle (kg)	Total Mass of Li-Ion batteries (tonne)
Transit Bus + Refuse Truck + Paratransit Shuttle + Delivery Truck + School Bus	29,002,253	206.1	226	5.98E+09	1.16	896.1	25,988,541
Light Truck/Van + Light-Duty Vehicle	601,327,324	42.1	205.8	2.53E+10	0.23	183.2	110,181,094
Passenger Car	695,160,429	46.8	270.1	3.25E+10	0.19	203.5	141,450,035
Motorcycle	62,109,261	21.5	322	1.34E+09	0.08	80.0	4,968,741
Total	1,387,599,267			6.52E+10			2.83.E+08
	1.39 billion vehicles			65.2 TWh of Batteries		Total Li-Ion battery mass 282.6 million tonnes	

Table 26.9. Non-fossil fuel annual electrical power generation capacity to phase out gas and coal – Scenario F (World Map Image by Clker-Free-Vector-Images from Pixabay)

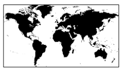
Sustainable Energy Task 	Non-fossil fuel power required to phase out fossil fuels (TWh)
Phase out coal electricity generation	10,100.5
Phase out coal based steel manufacture	56.5
Phase out gas electricity generation	6,182.8
Phase out gas based heating	2,816.0
Phase out oil electricity generation	802.8
Total (TWh)	19,958.6

So, in summary:

Electrical power required to charge EV batteries	6 158.4 TWh
	+
Electric power required to produce hydrogen for H_2-Cell vehicles	11 553.6 TWh
	+
Electrical power required to phase out gas and coal power generation	17 086.1 TWh
	+
Electrical power required to phase out gas building heating	2 816.0 TWh
	+
Electrical power required to phase out coal fired steel manufacture	56.5 TWh
	=
Total power requirements for Scenario F	**37 670.6 TWh**

Table 26.10 shows the number of non-fossil fuel power stations required to deliver this annual electrical power. The energy mix of these different power generation systems was estimated using the same method as shown in Figure 18.9 in Section 18.6. Figures 26.1 and 26.2 show the outcomes of Tables 26.10 graphically.

Table 26.10. Number of additional non-fossil fuel power stations to phase out fossil fuels – Hybrid Solution Scenario F (World Map Image by Clker-Free-Vector-Images from Pixabay)

Power Generation System 	Global non-fossil fuel electricity production in 2018 (Appendix B & Agora Energiewende and Sandbag 2019) (kWh)	Global Number Power Plants in 2018 (Global Energy Observatory) (number)	2018 ratio percent of non-fossil fuel electrical power systems (%)	Expanded extra required annual capacity to phase out fossil fuels (kWh)	Power Produced by a Single Average Plant in 2018 (kWh)	Estimated number of required additional new power plants of average size to phase out fossil fuels (number)
Nuclear	2.70E+12	438	28.35%	1.07E+13	1.28E+10	834
Hydroelectric	4.19E+12	3,163	44.00%	1.66E+13	1.33E+09	12,504
Wind	1.30E+12	16,048	13.68%	5.15E+12	8.12E+07	63,445
Solar PV	5.79E+11	17,526	6.08%	2.29E+12	3.30E+07	69,291
Solar Thermal	5.50E+09	52	0.06%	2.17E+10	7.70E+07	282
Geothermal	9.30E+10	108	0.98%	3.68E+11	6.03E+08	609
Biowaste to energy	6.53E+11	3,800	6.85%	2.58E+12	3.46E+07	74,628
Total (kWh)	9.53E+12	41,135		3.77E+13		221,594
Total (TWh)	9,528.7			37,670.6		

Tables 26.11 to 26.16 show the same estimates for the United States, Europe, and China.

Table 26.11. Tasks to phase out fossil fuels in the United States

Task to phase out fossil fuels 	Electrical Power Required (TWh)
<u>United States EV vehicle fleet</u>	
78.3 million Passenger Cars Travelled 1.43 trillion km	410.2
7.9 million Buses & Delivery Trucks Travelled 310.7 billion km	539.5
161 million Commercial Vans, Light Trucks Travelled 3.1 trillion km	1,237.7
16.2 million Motorcycles Travelled 61.5 billion km	10.2
<u>United States Industrial Tasks</u>	
Electrical Power Generation	2,850.8
Building Heating	998.4
<u>Hydrogen Production</u>	
4.7 million Class 8 HCV Trucks Travelled 479.2 billion km, requiring 38.4 million tonnes of hydrogen to be produced	2,219.6
Total	8,266.4

Table 26.12. Number of additional non-fossil fuel power stations to phase out fossil fuels in the United States – Hybrid Solution Scenario F

Power Generation System	United States non-fossil fuel electricity production in 2018 (Appendix B & BP Statistics 2019) (kWh)	2018 ratio percent of non-fossil fuel electrical power systems in United States (%)	Expanded extra required annual capacity to phase out fossil fuels (kWh)	Power Produced by a Single Average Plant in 2018 (kWh)	Estimated number of required additional new power plants of average size to phase out fossil fuels (number)
Nuclear	8.50E+11	52.77%	4.36E+12	1.28E+10	341
Hydroelectric	2.89E+11	17.93%	1.48E+12	1.33E+09	1,118
Wind	2.78E+11	17.25%	1.43E+12	8.12E+07	17,549
Solar PV	9.71E+10	6.03%	4.99E+11	3.30E+07	15,088
Other Renewable	9.70E+10	6.02%	4.98E+11	7.70E+07	6,470
Total (kWh)	1.61E+12		8.27E+12		40,566
Total (TWh)	1,610.1		8,266.4		

Table 26.13. Tasks to phase out fossil fuels in Europe (EU-28)

Task to phase out fossil fuels	Electrical Power Required (TWh)
European EV vehicle fleet	
222.7 million Passenger Cars Travelled 855.7 billion km	247.7
657 714 Buses Travelled 7.6 billion km	15.0
27.4 million Commercial Vans & Light Trucks Travelled 111.1 billion km	38.5
4.5 million Motorcycles Travelled 3.6 billion km	0.6
European Industrial Tasks	
Electrical Power Generation	1,330.9
Building Heating	856.9
Hydrogen Production	
5.7 million Class 8 HCV Trucks Travelled 122.5 billion km, requiring 9.8 million tonnes of hydrogen to be produced	567.5
Total	3,057.1

Table 26.14. Number of additional non-fossil fuel power stations to phase out fossil fuels in the Europe (EU-28) – Hybrid Solution Scenario F

Power Generation System	European non-fossil fuel electricity production in 2018 (Appendix B & BP Statistics 2019) (kWh)	2018 ratio percent of non-fossil fuel electrical power systems in Europe (%)	Expanded extra required annual capacity to phase out fossil fuels (kWh)	Power Produced by a Single Average Plant in 2018 (kWh)	Estimated number of required additional new power plants of average size to phase out fossil fuels (number)
Nuclear	8.27E+11	42.33%	1.29E+12	1.28E+10	101
Hydroelectric	3.45E+11	17.64%	5.39E+11	1.33E+09	407
Wind	3.79E+11	19.38%	5.92E+11	8.12E+07	7,292
Solar PV	1.28E+11	6.54%	2.00E+11	3.30E+07	6,049
Other Renewable	2.76E+11	14.12%	4.32E+11	7.70E+07	5,608
Total (kWh)	1.95E+12		3.06E+12		19,457
Total (TWh)	1,954.8		3,057.1		

Table 26.15. Tasks to phase out fossil fuels in the China

Task to phase out fossil fuels	Electrical Power Required (TWh)
Chinese EV vehicle fleet	
203.7 million Passenger Cars Travelled 944.1 billion km	270.3
1.2 million Buses and Delivery Trucks Travelled 15.0 billion km	29.8
18.4 million Commercial Vans & Light Trucks Travelled 88.2 billion km	30.6
1.86 million Motorcycles Travelled 1.79 billion km	0.3
Chinese Industrial Tasks	
Electrical Power Generation	4,966.7
Building Heating	342.4
Hydrogen Production	
7.1 million Class 8 HCV Trucks Travelled 293.5 billion km, requiring 23.5 million tonnes of hydrogen to be produced	1,359.2
Total	6,999.2

Table 26.16. Number of additional non-fossil fuel power stations to phase out fossil fuels in the China – Hybrid Solution Scenario F

Power Generation System	Chinese non-fossil fuel electricity production in 2018 (Appendix B & BP Statistics 2019) (kWh)	2018 ratio percent of non-fossil fuel electrical power systems in China (%)	Expanded extra required annual capacity to phase out fossil fuels (kWh)	Power Produced by a Single Average Plant in 2018 (kWh)	Estimated number of required additional new power plants of average size to phase out fossil fuels (number)
Nuclear	2.94E+11	13.72%	9.61E+11	1.28E+10	75
Hydroelectric	1.20E+12	56.06%	3.92E+12	1.33E+09	2,959
Wind	3.66E+11	17.06%	1.19E+12	8.12E+07	14,700
Solar PV	1.78E+11	8.28%	5.79E+11	3.30E+07	17,530
Other Renewable	1.05E+11	4.88%	3.42E+11	7.70E+07	4,439
Total (kWh)	2.15E+12		7.00E+12		39,703
Total (TWh)	2,145.0		6,999.2		

Figures 26.1 to 26.6 shows a graphical summary of Scenario F. Figure 26.7 shows a comparison of Scenario F to other scenarios.

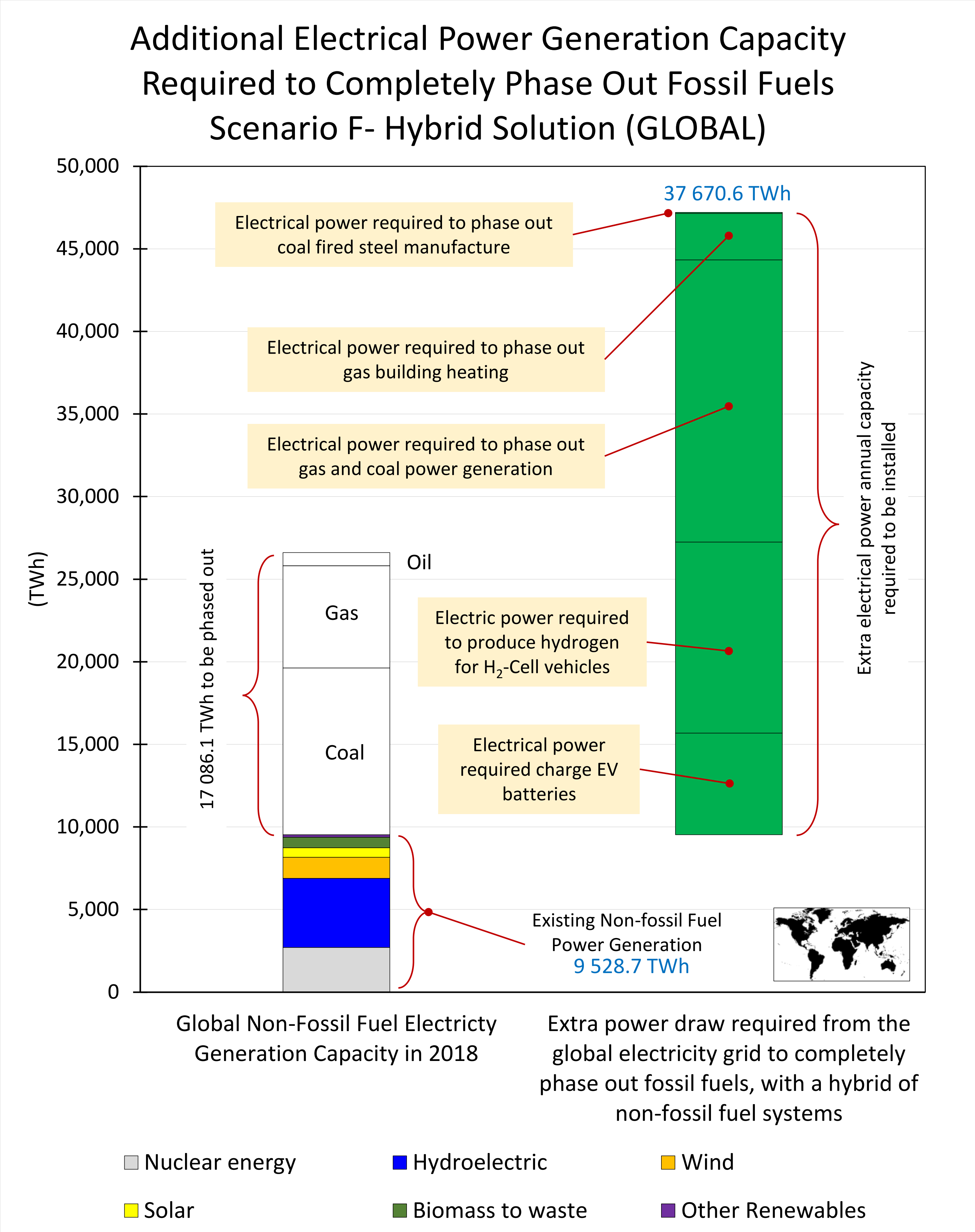


Figure 26.1. The estimated additional electrical power required globally to phase out fossil fuels, Scenario F hybrid solution (Image: Simon Michaux) (World Map Image by Clker-Free-Vector-Images from Pixabay)

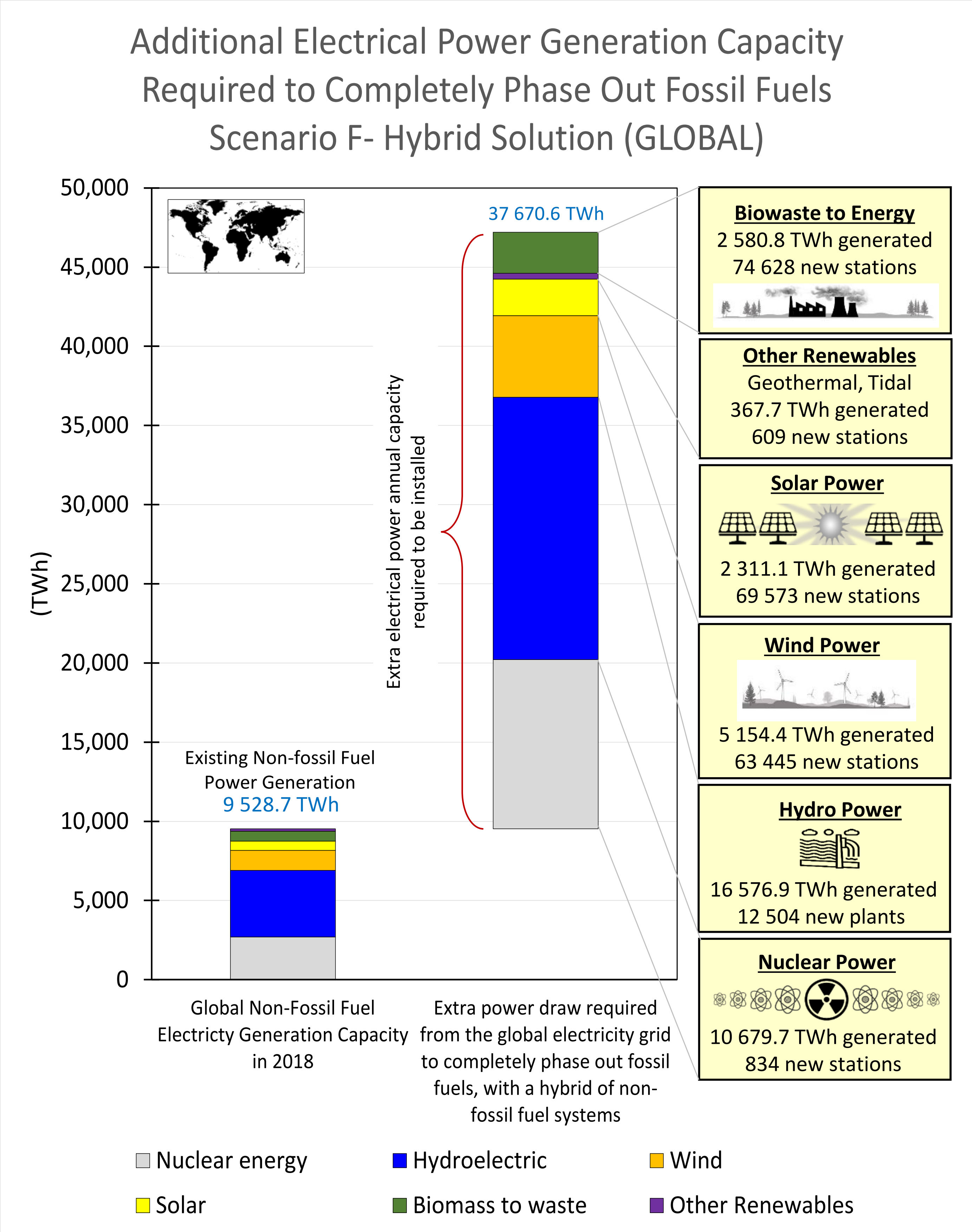


Figure 26.2. The estimated additional electrical power required globally to phase out fossil fuels, Scenario F hybrid solution (Image: Simon Michaux) (World Map Image by Clker-Free-Vector-Images from Pixabay)

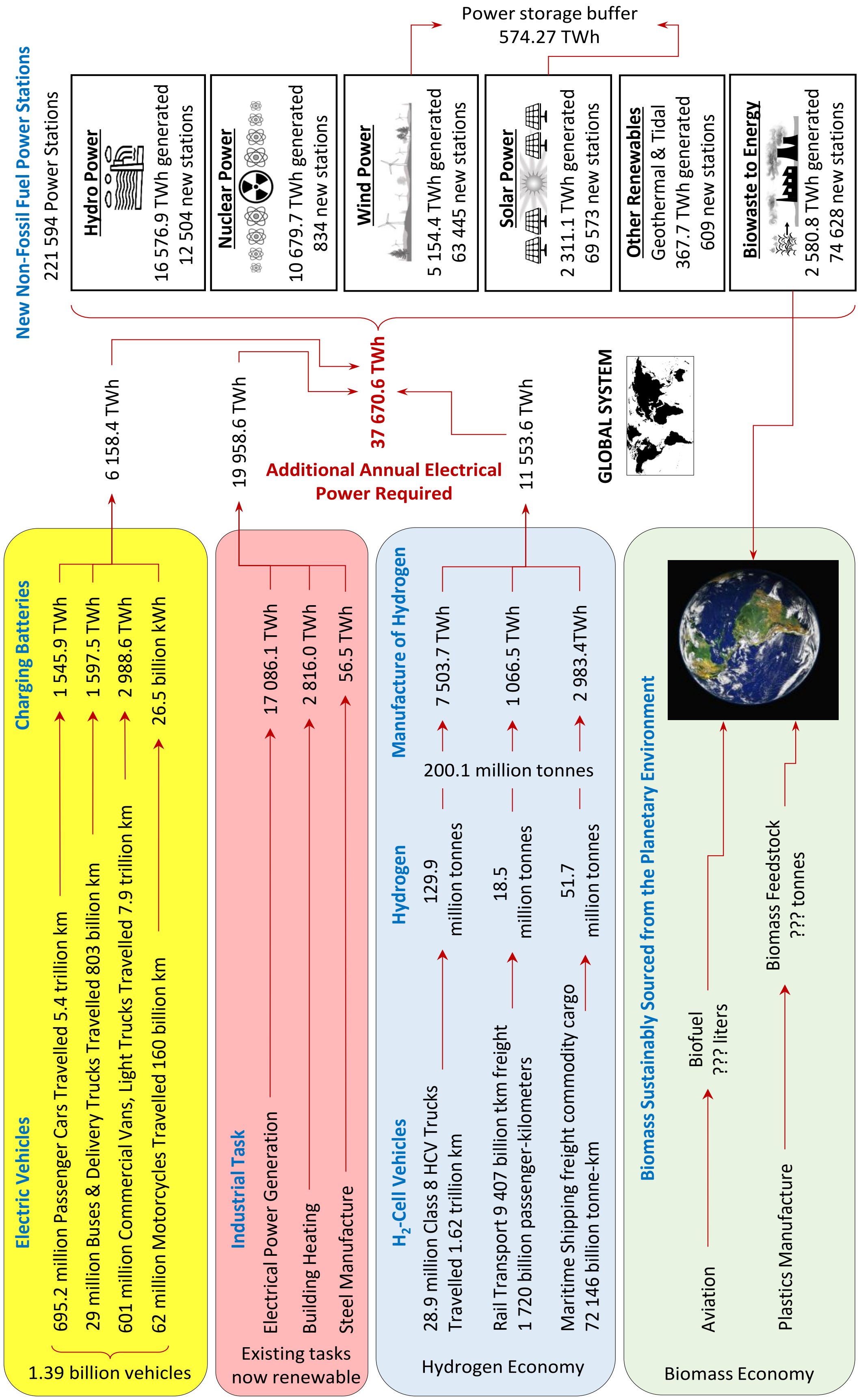


Figure 26.3. Scenario F - Phase out fossil fuel systems GLOBAL footprint (Image: Simon Michaux)
(Planet Earth Image by WikiImages from Pixabay) (World Map Image by Clker-Free-Vector-Images from Pixabay)

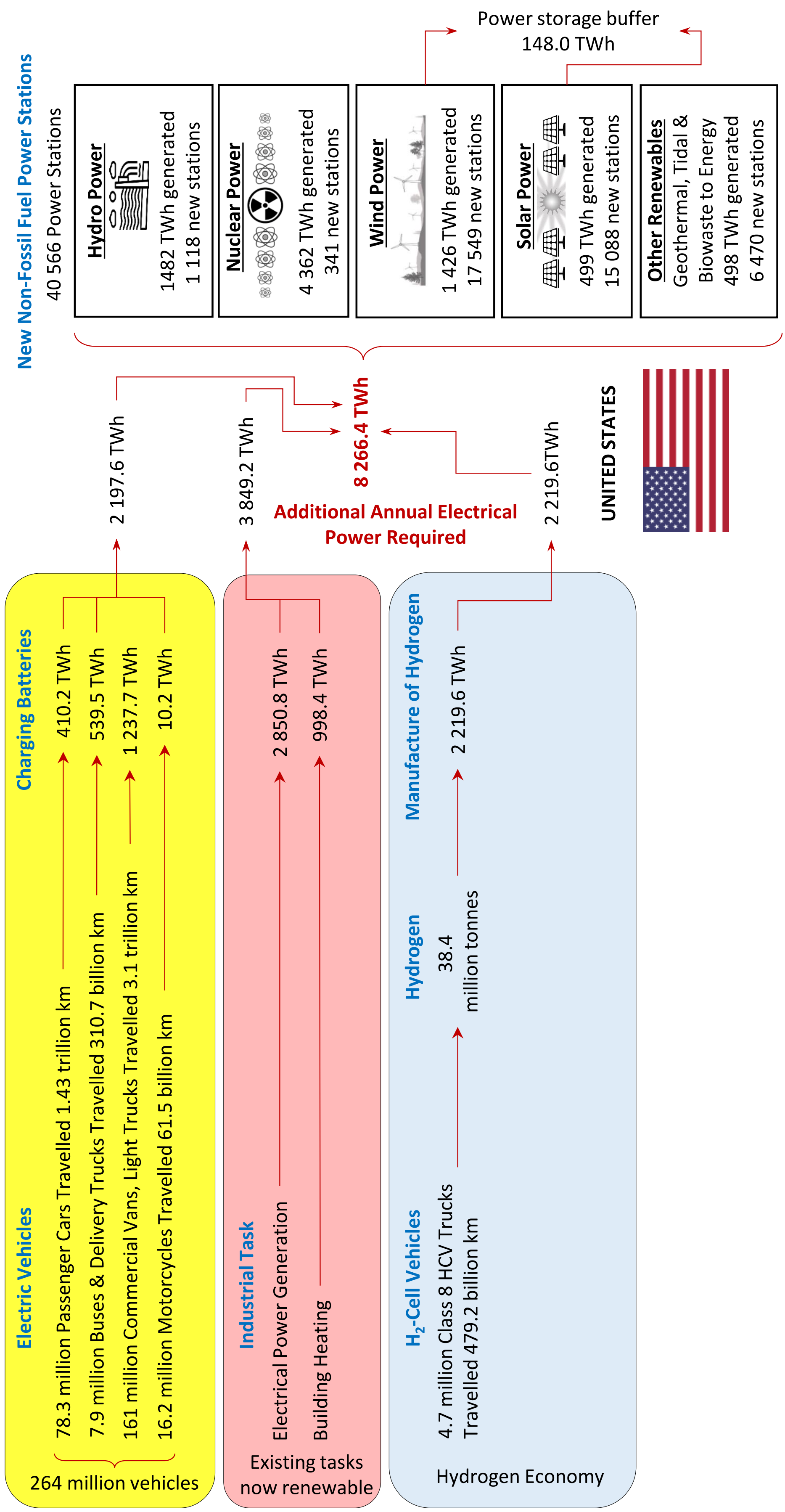


Figure 26.4. Scenario F - Phase out fossil fuel systems United States footprint (Image: Simon Michaux)

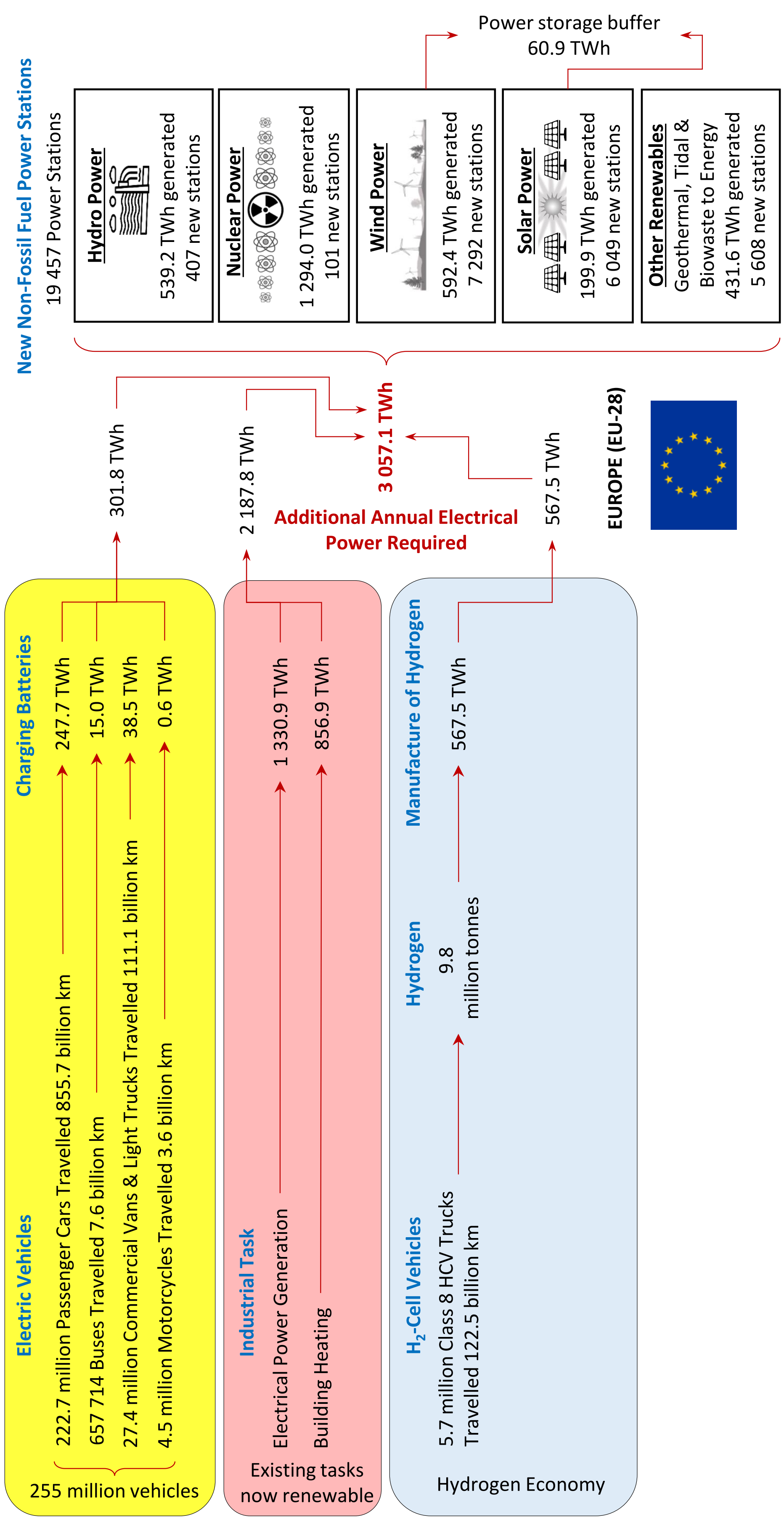


Figure 26.5. Scenario F - Phase out fossil fuel systems European (EU-28) footprint (Image: Simon Michaux)

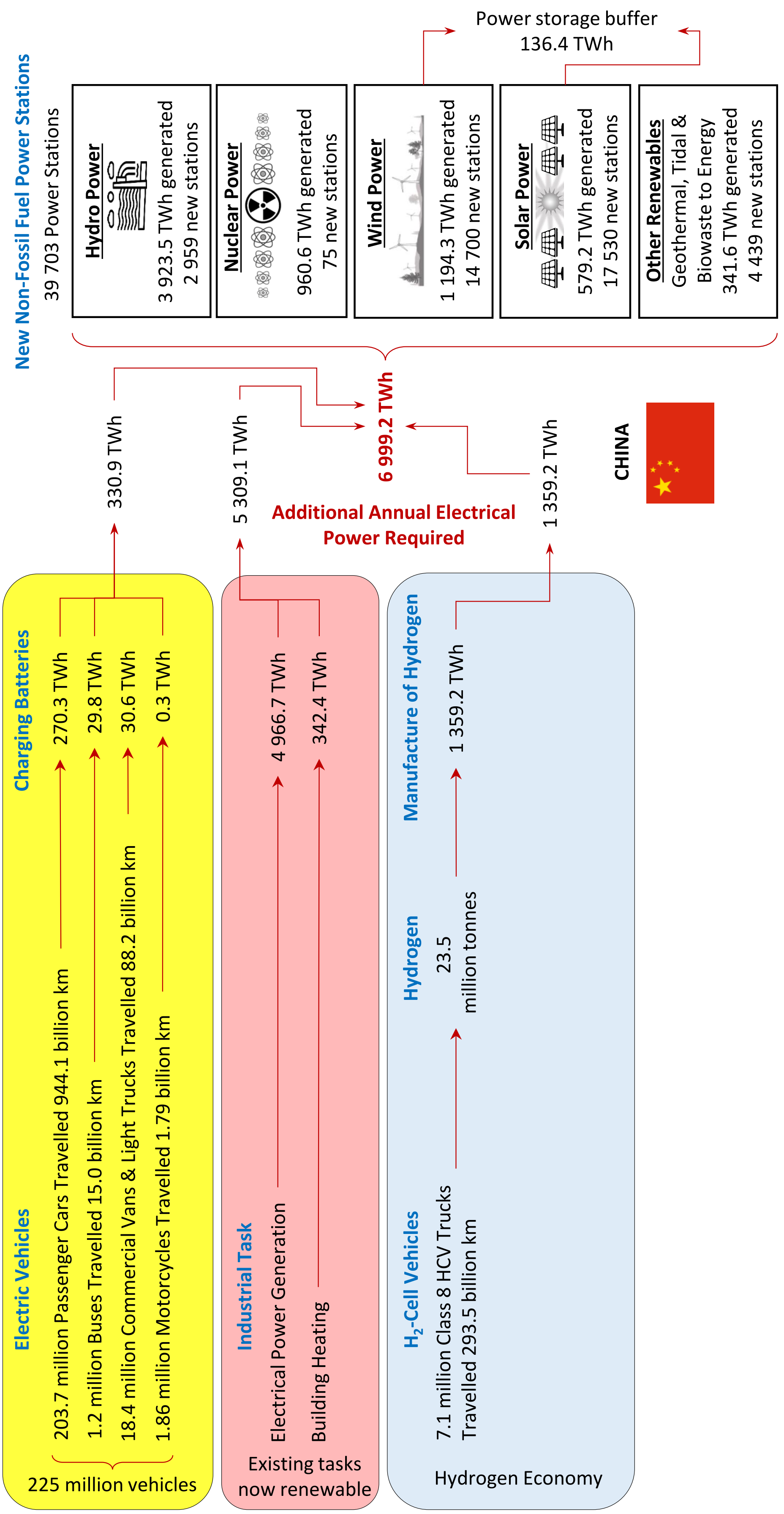


Figure 26.6. Scenario F - Phase out fossil fuel systems Chinese footprint (Image: Simon Michaux)

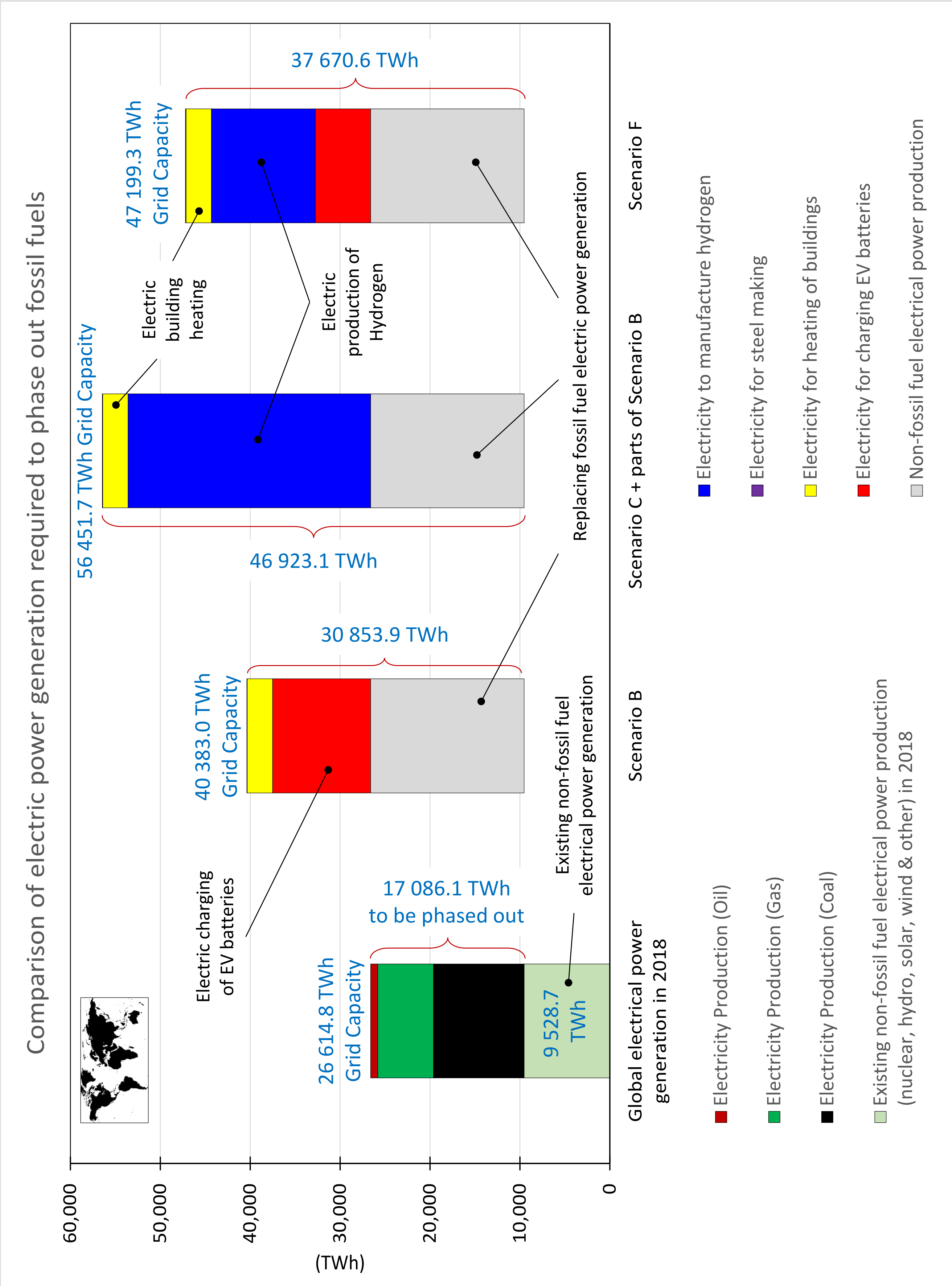


Figure 26.7. The electric power required to phase out fossil fuels, Scenario B, C and F compared (Image: Simon Michaux)

Scenario F is a hybrid compilation of the outcomes of Scenarios A, B, C, D and E. It is understood that this is a simplistic approximation only, for the purpose estimate the approximate scale and scope of what is required to phase out fossil fuels. There are many practicalities that this study does not address.

26.3.1 Power Storage Stations to Mitigate Intermittency of Supply from Solar and Wind

As previously discussed, wind and solar power generation systems are highly intermittent, and for them to be viable as a significant stable power supply, they require a power storage buffer. In the literature there are a number of opinions with regard to how much of a buffer. In Scenario A in Section 18, a buffer of just 48 hours was selected for the specific purpose of supporting the charging of electric vehicle batteries. The Droste-Franke (2015) study proposed a 1 month of energy storage to keep the grid up during seasonal variations. This was seen as a reasonably conservative estimated (where some suggestions were as long as 10 weeks) and was selected for this study.

Currently, pumped-storage hydropower (PSH) provides 98% of all the existing electrical energy stored in the world (Mongird *et al* 2019). While the volume of electrical power from renewable sources is relatively small this is a manageable issue. Once renewable power becomes a larger share of power generation, then infrastructure will be needed in electrical power storage. The required power storage for Scenario F is much larger than what is currently in place. Due to the number of required power storage stations, it is impractical to plan for more pumped storage stations as they are very geographically limited. There are other options, but the most flexible is the battery storage power station concept.

As of 2020, the largest battery storage power station in the world was the Australian Hornsdale Power Reserve, adjacent to the Hornsdale wind farm, built by Tesla (Parkinson 2017a). The plant is operated by Tesla and provides a total of 129 megawatt-hours (460 GJ) of storage capable of discharge at 100 MW into the power grid (Weatherill 2017). For this study, it is now assumed that all new power storage stations will be one of these 100 MW battery stations.

Table 26.17 below shows the required storage capacity (574.3 TWh), the number of stations (5.7 million) and the mass of lithium ion batteries (2.5 billion tonnes).

Table 26.17. Estimated number of 100 MW power storage stations to be built in the GLOBAL SYSTEM to address renewable source intermittency of supply (wind and solar) at the scope required to phase out fossil fuels entirely, Scenario F (World Map Image by Clker-Free-Vector-Images from Pixabay)

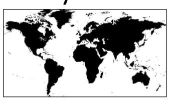
Power Generation System 	Expanded extra required annual global capacity to phase out fossil fuels (kWh)	Storage capacity for a 4 week period to manage winter period, with limited sun & wind (kWh)	Number of 100 MWh capacity power storage stations to meet power generation in a 4 week cycle (number)	Mass of Li-Ion batteries @230 Wh/kg (tonnes)
Wind	5.15E+12	3.96E+11	51,544,207	1.72E+09
Solar PV	2.29E+12	1.76E+11	22,894,041	7.66E+08
Solar Thermal	2.17E+10	1.67E+09	217,436	7.27E+06
Total Power Storage Capacity		5.743E+11 574.3 TWh	74,655,683 number of storage stations	2,496,845,599 tonnes of batteries

Table 26.17 shows that the required power storage would require 2.5 billion tonnes of lithium ion batteries. The batteries required for the Electric Vehicles (Table 26.8) was 282.6 million tonnes. This extra requirement for power storage may not be viable due to lack of mineral supply.

Table 26.18. Estimated number of 100 MW power storage stations to be built in the United States to address renewable source intermittency of supply (wind and solar) at the scope required to phase out fossil fuels entirely, Scenario F

Power Generation System	Expanded extra required annual U.S. capacity to phase out fossil fuels (kWh)	Storage capacity for a 4 week period to manage winter period, with limited sun & wind (kWh)	Number of 100 MWh capacity power storage stations to meet power generation in a 4 week cycle (number)	Mass of Li-Ion batteries @230 Wh/kg (tonnes)
Wind	1.43E+12	1.10E+11	14,257,371	4.77E+08
Solar PV	4.99E+11	3.83E+10	4,985,202	1.67E+08
Total Power Storage Capacity		1.480E+11 148.0 TWh	19,242,573 number of storage stations	643,564,323 tonnes of batteries

Table 26.19. Estimated number of 100 MW power storage stations to be built in Europe (EU-28) to address renewable source intermittency of supply (wind and solar) at the scope required to phase out fossil fuels entirely, Scenario F

Power Generation System	Expanded extra required annual EU-28 capacity to phase out fossil fuels (kWh)	Storage capacity for a 4 week period to manage winter period, with limited sun & wind (kWh)	Number of 100 MWh capacity power storage stations to meet power generation in a 4 week cycle (number)	Mass of Li-Ion batteries @230 Wh/kg (tonnes)
Wind	5.92E+11	4.56E+10	5,924,110	1.98E+08
Solar PV	2.00E+11	1.54E+10	1,998,683	6.68E+07
Total Power Storage Capacity		6.094E+10 60.9 TWh	7,922,793 number of storage stations	264,976,351 tonnes of batteries

Table 26.20. Estimated number of 100 MW power storage stations to be built in China to address renewable source intermittency of supply (wind and solar) at the scope required to phase out fossil fuels entirely, Scenario F

Power Generation System	Expanded extra required annual Chinese capacity to phase out fossil fuels (kWh)	Storage capacity for a 4 week period to manage winter period, with limited sun & wind (kWh)	Number of 100 MWh capacity power storage stations to meet power generation in a 4 week cycle (number)	Mass of Li-Ion batteries @230 Wh/kg (tonnes)
Wind	1.19E+12	9.19E+10	11,942,750	3.99E+08
Solar PV	5.79E+11	4.46E+10	5,791,908	1.94E+08
Total Power Storage Capacity		1.364E+11 136.4 TWh	17,734,658 number of storage stations	593,132,380 tonnes of batteries

26.4 Comparison of battery mass metal requirements to global mineral reserves

The mass of batteries required in Table 26.11 is enormous. So enormous, it becomes now appropriate to ask is it even possible in context of mineral reserves available. Section 26.4 will first examine approximately how much quantity of minerals will be needed to produce just enough lithium ion batteries to replace the estimated 2018 global transport fleet. After that, the same calculation will be extended to include power storage stations as per Table 26.11.

Figure 26.8 below shows the approximate metal content portions in a Lithium Ion battery (there are currently five lithium ion battery chemistries in the battery market, so this estimation will be an approximation). The metal content of each battery used in this calculation, which is based on the required 282.6 million tonnes of Li-Ion batteries from Table 26.8, is shown in Table 26.21.

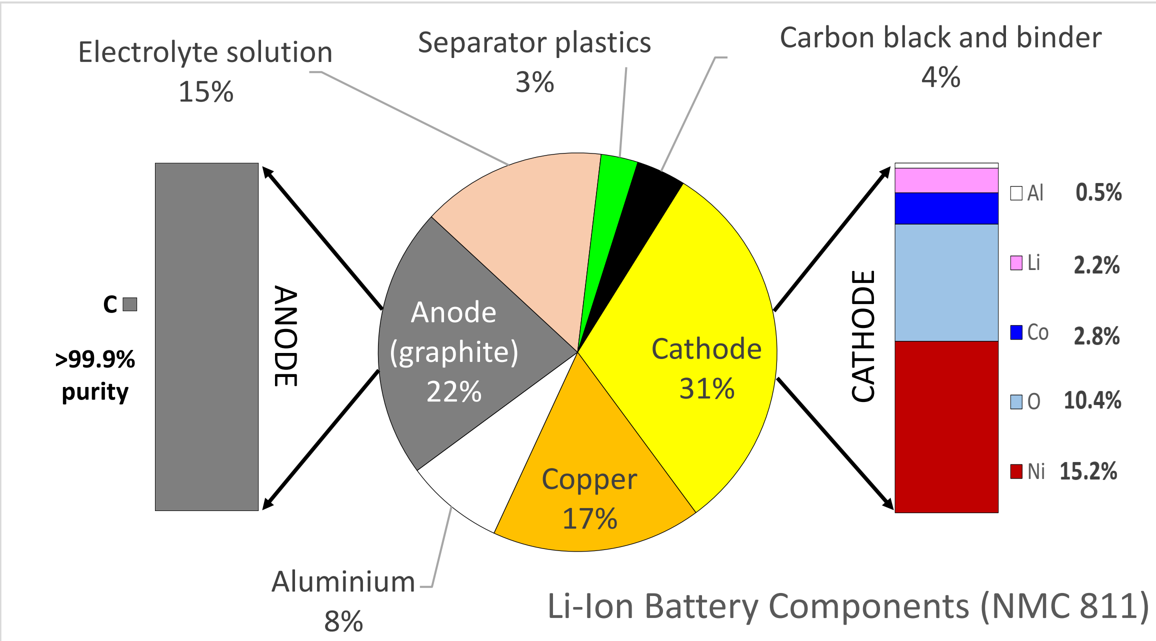


Figure 26.8. Lithium Ion Battery components by metal
(Image: Simon Michaux) (Source: Argonne National Laboratory)

Table 26.21. Estimated mass of metal required to manufacture batteries for EVs (Source: USGS Mineral Statistics)

Metal	Proportion in Li-Ion Battery (%)	Mass in 1 tonne of Li-Ion batteries (kg)	Mass in 282.6 million tonnes of Li-Ion Batteries (million tonnes)	Global Reserves (2018) (million tonnes)
Copper	17.0 %	170	48.0	830.0
Aluminium	8.5 %	85	24.0	
Nickel	15.2 %	151.9	42.9	89.0
Cobalt	2.8 %	27.9	7.9	6.9
Lithium	2.2 %	21.7	6.1	14.0
Graphite	22.0%	220	62.2	300.0

Figure 26.9 shows the graphical comparison between the needed quantity of metals and global reserves. Global reserves data was source from the United States Geological Survey Mineral Statistics. It is to be remembered that this mineral/metal sourcing, is to produce just one battery for each of the vehicles in the current global transport fleet, where the fleet size of 1.416 billion was an estimate from several sources which included most of the whole planet, with an average date of 2016 (Appendix J), which means this is a conservative calculation and the real number would be larger. Each of these lithium ion batteries will have a useful working life of 8 to 10 years only (IEA 2019b). So, 8-10 years after manufacture, new replacement batteries will be required, from either a mined mineral source, or a recycled metal source. As less than 0.5% of the current transport fleet is EV, these batteries cannot be resourced from recycling. The first generation has yet to be manufactured. Once that first generation is worn out, they can be recycled, which has its own challenges. Figure 26.9 shows only what is required to make one battery for each vehicle. It does not allow for mass estimations for other batteries like mobile phones, computers, or appliances. Nor does it allow for other demand applications for these metals outside battery manufacture, like metal alloy production, or ammunition production.

In theory, there are enough global reserves of nickel and lithium if they were exclusively used just to produce li-Ion batteries for vehicles. To make just one battery for each vehicle in the global transport fleet (excluding Class 8 HCV trucks), it would require 48.2% of 2018 global nickel reserves, and 43.8% of global lithium reserves (Source: USGS Mineral Statistics). There is not enough cobalt in current reserves to meet this demand and more will have to be discovered in exploration.

In practice, this will not work due to other demand application requirements, and that this represents only one generation of batteries of the current vehicle fleet. Every ten years from that point onwards, the same mass requirement would be needed all over again to produce the next generation of EV battery.

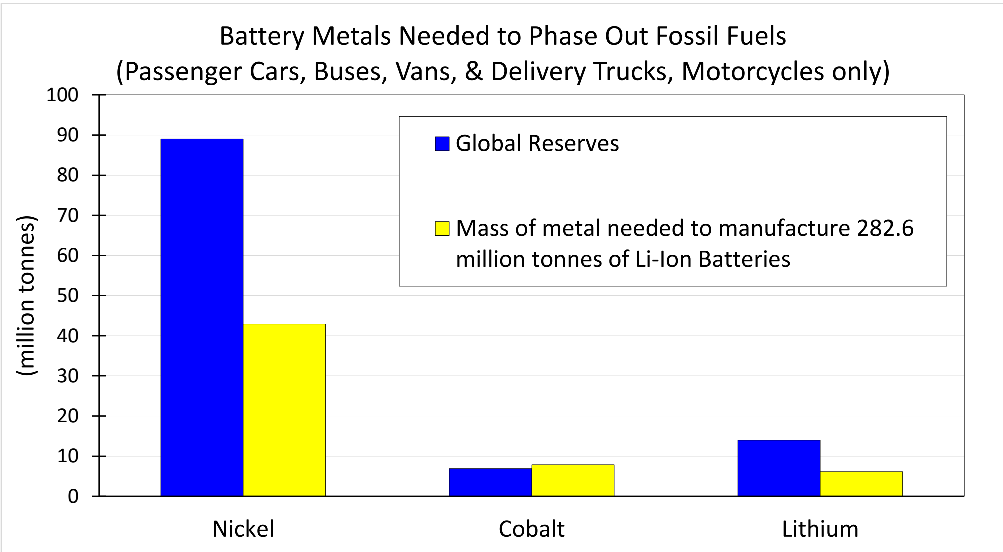


Figure 26.9 Estimated mass of metals to manufacture one generation of Li-Ion batteries for EV's (the 2018 scope of vehicles) required for Scenario F compared to global reserves (Source: USGS Mineral Statistics for global reserves)

Figure 26.9 above is based on 2018 global reserves, production in the year 2018 for each of these metals was much smaller, as shown in Table 26.22. If production rates in 2018 were to be maintained, it will take several decades to produce the minerals needed to manufacture just one generation of batteries for the 2018 transport fleet, in Scenario F (passenger cars, vans, buses and delivery trucks only). This highlights the need to expand existing production and open up new mines in known mineral deposits. It also highlights the potential for a mineral scarcity and shortage, which could have geopolitical implications.

Table 26.22. Estimated mass of metals to manufacture one generation of Li-Ion batteries (the 2018 scope of vehicles) required for Scenario F compared to 2018 annual production (Source: USGS Mineral Statistics for production data)

Metal	2018 Global Annual Production (tonnes)	Mass of metal needed to manufacture 282.6 million tonnes of Li-Ion Batteries (million tonnes)	Years of Production at 2018 Capacity Required to Phase Out Fossil Fuels (years of production)
Copper	21,000,000	48.0	2.3
Aluminium Metal from smelter production	60,000,000	24.0	0.4
Nickel	2,300,000	42.9	18.7
Cobalt	140,000	7.9	56.3
Lithium	85,000	6.1	72.1
Graphite	930,000	62.2	66.8

If the required power storage station capacity to mitigate intermittency of power supply from solar wind, was delivered using lithium ion batteries (as per Table 26.11), then an extra 2.5 billion tonnes of Li-Ion batteries in addition to the 282.6 million tonnes from Table 26.8. Figure 26.10 below is the data from Figure 26.9, with an additional 2.5 Billion tonnes of batteries added to the estimate (282.6 + 2 496 = 2 772.6 million tonnes of batteries needed).

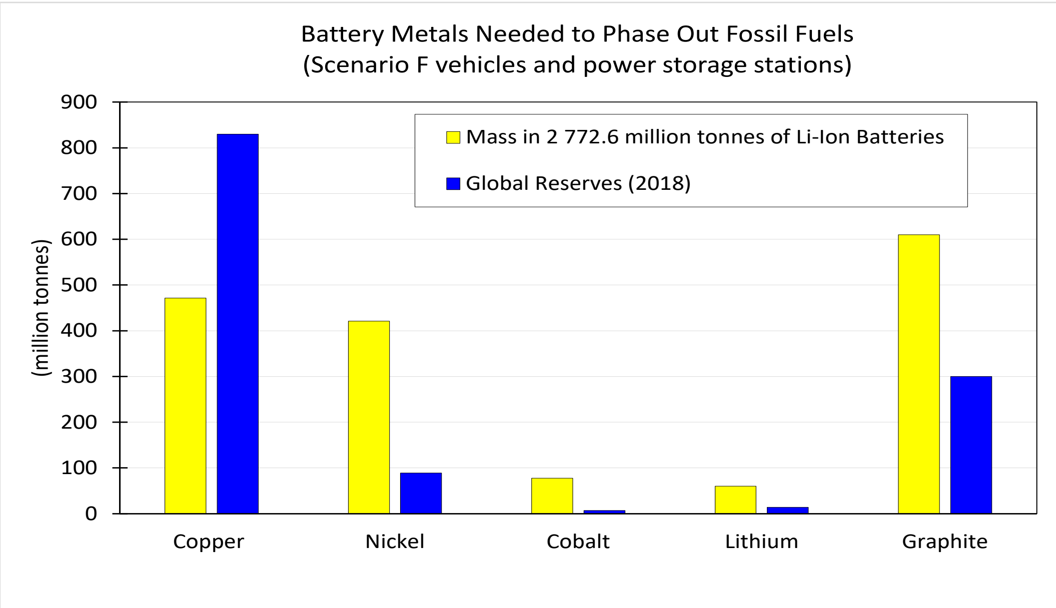


Figure 26.10. Estimated mass of metals to manufacture one generation of Scenario F Electric Vehicle Li-Ion batteries and Lithium Ion battery banks for power storage stations required for Scenario F compared to global reserves
(Source: USGS Mineral Statistics for global reserves)

Figure 26.10 shows clearly that the lithium ion battery solution for power storage stations will not work. There are not enough minerals in current global reserves, and there is not enough time or capacity to explore and discover the required additional volume. This is a problem as lithium ion battery power stations were the favored solution to mitigate intermittency of renewable power generation. In 2020, 98% of power storage capacity was in the form of pumped storage attached to a hydroelectric power generation system. Commissioning another 574.3 TWh of storage capacity will be very difficult if not impossible by constructing more such pumped storage systems. It is now shown to be just as difficult to do this with lithium ion battery banks.

26.5 Comparison of Scenario F to conventional planning for the future (Section 2)

The task for phasing out the ICE transport fleet is much larger than the current paradigm allows for. According to the World Economic Forum, the market share of Electric Vehicles will increase to 30 %, representing 245 million registered EV's in the global fleet (World Economic Forum 2019) (see Section 2). This has also been a stated goal for the European Commission (European Commission 2019a Going climate-neutral by 2050). As shown in Appendix J, the global fleet of vehicles is conservatively estimated at 1 416 528 615, or 1.416 billion registered vehicles. A 30 % fraction of this estimate would be 424 958 585 vehicles, or 425 million vehicles. This would suggest the current paradigm has underestimated the number of vehicles in the global fleet, thus will underestimate the requirements to transform the whole fleet to EV.

The World Economic Forum study (2019) also estimated that global power demand for the electrical charging of EV batteries could be 1 000 TWh in the ambitious Sustainable Development Scenario (SDS) (Figure 2.3 in Section 2). If this represented 30% of the global fleet, then 30% of the Scenario F power demand (6 158.4 TWh for EV charging + 11 553.6 TWh for hydrogen manufacture = 17 712 TWh) would be 5 313.6 TWh (30% of 17 712 TWh is 5 313.6 TWh), as shown in Figure 26.11.

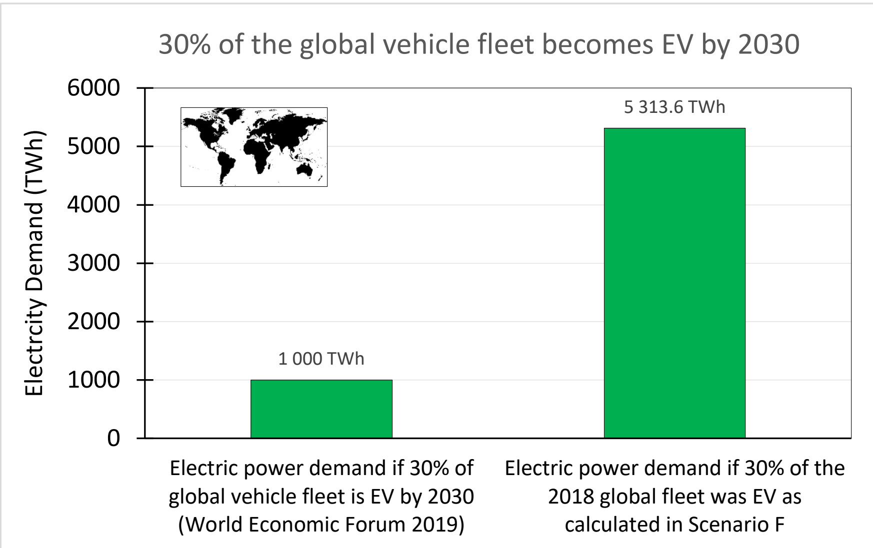


Figure 26.11. Comparison of current projections of required electric power demand to charge EV batteries vs. outcomes of Scenario F (World Map Image by Clker-Free-Vector-Images from Pixabay)

The same study also estimated the volume of batteries to be manufactured by 2030 to be 2 623 GWh (World Economic Forum 2019, and Figure 2.4 in Section 2). If this represented 30% of the global fleet, then 30% of the Scenario F battery requirement would be 19 556 GWh (30% of 65 188 GWh, or 65.2 TWh, is 19 556 GWh) as shown in Figure 26.12.

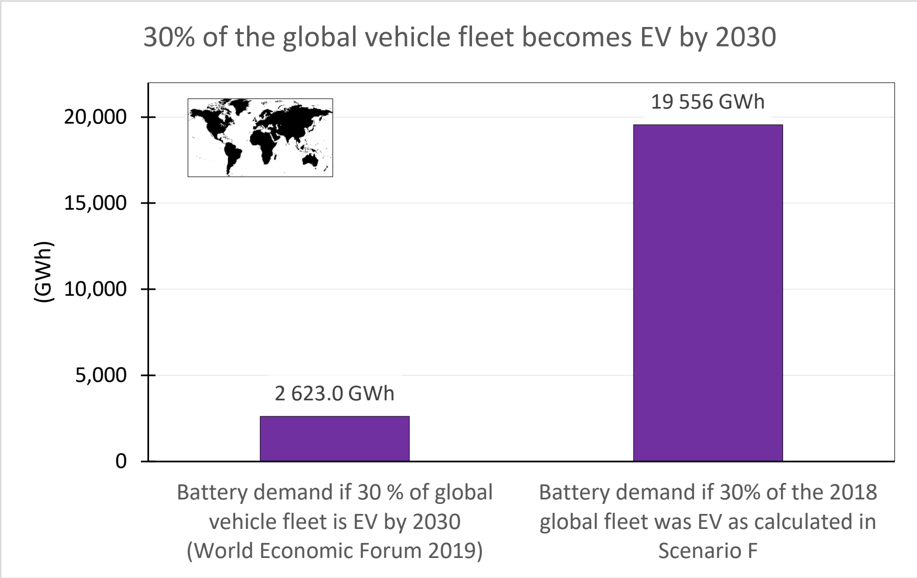


Figure 26.12. Comparison of current projections of required battery to be manufactured demand vs. outcomes of Scenario F (World Map Image by Clker-Free-Vector-Images from Pixabay)

If Scenario F was applied in full, then an extra global annual capacity 37 670.6 TWh, generated by a number of non-fossil fuel power plants would be required to be constructed and connected to the electrical power grid (as per Table 26.10). This means that 221 594 new power plants would be constructed, expanding the total global annual non-fossil fuel electrical generation capacity to 47 199.3 TWh (37 670.6 TWh + 9528.7 TWh of existing non fossil fuel generation capacity).

This task will not be completed over night and will be deployed in a staged form. As shown in Section 2, the European Union had recently agreed a new renewables target of 32 % by 2030 (European Commission 2019a Going climate-neutral by 2050). The IEA published a study (IRENA 2020) predicted how the global market share of renewable power generation systems would increase with two scenarios passing the year 2030 and the year 2050. These were (Section 2):

3. **The Planned Energy Scenario (PES).** This is the primary reference case for the IRENA study, providing a prediction outcome based on current energy plans and other planned targets and policies (as of 2019). This was based on an estimation of Nationally Determined Contributions under the Paris Agreement for signatory nation states. By 2030, 38% of the global electrical power generation capacity would be renewable. By 2050, this market share would be 55%.
4. **The Transforming Energy Scenario (TES).** An energy transformation pathway based largely on renewable energy sources and steadily improved energy efficiency (though not limited exclusively to these technologies). By 2030, 57% of the global electrical power generation capacity would be renewable. By 2050, this market share would be 86%.

Scenario F was designed to estimate the extra power generation capacity required to phase out fossil fuels completely. To achieve this, an extra 37 670.6 TWh in the global annual electrical power generation capacity would be required to be commissioned and added to the existing annual non-fossil fuel power generation fleet of 9 528.7 TWh, giving a total global annual capacity of 47 199.3 TWh (9 528.7 + 37 670.6 = 47 199.3). Figure 26.13 shows the two scenarios PES and TES in the years 2030 and 2050, given a required 100% capacity of 47 199.3 TWh. Table 26.23 shows the estimated number of non-fossil fuel power plants to meet these targets.

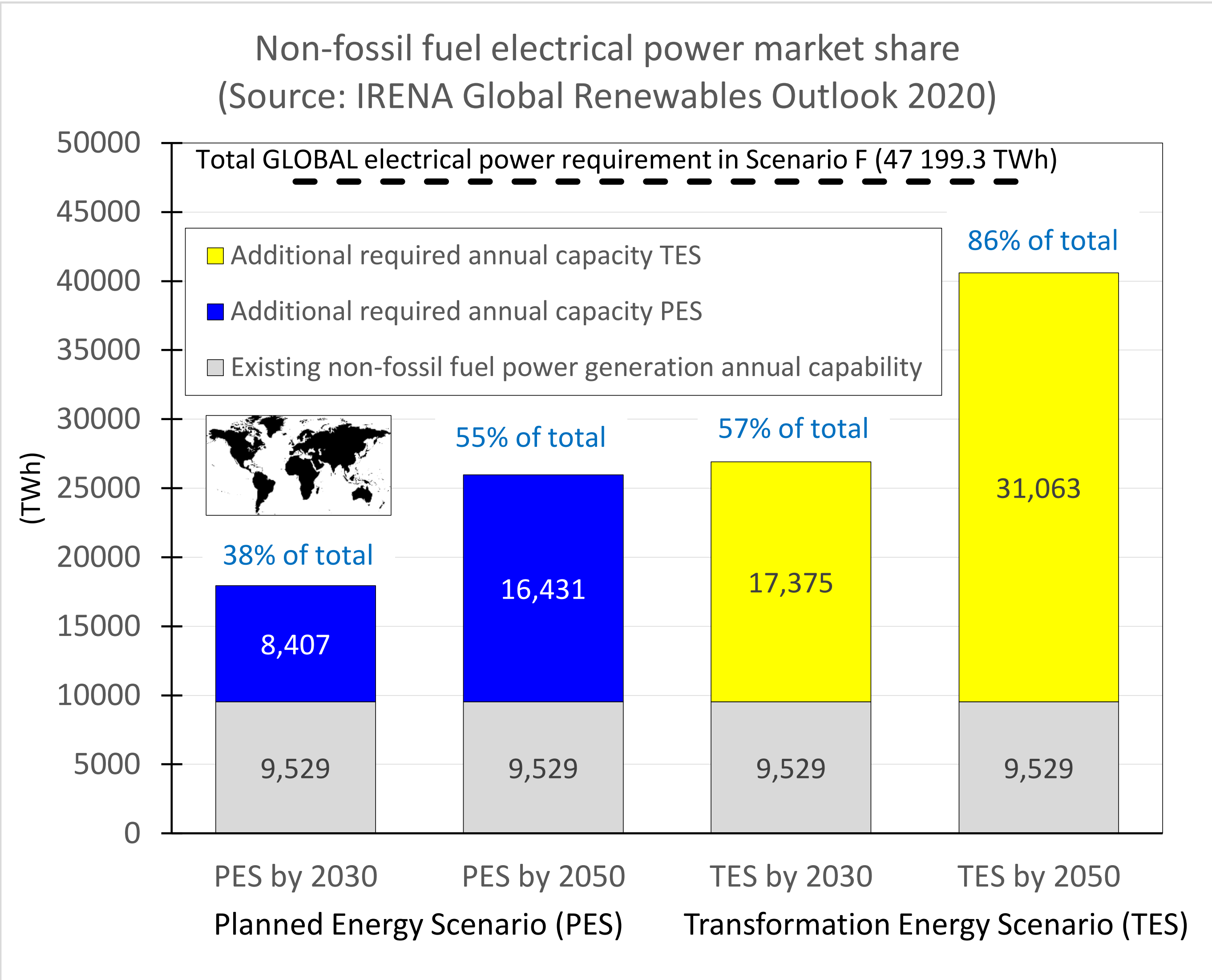
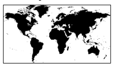


Figure 26.13. Estimated additional annual global non-fossil fuel electrical power capability required to meet PES and TES sustainability targets (Source: IRENA Global Renewables Outlook 2020)
(World Map Image by Clker-Free-Vector-Images from Pixabay)

Table 26.23. Estimated number of new non-fossil fuel power stations required to meet PES and TES sustainability targets if Scenario F was applied (Source: IRENA Global Renewables Outlook 2020)
(World Map Image by Clker-Free-Vector-Images from Pixabay)

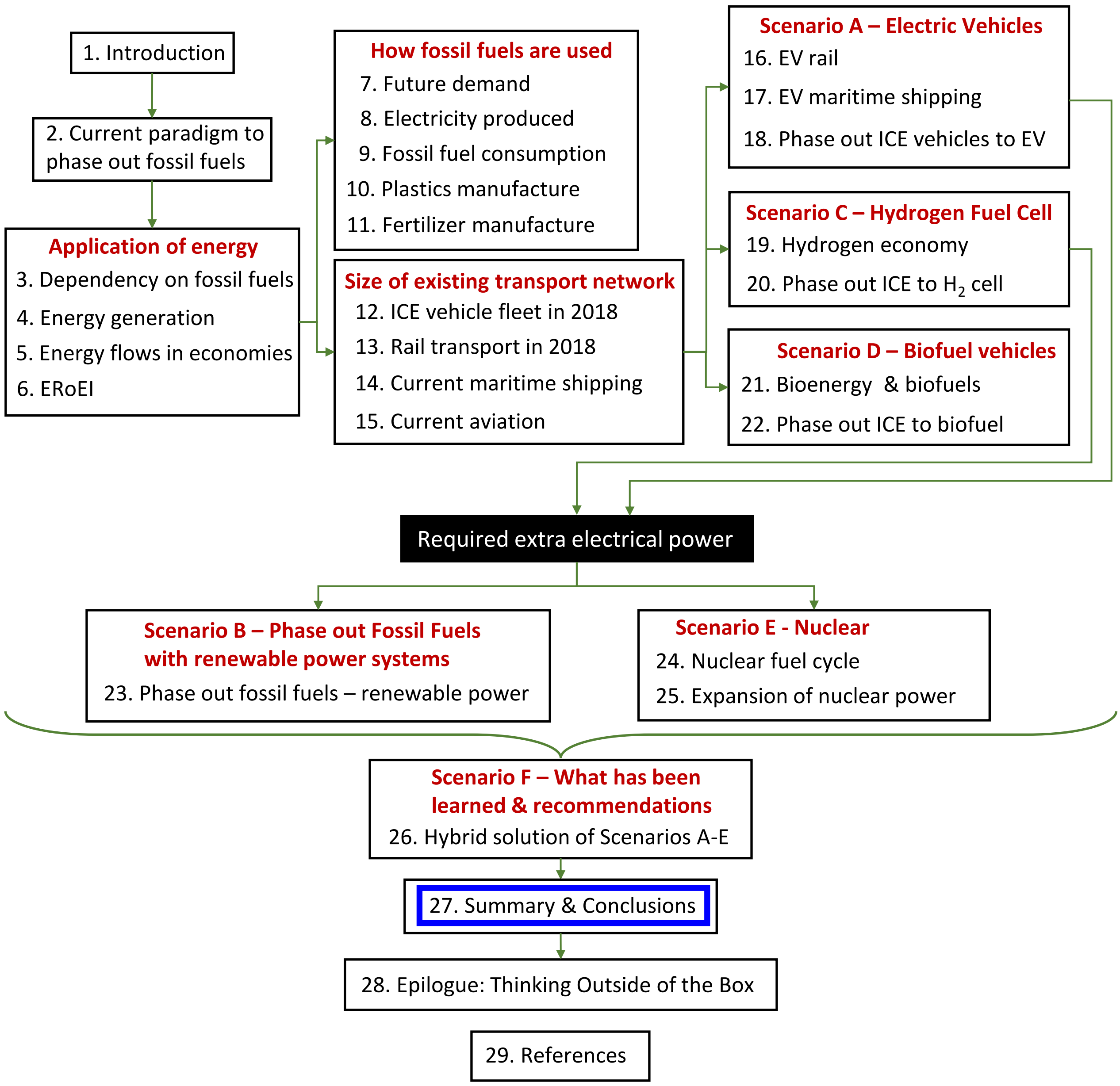
Non-fossil fuel generation System 	Global PES non-fossil fuel power generation by 2030 (number of new plants)	Global PES non-fossil fuel power generation by 2050 (number of new plants)	Global TES non-fossil fuel power generation by 2030 (number of new plants)	Global TES non-fossil fuel power generation by 2050 (number of new plants)
Nuclear	317	459	475	717
Hydroelectric	4,751	6,877	7,127	10,753
Wind	24,109	34,895	36,164	54,563
Solar PV	26,330	38,110	39,496	59,590
Solar Thermal	107	155	161	243
Geothermal	232	335	347	524
Biowaste to energy	28,359	41,045	42,538	64,180

Scenario F global annual electrical power generation capacity = 47 199.3 TWh	38% of global electrical power generation = 17 935.7 TWh	55% of global electrical power generation = 25 959.6 TWh	57% of global electrical power generation = 26 903.6 TWh	86% of global electrical power generation = 40 591.4 TWh

For this to work, a fundamental change in how our industrial systems are managed is needed. Currently, the global system is having difficulty maintaining the existing fleet of power stations. The time period required to design and construct a single coal fired power station is 3-6 years. For a new nuclear power plant, the incubation time period is closer to 10 to 15 years when things go well and as much as 30 years when they do not. This suggests that the 2050 climate neutral target (European Commission 2019) task is much greater than current planners understand.

27 SUMMARY & CONCLUSIONS

The following summary and conclusions can be made with regards to the findings of this report.



Assessment of the Extra Capacity Required of Alternative Energy Electrical Power Systems to Completely Replace Fossil Fuels

27.1 Energy is the master resource

It has been noted that without energy, no physical work can be done, but it has become so ubiquitous and inexpensive over the last 120 years that it is now largely taken for granted. As a result, we have become an energy blind society, such that there is little understanding of how energy empowers our daily lives.

This report emphasizes that every developed economy around the World is highly dependent on fossil fuels, which in turn is linked to industrial activity, economic GDP, food production. A case has been made that the price of oil, in particular, correlates with global economic downturns, as well as other geopolitical events. The Food Index, Metals Index and Crude Oil Index (as measured by the IMF and World Bank) all correlate strongly and are therefore interdependent. Furthermore, since 1980, changes in Chinese industrial output also correlates with changes in the oil price.

It is also clear that the growth in consumption of fossil fuels (energy) correlates strongly with global human population growth, and with increasing sophistication in technology, the amount of energy needed per capita has increased along with it. Thus, it is clear that each individual in the human population has been consuming more and more energy with each passing year.

27.2 The task to phase out fossil fuels is much larger than the current paradigm allows for

In researching this report, it was found that all previous studies examined only part of the requirements for a new global system. Either the study was limited to one nation (such as the United States), or only examined only one vehicle class (for example passenger cars). Typically, only one renewable power system was considered, and not in a wide enough scope to be useful. The occasional study that did examine the global systems, often presented data with limited traceability to a source.

This study, on the other hand, investigated how many EV's, H-cells, biofuels, solar panels, and wind turbines would be needed to completely phase out fossil fuels, from a bottom-up approach, using new calculations not attempted before.

Calculations for the United States, Europe, and China, are the main emphasis here, but global trends in the industrial ecosystem value chain are the most useful, especially when it comes to the manufacture of large numbers of vehicles, or the construction of large industrial sites like power plants, or the sourcing of raw materials (oil, gas, coal, uranium, lithium, cobalt, nickel, etc.). No one nation state is completely self-sufficient and therefore we all rely on global trade. Therefore, whilst it is useful to understand what is required for each of the larger economies, the effects of the global footprint is what is required to plan for the future.

This study suggests there are an estimated 1.42 billion vehicles in the global transport fleet, comprising 268.9 million vehicles in the United States, 250 million in China, and 261 million vehicles in the European Union. This it should be noted is only a crude estimate, based on an aggregate of sources, from data known as at 2016. The actual number for 2018 is probably a little higher than this. However, for the purposes of this study, the vehicles in the global transport fleet (1.43 billion), are calculated to have traveled 15.87 trillion km in 2018. Non-fossil fuel system substitution for ICE technology (EV's Hydrogen cells, or biofuels) is technologically viable. The challenge now is simply one of logistics – how to produce enough of these substitute non-fossil systems to perform the same tasks as before, on a global scale.

It was suggested in Scenario F (Section 26) that, by studying each of the different non-fossil fuel transport systems and non-fossil fuel electrical power generation systems separately, each had their own clear advantages and disadvantages.

Petroleum consumption currently represents the largest proportion of primary energy consumption, so this report first examined the potential of phasing out of the Internal Combustion Engine (ICE). This was followed by a comparison an EV vehicle system to a H_2-cell vehicle system. Two outcomes were apparent:

1. It was found that in order to produce enough hydrogen to power a fleet of vehicles travelling a set distance, approximately 2.5 times the electrical power required to charge the lithium ion batteries of an entirely electric global transport fleet of vehicles of the same size, travelling the same distance and perform the same tasks (the outcome of Scenario A compared to Scenario C), is needed.

2. A comparison of the mass of the storage systems between EV batteries and compressed hydrogen tanks showed that the battery mass was approximately 3.2 times the mass of the hydrogen tank mass. If liquid hydrogen in cryogenic tanks was compared to the battery mass of the equivalent EV system, the ratio was approximately 9.1 times.

Clearly, these outcomes start to reveal why in some cases, one technology is better than the other, depending on the situation.

It is concluded that all comparatively short-range transport is best done by an Electric Vehicle. This means that all passenger cars, commercial vans, delivery trucks and buses (1.39 billion vehicles), would travel 14.25 trillion km in a 365 day cycle. However, in order to do this, *65.19 TWh of batteries (282.6 million tonnes of Li-Ion batteries) will be required to be produced, and an annual additional 6 158.4 TWh of electricity will be required from the global power grid to charge those batteries*.

Conversely, all long-range distance transport could be done with a hydrogen fuel cell powered vehicle. This suggests all Class 8 HCV trucks, the remainder of the rail transport network (including freight), and the whole maritime ship fleet, should be H_2-cell powered. According to the calculations reported here, the global transport fleet comprises around 28.9 million Class 8 HCV trucks, which travelled 1.62 trillion km in the year 2018. If all of these trucks were to become hydrogen cell-powered and perform the same tasks, 130 million tonnes of hydrogen would be required annually, and 7 503.7 TWh of electricity required to produce that hydrogen. An estimated 18.5 million tonnes of hydrogen is needed to fuel just the rail transport fleet that is currently fossil fuel ICE powered (requiring 1 066.5 TWh of electricity to produce that H_2). An estimated 51.7 million tonnes of hydrogen will be needed to fuel the global maritime fleet (requiring 2 983.4 TWh of electricity to produce that H_2). *In total, 200.1 million tonnes of hydrogen would be needed annually,* and to make that hydrogen*, 11 553.6 TWh of electricity of extra capacity is required.*

A further 19 958.6 TWh of additional non-fossil fuel electrical power is required (part of Scenario B) to substitute for fossil fuel power generation (gas & coal), heating of buildings, and coal-fired steel manufacture. The grand total additional non-fossil fuel electrical power annual capacity to be added to the global grid was calculated to be an astonishing **37 670.6 TWh**.

If the same non-fossil fuel energy mix as that reported in 2018 was assumed, then this translates into an **extra 221 594 new power plants** that would need to be constructed and commissioned. To put this in context, the total power plant fleet in 2018 (all types including fossil fuel plants) was only 46 423 stations.

27.3 Current planning for the phasing out of fossil fuels has significantly underestimated the size of the task

In all previous studies examined, it was found that they had consistently and significantly underestimated what is required to phase out fossil fuels. Existing policy planning by nation states and alliances, such as the European Union, are based around predictive studies done by the World Economic Forum and the International Energy Agency (WEF 2019 and IEA 2019b), where two major milestones - 2030 and 2050 - are used. Many nations, including the European Union have committed to decarbonization policies with stated milestones to be met on these dates. By way of example, they quote that a commitment of 30% of the global transport fleet to be non-fossil fuel powered by 2030, leads to a number much lower number (245 million vehicles) than that calculated in the present study.

It was noted in Section 26.5, that the number vehicles in the global fleet is believed to have been significantly underestimated. If there are 1.43 billion vehicles in the global fleet, then 30% would be 425 million vehicles. Similarly, it follows that the amount of electrical power required to charge the required number of batteries was also underestimated. As predicted by the World Economic Forum (WEF 2019), an estimated 1000 TWh of power will be needed to service the non-fossil fuel powered vehicle fleet by 2030. If this represented 30% of the global fleet, then 30% of the Scenario F power demand (6 158.4 TWh for EV charging + 11553.6 TWh for hydrogen manufacture = 17 712 TWh) would be 5 313.6 TWh (30% of 17 712 TWh is 5 313.6 TWh).

The same study also estimated the volume of batteries to be manufactured by 2030 to be 2 623 GWh (World Economic Forum 2019, and Figure 2.4 in Section 2). If this represented 30% of the global fleet, then 30% of the Scenario F battery requirement would be 19 556 GWh (30% of 65 188 GWh, or 65.2 TWh, is 19 556 GWh).

There were also commitments to phase out fossil fuel power generation systems according to two scenarios: the planned policies scenario PES; and the transforming scenario TES. It was found that both of these scenarios had seriously underestimated the amount of additional electrical power that will be required to phase out fossil fuels, and further had underestimated the effectiveness of renewable power generation systems. This was concluded after calculating the required number of new non-fossil fuel power plants that would need to be constructed to meet the desired targets at each milestone year. If the global community delivered on the planned policies scenario (PES), 84 206 new non-fossil fuel power stations would need to be constructed and connected to the global electric power grid by the year 2030 (8.5 years from now, as seen in Table 26.14).

Another significant finding was that in 2019, it was estimated that there were 7.2 million Electric Vehicles (IEA 2020) in use. The global fleet of vehicles was estimated to be 1.416 billion vehicles (Appendix J). This suggests that only 0.51% of the global fleet is currently EV technology, and that 99.49% of the global fleet has yet to be replaced.

In 2018, the global system was still 84.7% dependent on fossil fuels, where renewables (including solar, wind, geothermal and biofuels) accounted for 4.05% of global energy generation (Figure 12). At the very least, 84.7% of the primary energy supply will be required to be replaced with non-fossil fuel systems.

Worryingly, this report highlights that the majority of infrastructure and technology needed to phase out fossil fuels has yet to be manufactured. Recycling cannot be done on products that have yet to be manufactured. The current focus of the Circular Economy concept appears to be recycling, with the perception that the extraction of mineral resources (minerals) not being is not as important. However, the system to phase out fossil fuels (whatever that is) has yet to be constructed, and this will require a historically unprecedented volume of minerals/metals/materials of all kinds.

Preliminary calculations show that current extraction (production) rates for metals like lithium, nickel and cobalt are lower than what is required. It is suggested that a sharp increase (not decrease) is required in the near future. It is predicted that current known global reserves may not be enough, thus requiring more on-going exploration for new yet to be discovered mineral deposits.

A major conclusion therefore is that the goal of industrial-scale transition away from fossil fuels into non-fossil fuel systems is a much larger task than current thinking allows for. To achieve this objective, among other things, an unprecedented demand for minerals will be required.

27.4 Biofuel and Biomass are needed but cannot be scaled-up (Scenario D)

It is suggested by some, and in this report, that biofuels and biomass feedstock may be the only way to resource parts of the industrial ecosystem. The plastics industry, for example, is currently dependent on petrochemical technology (sourced from oil, gas, and coal), and a viable replacement technology might be bioplastics that are manufactured from biomass feedstock. Biofuels sourced from corn or soybeans could be a viable way to keep the aviation transport industry operational. Biofuels sourced from algae are not viable due to its negative Energy Returned on Energy Invested ratio. Biomass in Combined Heat and Power (CHP) plants are able to generate high temperature heat in a sustained fashion. Some industrial manufacturing processes cannot operate without sustained high temperature heat being applied. Biomass fueled CHP plants could the most sustainably effective way to do this.

However, there is a complication that makes biomass sourced biofuels difficult to scale. The outcomes of Scenario D show clearly that the footprint of the proposed biofuel production done at a scale large enough to substitute petroleum product consumption far exceeds the planetary environmental capability and is also logistically impractical. The problem centres around the required volume of biofuel needed vs. the global arable land availability, and the global availability of freshwater. Biofuel production technologies work well on a small-scale. The issues raised only become unmanageable when examining what is required to scale-up production to replace petroleum.

If all biofuels were to be sourced from soybean or corn feedstock, the arable land required to grow enough biomass would far exceed the current global land used for food production (crops). That arable land used for food production has been subject to persistent degradation and deterioration, which is projected to continue while current industrial agricultural production methods remain standard practice. The expansion of crop land into other land use sectors, such as livestock grazing, is often not possible because the land is not suitable to grow crops, because all of the best arable land is already used to grow food. The additional area required for biofuel feedstock is comparable to the remaining planetary forested area. Proposing the complete deforestation of the entire planet, just to keep the existing transport fleet operating would be environmentally irresponsible. It is concluded therefore that the extra capacity to grow biofuel feedstock is in direct competition with existing food production.

Further challenges for biofuels are to do with the water consumption footprint of growing the needed feedstock of corn and soy. These two crops in particular are very water intensive. Scenario D demonstrated that the required additional fresh water required for biofuels is approximately 9 times the existing global freshwater withdrawals. The existing freshwater withdrawals by the global human society is historical high. Simultaneously, there are multiple regions around the world that are subject to fresh water supply stress. In summary, the extra water highlighted here is probably unlikely to be considered.

Scenario F proposed that a small proportion of the plastics industry was kept operational with the manufacture of bioplastics, and a small proportion of the aviation transport fleet was kept operational with the use of biofuel sourced from corn and soybean. Part of the proposed energy mix will also include biowaste to energy CHP plants, which could also be used to support some industrial manufacturing operations.

Biomass energy operations (referred to as the Biomass Economy) therefore should be decided upon only after careful consideration of the regional- and planetary-scale environmental impact, and balanced against the need and true value of those produced plastics, biofuels, and manufactured goods.

27.5 Nuclear will be needed but cannot replace fossil fuel power generation (Scenario E)

This report highlights the known fact that nuclear-generated electrical power is the only existing non-fossil fuel power system that can reliably deliver large quantities of concentrated electrical power in all weather conditions, 365 days a year. It is the most reliable power source to support industrial power consumption and the best power source to service building heating needs through winter in large human population centers. It is concluded therefore that nuclear power will be required in the future energy mix for the industrial ecosystem.

Scenario E was developed to answer the question of whether the nuclear power plant fleet could be expanded to the point where it would supply all the electric power needed to phase out fossil fuels (examining several nuclear technology options). This scenario was developed assuming all logistical bottlenecks that currently prevent full productivity were removed, the global industrial ecosystem fully supported nuclear power and aggressively expanded the Nuclear Power Plant (NPP) fleet with all support systems. The present study shows that, even with ambitious expansion (25 new Generation III+ reactors each year), the NPP fleet will not be able to supply enough electrical power to completely replace fossil fuel power generation by supporting EV's or H-Cell vehicles (based on the required 37 670.6 TWh from Scenario F). It was demonstrated that after continuous expansion for 76 years, the NPP fleet capacity was able to deliver only an annual electrical power of 26 294 TWh, which was only 69.8% of the required 37 670.6 TWh from Scenario F. After this point of production, all known uranium resources classes were calculated to be exhausted, and the stockpile of Spent Nuclear Fuel (summed total of all SNF waste classes) had expanded 4 137 % from 2016 quantities. While it could be possible to explore for more uranium deposits, the simulation was discontinued as it was shown the NPP fleet would not be able to deliver the required power in a timely fashion to be useful in phasing out fossil fuels.

To conclude, nuclear power will certainly need to be part of the future energy mix, perhaps with a slightly larger footprint than it currently has. If the current NPP fleet was developed in its current trajectory, all existing uranium classes would last 300 years before any new mineral exploration is required. So, this existing capacity should be expanded in a moderate fashion only. Scenario E has shown that nuclear power on its own cannot directly substitute for fossil fuel power generation and should be managed carefully to more realistic targets.

27.6 Non-fossil fuel systems may not be effective enough to replace fossil fuel systems

To phase out fossil fuels, the entire industrial ecosystem will have to be redesigned, retooled, and completely rebuilt around a new energy power generation source (not fossil ules) and a new transport technology (not ICE). This will require more energy than ever consumed before.

It is suggested that replacing fossil fuels will take more work than previously thought. For example, to replace a single coal-fired powered station of average size (average coal fired plant in 2018 was 861.3 MW installed capacity, producing 7.0 TWh of annually), 213 average sized solar PV array farms (33 MW installed capacity, producing 33 GW annually) would be required. Similarly, it can be calculated that it would take 87 wind turbine array farms of average size (37.2 MW installed capacity, producing 81.2 GW annually) to replace that fired power station. The reason for the large numbers is related to the difference in Energy Returned on Energy Invested (ERoEI) ratio.

In summary, the ERoEI ratio energy of energy sources used to support industrialization 100 years ago were much more effective and profitable compared to energy sources being used today, where the consistently the best source is the oil & gas industry with an ERoEI ratio between 12 and 30, and coal up to 80:1. Recently, the oil industry has been struggling to produce a profit and expand, as all the high quality and easy-to-extract reservoirs have been depleted (Michaux 2019).

A consequence of the above is that renewable energy sources tend to have lower ERoEI ratios compared to fossil fuels, which means that these systems will have to work harder to replace fossil fuels. Thus, future non fossil fuel energy systems are likely to have a lower energy productivity compared to fossil fuel equivalents that they are replacing.

So, it follows then that in order to replace each fossil fuel power station, many more renewable systems will be required to be operating than current thinking assumes. This suggests that the future non-fossil fuel energy system may well be smaller in capacity than the current fossil fuel supported energy system.

A note of caution is that the logistical challenge to construct the projected large number of renewable power plants may result in an electrical power generation ecosystem that is much smaller than the current fossil fuel power generation network.

27.7 Challenges to overcome

The calculated required annual power to phase out fossil fuels in the present report is 37 670.6 TWh (Scenario F). To reach this target, there are a number of practical challenges to be met. Six of the main ones are:

- *Challenge 1: Not enough time to meet construction targets*

The most immediate challenge to phasing out fossil fuels, with the introduction of renewable electrical power, Electric Vehicles and Hydrogen Cell vehicles, is that the task is much larger than first thought and will take much longer than what was planned. At the time of writing this report (2021), it takes approximately 5 years to construct a coal fired power station, after the design, community consultation and tender process is completed. Constructing a wind turbine farm array, or a solar panel farm array may take a shorter time period (possibly 2-4 years). The incubation time for a nuclear power plant is something like 20 to 30 years. The time to be taken to construct 221 594 new power plants (Scenario F outcome), and all the necessary support systems for each station, will exhaust the global construction capacity.

In summary, determining how long this will take, accounting for practical and logistical considerations, is beyond the scope of this study. But it is probably reasonable to assume that this construction task of unprecedented scope and scale will take many decades. This will likely be much longer than the planned 8.5 years to achieve a 30% market share for renewable energy power and non-fossil powered vehicles. The year 2050 is now only 29 years away. Current policy targets hope to have between 55% to 86% of this task completed by 2050. If it becomes apparent that the supply of oil and gas becomes unreliable (Michaux 2019), then the industrial ecosystem will find itself in the following difficult net position. Soon the primary energy resources (oil and gas) could become unreliable, at a time when the majority industrial ecosystem is still heavily dependent on fossil fuels, and the proposed plan to phase in renewable energy systems will take decades, and may not be strong enough to be viable.

- *Challenge 2: Sourcing enough minerals to supply manufacture of renewable technology*

It is suggested here that in order to phase out fossil fuels, an enormous network of new transport technologies and power generation technologies will be required to be manufactured. In Scenario F, only some of the vehicle fleet are recommended to become EV's, whereas the Class 8 HCV trucks were suggested to be H_2-Cell powered). The mass of lithium ion batteries required to power these 1.39 billion lithium ion batteries, would be 282.6 million tonnes (see Section 27.2). Preliminary calculations show that global reserves, let alone global production, may not be enough to resource the quantity of batteries required.

Each of the 1.39 billion lithium ion batteries could only have a useful working life of 8 to 10 years (IEA 2019b). So, 8-10 years after manufacture, new replacement batteries will be required, from either a mined mineral source, or a recycled metal source. As less than 0.7% of the current transport fleet is EV, these batteries cannot be resourced from recycling. The first generation has yet to be manufactured. Once that first generation is worn out, they can be recycled, which has its own challenges.

In theory, there are enough global reserves of nickel and lithium if they were exclusively used just to produce li-Ion batteries for vehicles. To make just one battery for each vehicle in the global transport fleet (excluding Class 8 HCV trucks), it would require 48.2% of 2018 global nickel reserves, and 43.8% of global lithium reserves (Source: USGS Mineral Statistics). There is not enough cobalt in current reserves to meet this demand and more will have to be discovered.

In practice, this will not work due to other industrial demands for these metals, and that this represents only one generation of batteries of the current vehicle fleet. Every ten years from that point onwards, the same mass requirement would be needed all over again to produce the next generation of EV battery.

The decision to focus on lithium ion batteries only for this report was based on current trends in funding and development that tend to focus mainly on lithium ion solutions. Other battery chemistry options (vanadium, or sodium based) are possible conceptually, but have yet to progress to industrial scale feasibility. The five lithium ion battery chemistries considered here are the known most effective transport solutions, and all required battery mineral volumes are estimated using those required for Li-Ion technologies.

This approach highlights the challenges of supplying (the same) minerals to resource other parts of the planned renewable system (for example wind turbines, solar panels, or semiconductors).

- *Challenge 3: Developing enough power storage to manage intermittent power supply*

Electrical power generated from solar and wind sources are highly intermittent in supply volumes, both across a 24-hour cycle and in a seasonal context. A power storage buffer is required if these power generation systems are to be used on a large scale. How large this power buffer needs to be is subject to discussion. A conservative estimate selected for this report was a 4-week power capacity buffer for solar and wind only (where other estimates are 4-12 weeks of the total power capacity), where the most challenging period would be the winter season in the Northern Hemisphere. From Scenario F, the power storage buffer capacity for the global electrical power system would be 573.4 TWh.

In 2018, pumped storage attached to a hydroelectric power generation system accounted for 98% of power storge capacity. Expanding this capacity will be very challenging due to geographical constraints. There are a number of technological options to construct a power storage station. If pumped hydro cannot be expanded much beyond what it is now, other options could be spinning flywheels, compressed air reservoirs, or battery banks. Due to industry acceptance levels, strategic policy makers have proposed the use of lithium ion battery banks. Using the largest know example of this (the Hornsdale 100 MW station in Australia, Parkinson 2017a), each example station in this study would have a 100 TWh capacity. To deliver the required storage capacity (574.3 TWh), the number of 100 MW stations would be 5.7 million, and the mass of lithium ion batteries would be 2.5 billion tonnes.

If the required power storage station capacity to mitigate intermittency of power supply form solar wind, was delivered using lithium ion batteries, then an extra 2.5 billion tonnes of Li-Ion batteries in addition to the 282.6 million tonnes (resulting in 2.78 billion tonnes of batteries needed). This far exceeds the 2018 global reserves by many times and is impractical (5 times 2018 global nickel reserves, 11 times 2018 global cobalt reserves, and 4 times global lithium reserves).

It is unlikely that the above scenario will ever happen as the required mineral volumes to manufacture the 2.5 billion tonnes of Li-Ion batteries far exceeds existing global reserves, and where enough exploration to make up the shortfall is impractical. It is suggested that a new form of stored power needs to be invented, where it can be deployed on this scale. If this is not achieved, the ERoEI for solar and wind power generation would become very negative, and both power systems would become unviable on a large scale application (but quite successful on a small scale).

- *Challenge 4: Finding enough new sites for hydroelectric power plants*

Hydroelectricity shows the most promise as a renewable energy source with a high ERoEI of 50:1. However, it is geographically limited, and cannot be placed anywhere. Scenario F, using the same non-fossil fuel energy mix as was reported in 2018, proposes an additional 16 576.9 TWh to be supplied with the application of hydroelectric power plants in the global system. This would be 12 504 average sized plants of 225 MW installed capacity. Most of the effective geographical sites for this kind of power generation are already established as hydroelectric plants. Finding another 12 504 such sites will therefore be challenging.

- *Challenge 5: Phasing out petrochemical fertilizers, herbicides, and pesticides*

Approximately 9 % of global gas demand is used to produce ammonia for the industrial manufacture of fertilizer, which in turn is critical for global food production. This fossil fuel consumption stream needs to be addressed in some form. At the time of writing this report (2021), the author was unable to cite any viable substitute for the use of natural gas in the production of petrochemical fertilizers. This means that eventually, industrial agriculture will not be able to operate the way it does now.

The application of industrial agriculture (which depends on industrially-produced petrochemical fertilizers) has resulted in widespread land degradation, where topsoil is lost, and that land can no longer support the growing of crops.

All proposed solutions to meet the land degradation issues propose a combination of new generation fertilizers in conjunction with a return to a more natural balance of the phosphorus (and nitrogen) cycles. This involves the rebuilding of soil in areas that have now been sterilize, in a fashion where the soils humus organic component is increase to 20-25%.

It is recommended here to consider the phasing out the use of industrial fertilizers, which would mean a restructuring of what is termed industrial agriculture. The most environmentally balanced solution would be the widespread application of small-scale organic farming, and the use of organically produced fertilizers, that have been produced at an industrial scale.

- *Challenge 6: Human population growth*

Underlying all of these other challenges is the ever-growing human population. With each passing year, energy consumption *per capita* has been increasing due to the ever-increasing complexity of the industrial ecosystem. This puts more pressure on all natural our resources. As society now attempts to transition away from fossil fuels (the most calorifically dense energy source historically ever seen), by rebuilding the largest and most technologically complex economy in history, using comparatively less effective energy systems, there is greater pressure than ever before to do more with less resources.

27.8 Final summary

Current thinking is that global industrial businesses will replace a complex industrial ecosystem that took more than a century to build. The current system was built with the support of the highest calorifically dense source of energy the world has ever known (oil), in cheap abundant quantities, with easily available credit, and seemingly unlimited mineral resources. This replacement is hoped to be done at a time when there is comparatively very expensive energy, a fragile finance system saturated in debt, not enough minerals, and an unprecedented world population, embedded in a deteriorating natural environment.

Most challenging of all, this has to be done within a few decades. It is the authors opinion that this will not go according to plan.

This report has produced new numbers that are quite different to previous studies. This could be due in part to the difference in paradigm that defined these studies. The present report was constructed from a bottom-up approach, by calculating the required number of vehicles, fossil fuel consumption applications and the tasks they performed. Previous studies have tended to make made top-down estimations. The resulting outcomes of the present report suggest there is a large disparity in the size of the task ahead of the industrial ecosystem in context of what will be required to completely phase out fossil fuel energy sources. Policy makers and research analysts are not seeing the true scope of the task, nor are they seeing the true logistical boundary conditions. Many of the solutions discussed in the open literature might work quite well at a comparatively small-scale but cannot function when scaled-up to a global scope to mimic the size of the existing fossil fuel sourced system. Usually, the bottleneck making this happen is the quantity of minerals required, the manufacturing capacity, or simply the required time to roll out production. Most analysts examine only one part of the ecosystem or only one function in isolation, where what is really required is a holistic systems network engineering approach, that honors the inherent complexity. That approach has been presented here.

A fundamental conclusion is that replacing the existing fossil fuel powered system (oil, gas, and coal), using renewable technologies, such as solar panels or wind turbines, will not be possible for the global human population in just a few decades. There is just not the time, nor resources to do this. What may well happen is a significant reduction of societal demand of all resources of all kinds. This implies a very different social contract and a very different system of governance to what is in place today.

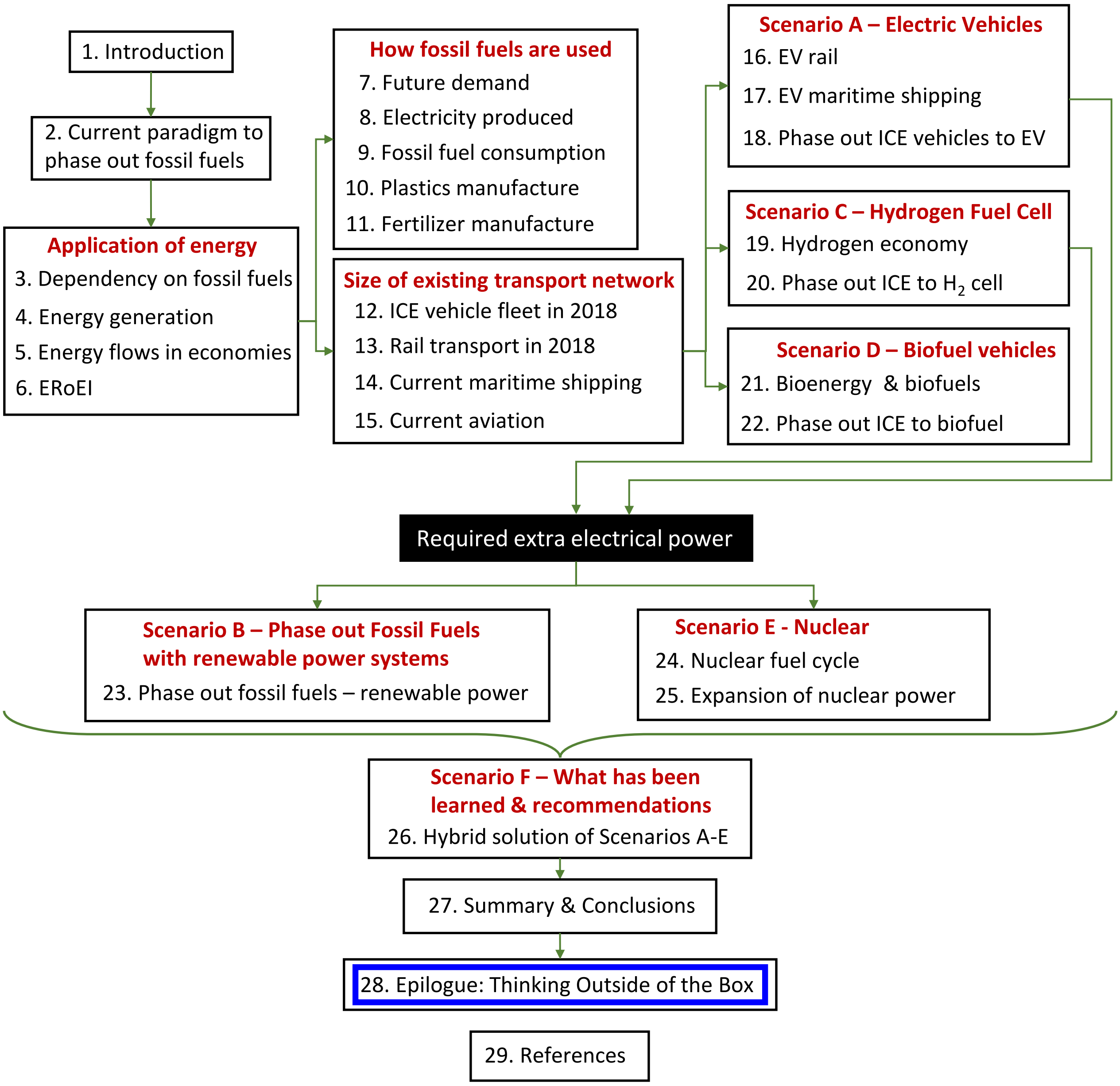
This report has shown that the widespread trend of funding and developing only a small number of renewable technology solutions (lithium -ion batteries, hydrogen cells, wind turbines and solar panels), to the exclusion of other known, but less developed solutions, is short sighted. We need to continue also seeking alternative technologies that could be developed and scaled up and overcome the desire for the 'magic bullet' solution that will fix everything in one step. The reality is that the industrial ecosystem should consider as many parallel technology options as possible, with each one linked back to the quantity of resources required to apply them.

"What are the chances of successfully solving a problem if we insist on working on solutions that are not scalable, and stop thinking outside of the box?"

Finally, everything points to the existing renewable energy sector and the EV technology system being a steppingstone to something else as opposed to the final solution. It is recommended that some thought is given to this and what that something else might be.

28 EPILOGUE - THINKING OUTSIDE THE BOX

This report has shown that the phasing out of fossil fuels will probably not go to plan or be sufficient for our needs to build a new industrial ecosystem to match the existing system. The current industrial ecosystem dependence on fossil fuels, oil in particular, could soon become unreliable due to the challenges facing the oil and gas industry (Michaux 2019). Conventional thinking will be insufficient, and the human propensity to innovate in the face of adversity is now needed. Necessity is the mother of invention. The ideas presented in this section (Section 28) have historically been the subject of intense debate and often not accepted. Now is the time to consider unorthodox ideas once again for industrial problem-solving.



Assessment of the Extra Capacity Required of Alternative Energy Electrical Power Systems to Completely Replace Fossil Fuels

As already mentioned, the current report has revealed that the task to phase out fossil fuels is much larger than what is currently understood. As most of the planned substitute technologies have a lower Energy Returned on Energy Invested (ERoEI) than the fossil systems they are replacing, the number of power stations needed (and supporting infrastructure) is many times larger than the existing power plant fleet. To construct a single power plant can take years. To construct several hundred thousand power plant stations will likely take five to six decades. Current climate change mitigation targets are planning to have 1/3rd of this task done in a little over 8 years (by 2030). We clearly do not have the time to deploy this strategy.

Each of the proposed renewable technology systems (EV's, H_2-Cell vehicles, PV solar power, wind, hydro and biowaste) all work well, at a small scale, especially when supported by a fossil fuel power generation system. Scaling-up these renewable systems so they are accessible to all people has limitations, however, may not be possible.

Energy sources such as solar, wind or water are all technically renewable. To harvest energy from these sources requires wind turbines, solar panels, and water turbines. To store this energy so it can be used in transport applications require batteries. Each of these units require manufacture, sourced from non-renewable finite mineral resources. Each of these units has a working life of approximately 10 to 20 years (with the possible exception of hydro), after which they need to be decommissioned and replaced with new units. This means the non-fossil fuel systems are not really renewable at all but are in fact better described as '<u>replaceable</u>' (Hagens 2021).

Given this, a realistic assessment of the volume of minerals needed is required. Preliminary calculations in the current study indicates the required number of units will require more minerals, metals and materials than is in current known global mineral reserve inventories. The disparity is so large that exploring for new mineral deposits, with the sole objective of opening more producing mines in the required time frame, cannot be the only solution.

Even if the planned renewable system was constructed, it is possible that the final outcome is not effective enough to replicate what fossil fuels contribute to the current industrial ecosystem. All indications suggest that the planned renewable energy systems need to be considered merely as a steppingstone to something else.

The strategic tasks before us now are all enormous in scale and individually unprecedented, and include:

- Rebuild the fossil fuel energy system and supporting infrastructure in a few decades
- Mitigate climate change
- Rehabilitate arable land that has been degraded with improper application of industrial agriculture, by reestablishing the soil food web in whole geographical regions.
- Remove plastic pollution from the ocean
- Reverse ocean acidification
- Revegetate large regions of the planet, to reestablish the natural biodiversity of flora and fauna.

Additionally, we are required to address these challenges in a 20 – 50 year time frame. To do this, a reliable energy source that is available to most of the human population with an ERoEI ratio of something like 50:1 is required. Even existing fossil fuels are not effective enough, as they are now. Renewable technology on its own is not enough to meet these requirements. Something radically new is required.

If society is to continue to function at current levels, then all problem solvers, innovators, inventors, researchers, engineers, scientists, and artists of all kinds, are now required to imagine a new kind world with a novel approach to industrialization. At this time, so called "out of the box thinking" is urgently required.

28.1 Restructure society and the industrial ecosystem to consume less

The logistical challenges to replace fossil fuels are enormous. It may be so much simpler to reduce demand for energy and raw materials in general. This will require a restructuring of society and its expectations, resulting in a new social contract. Social License to Operate (SLO) issues will become more intimately involved in the viability and operation of whatever new industrial ecosystem is to be developed.

For the last 200 years, the industrial ecosystem has grown at an unprecedented rate, which has been facilitated with the discovery and use of fossil fuels. Human population is also at an unprecedented size, requiring ever more natural resources each passing year. This has been called the carbon pulse (Hagens 2021), where an unprecedented spike in the consumption of natural resources has happened. Never before in human history has such a circumstance happened. The fundamentals that allowed this to happen are dependent of finite nonrenewable natural resources (oil, gas, and coal). To transition away from fossil fuels will require the redesigning, retooling and reconstruction of the entire industrial ecosystem.

As the energy source at the foundation of the new industrial system will be different to what is used now, that industrial ecosystem will operate to a different set of limitations and capabilities. The past 200 years have been a period of very fast growth of industrial scope and complexity, based on an energy source that is no longer appropriate. It is entirely possible that we are required to develop a low energy future with an associated much simpler level of technological complexity.

At this time, the global industrial ecosystem is very international in nature. No one nation state has everything it needs to manufacture a single advanced technological unit like a computer. Resources are drawn from all over the world, components are manufactured in different places again, the final product is manufactured and then dispersed all over the planet for use. If the system was forced to contract in size and complexity without international cooperation, then there would be whole geographical regions experiencing shortages of all kinds. Without most nations around the world cooperating in this task, there is a high risk of resource wars being started to secure long term security of some of those nations at the expense of others.

What is proposed here is a complete reinvention of societies relationship with natural resources, and more importantly the planetary environment. A possible contribution to this important discussion is shown in (Michaux 2021a). Current society has become addicted to material goods and access to technological capability underpinned by energy on demand (Hamilton 2003, Hamilton & Denniss 2005). This is a result of the last 200 years of a system dependent on exponential growth of many important metrics. This will have to change. It will not be easy or simple.

28.2 Reinvent oil based technology that is more efficient and has much less waste pollution

Assessing all the energy sources available to society, oil is still the most calorifically dense. There are two fundamental reasons to phase oil. The first being to mitigate climates change, where the problem is the carbon pollution waste plume from the use of ICE engine technology. The second is that the needed volumes of oil to service global demand may become erratic in delivery, due to the oil price not being high enough for oil product producers to survive, and low enough for consumers to access those oil products in large enough numbers to facilitate economic growth (Michaux 2019). Thus, the push to phase oil and fossil fuels out.

Both of these broad issues could be resolved if a technology was developed that would use fossil fuels as a source, was more efficient and had a much smaller waste plume. Consider for example, the ICE engine (energy efficiency between 25 and 45%), was replaced by another technology that was 95% energy efficient and had almost no was plume exhaust (thus no carbon pollution). This would entail the replacement of the ICE technology, not fossil fuels per se. This may sound outlandish, but are there possible solutions like this in development but have been ignored? As the whole oil extraction infrastructure could be used, this (if possible) would allow society to function for a extra time period it currently does not have, while the 'after oil' plan could be developed.

28.3 Develop multiple different batteries chemistries in parallel -optimized to application

The preliminary calculations in this report suggest that, in order to manufacture the needed number of lithium ion batteries to phase out fossil fuels, there is currently is not enough global mineral reserves, let alone global production capacity to supply the needed quantity of lithium, cobalt and nickel metals (Section 26.4). There are alternative battery chemistries. This report has specifically focused on Li-Ion batteries because it is the most favoured current technology. Other battery chemistry systems have been demonstrated, but not yet at industrially-relevant scales.

This propensity for human society to focus on a quick fix 'magic bullet' one simple solution to address complex problems, is actually part of our psychology (Hagens 2021). This is ironic as the human society demand architecture is so complex it is difficult to map.

One strategy could be to develop several battery chemistry systems in parallel, and to optimize what their applications would be based on a whole industrial ecosystem-need hierarchy. For example, lithium ion batteries could be reserved for some applications that need high power and low mass and volume batteries. Vanadium redox batteries, on the other hand, could be reserved for industrial sized standalone battery banks that are of strategic value (with a very different working Life Cycle). The classic lead acid batteries could be used for applications that do not require weight or volume limitations.

Currently, the most investigated battery chemistries are lithium ion batteries (LIBs), which use lightweight lithium ions as a charge carrier (Gschwind *et al* 2016). These LIBs are considered the best performing systems. Additionally, systems based on H^+, OH^-, Na^+, and Mg^{2+} as shuttle ions are currently in use or being investigated (Linden *et al* 2002, Berndt & Spahrbier 2014a, Berndt & Spahrbier 2014b, Berndt 2014, Spahrbier 2014). Despite these advances, it is acknowledged all of these suffer from various limitations (Tarascon & Armand 2001, Palomares *et al* 2012, Muldoon *et al* 2012).

There are other systems that show promise. Figure 28.1 shows two heat maps of theoretical combinations of fluoride chemistries for anode (negative) to cathode (positive) electrode combinations (after Gschwind *et al* 2016). The upper heat map shows the gravimetric capacity for anode/cathode combinations. The lower heat map shows the volumetric energy density of fluoride chemistries for anode (negative) to cathode (positive) electrode combinations.

Figure 28.2 shows the grouping of battery chemistry energy footprint for several chemistries, where the x-axis is similar to the upper heat map in Figure 28.1 and the y-axis is similar to the lower heat map. This implies that lithium ion battery chemistry may not be the best option to pursue for high density applications.

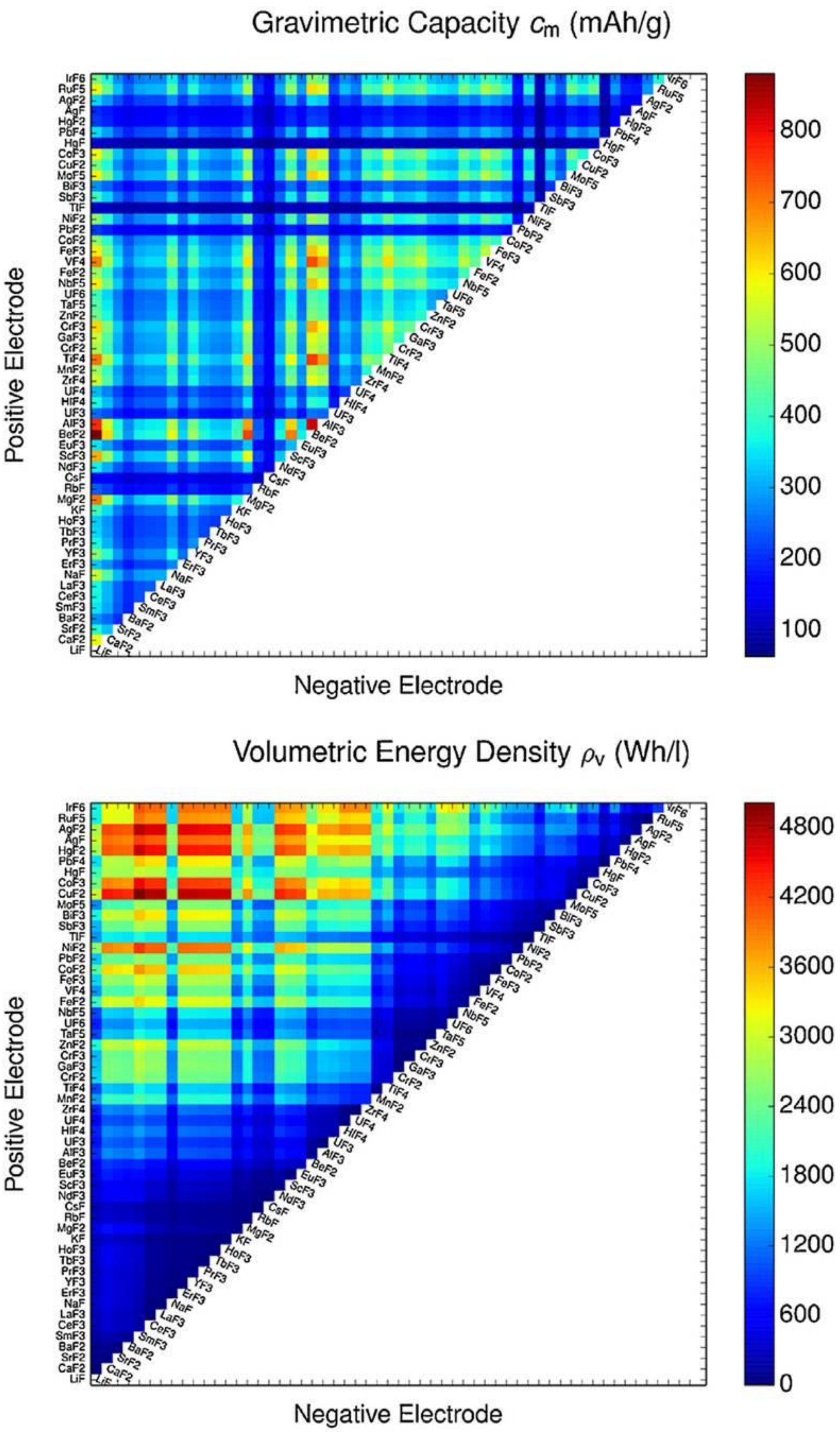


Figure 28.2. Overview of the different anode/cathode combinations in terms of specific capacity and volumetric energy density (Source: Gschwind *et al* 2016)

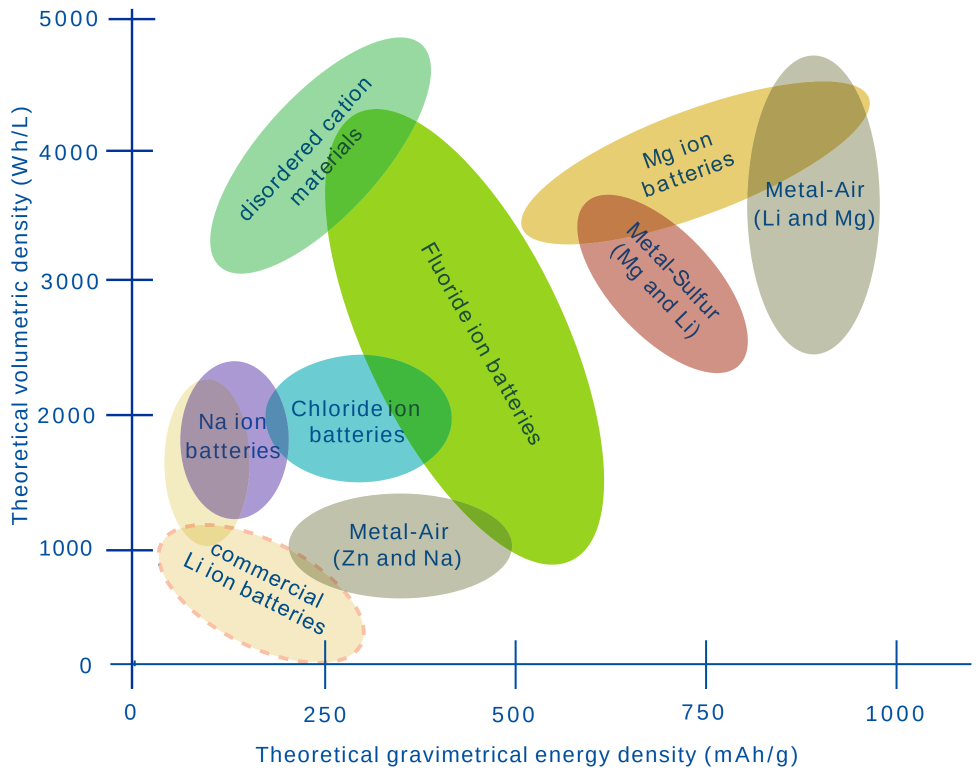


Figure 28.1. Comparison of theoretical gravimetrical energy density to theoretical volumetric density for several battery chemistries (Source: Witter 2021)

These ideas are not considered as part of the conventional problem solving paradigm at this time. Aspects have been discussed but are not developed beyond conceptual state of readiness. Even so, these solutions will not be enough, as they represent step changes only. As stated in the beginning of this section, a reliable energy source that is available to most of the human population with an ERoEI ratio of something like 50:1 is required (or even higher). Existing fossil fuels are not effective enough, nor appropriate. Renewable technologies on their own are not enough to meet these requirements.

A fundamental restructuring of how we see energy, how we harness it and how we use it is required.

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30 APPENDIX A - GLOBAL ENERGY CONSUMPTION

Table A1. Global primary energy consumption (Mtoe) (Source: BP Statistical Review of World Energy 2019)

Consumption*

Million tonnes oil equivalent	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Growth rate per annum 2018	Growth rate per annum 2007-17	Share 2018
Canada	321.5	304.9	312.0	327.2	324.7	337.0	341.8	339.0	338.2	343.7	**344.4**	0.2%	0.7%	2.5%
Mexico	170.8	169.5	174.6	183.1	184.2	185.0	184.1	184.0	186.4	189.3	**186.9**	-1.3%	1.2%	1.3%
US	2258.6	2148.7	2223.3	2204.1	2148.5	2208.0	2232.9	2213.2	2212.7	2222.5	**2300.6**	3.5%	-0.4%	16.6%
Total North America	2751.0	2623.1	2709.8	2714.4	2657.4	2730.1	2758.9	2736.2	2737.2	2755.5	**2832.0**	2.8%	-0.2%	20.4%
Argentina	74.7	73.3	77.2	78.7	81.0	84.5	84.1	86.1	85.9	86.1	**85.1**	-1.2%	1.6%	0.6%
Brazil	239.9	238.6	263.1	275.8	281.3	292.4	299.4	295.9	289.4	293.9	**297.6**	1.3%	2.5%	2.1%
Chile	32.2	31.5	31.7	34.5	35.3	35.7	35.1	35.9	37.7	38.3	**40.1**	4.7%	1.7%	0.3%
Colombia	33.3	31.8	34.1	35.7	38.3	38.9	41.0	41.3	44.2	45.5	**46.9**	3.2%	4.0%	0.3%
Ecuador	12.1	11.9	13.2	14.0	14.8	15.3	16.1	16.1	16.0	16.7	**17.6**	5.8%	3.9%	0.1%
Peru	16.6	17.0	18.8	20.9	21.3	21.9	22.6	24.2	25.5	25.4	**27.0**	6.3%	5.2%	0.2%
Trinidad & Tobago	15.9	16.0	17.5	17.6	16.7	17.2	16.8	16.9	15.4	15.2	**15.3**	0.1%	-0.7%	0.1%
Venezuela	84.6	84.4	79.7	83.4	86.9	84.9	82.1	79.3	72.3	73.6	**64.6**	-12.2%	-1.0%	0.5%
Other S. & Cent. America	91.6	89.6	91.8	94.6	95.1	95.1	95.7	99.5	104.6	105.1	**107.8**	2.6%	1.3%	0.8%
Total S. & Cent. America	600.8	594.2	627.1	655.3	670.9	685.9	692.9	695.3	691.1	699.8	**702.0**	0.3%	1.8%	5.1%
Austria	35.4	34.3	35.6	33.3	35.0	34.7	33.3	33.4	34.6	35.5	**35.0**	-1.5%	0.2%	0.3%
Belgium	67.7	63.4	67.5	63.0	60.7	62.2	58.2	59.1	63.9	64.1	**62.2**	-3.0%	-0.4%	0.4%
Czech Republic	43.9	42.2	44.0	43.0	42.8	42.1	41.2	40.5	39.9	41.8	**42.1**	0.9%	-0.7%	0.3%
Finland	31.4	29.3	31.9	29.7	28.8	29.1	28.1	28.0	28.8	28.1	**29.3**	4.2%	-1.5%	0.2%
France	261.9	248.0	256.0	246.9	247.3	250.1	240.4	241.9	238.4	237.5	**242.6**	2.2%	-0.9%	1.7%
Germany	335.5	315.1	327.9	316.1	320.5	329.8	316.4	322.5	328.1	333.9	**323.9**	-3.0%	0.1%	2.3%
Greece	35.3	34.2	32.5	31.7	30.0	28.5	26.8	27.0	26.6	28.0	**28.3**	1.0%	-2.6%	0.2%
Hungary	25.3	23.2	23.8	23.6	21.9	20.9	21.0	22.0	22.4	23.5	**23.7**	0.8%	-0.9%	0.2%
Italy	181.0	169.2	174.4	170.5	165.8	158.2	149.7	153.1	154.7	156.3	**154.5**	-1.1%	-1.6%	1.1%
Netherlands	93.8	92.4	97.8	93.7	90.6	87.9	83.1	84.1	85.7	84.5	**84.8**	0.3%	-1.2%	0.6%
Norway	46.4	43.1	41.6	42.4	47.3	44.3	45.7	46.5	47.2	47.6	**47.4**	-0.5%	0.5%	0.3%
Poland	97.4	93.9	100.0	100.5	97.5	97.8	94.2	95.2	99.4	103.4	**105.2**	1.7%	0.8%	0.8%
Portugal	24.4	24.5	25.8	24.7	22.6	24.7	24.9	24.8	26.2	25.8	**26.0**	0.8%	0.2%	0.2%
Romania	38.6	33.8	34.0	34.9	33.6	31.4	32.7	32.8	32.8	33.4	**33.4**	0.1%	-1.4%	0.2%
Spain	154.5	143.4	146.5	143.9	143.2	135.9	133.5	135.4	136.9	138.8	**141.4**	1.8%	-1.3%	1.0%
Sweden	53.0	48.7	51.8	51.4	54.7	51.5	51.5	53.3	52.6	54.4	**53.6**	-1.4%	0.1%	0.4%
Switzerland	29.9	29.9	29.2	27.8	29.4	30.3	29.0	28.4	26.8	26.9	**27.8**	3.5%	-0.7%	0.2%
Turkey	100.8	102.2	107.6	115.1	122.3	121.5	125.4	137.2	144.6	152.7	**153.5**	0.5%	4.3%	1.1%
Ukraine	133.5	113.4	121.5	126.3	123.1	117.3	103.2	85.7	89.8	83.4	**84.0**	0.8%	-4.7%	0.6%
United Kingdom	220.0	209.4	214.6	202.2	204.8	204.1	192.5	195.1	193.5	193.2	**192.3**	-0.5%	-1.4%	1.4%
Other Europe	163.5	154.9	160.6	156.9	150.3	152.3	147.4	150.8	154.7	157.3	**159.8**	1.6%	-0.3%	1.2%
Total Europe	2173.3	2048.4	2124.6	2077.7	2072.3	2054.7	1978.3	1996.8	2027.5	2050.0	**2050.7**	◆	-0.6%	14.8%
Azerbaijan	12.8	11.3	11.2	12.5	12.8	13.2	13.5	14.7	14.6	14.3	**14.4**	0.6%	1.2%	0.1%
Belarus	25.9	24.5	26.0	25.9	28.0	24.7	25.5	23.2	23.0	23.4	**24.6**	5.0%	-0.9%	0.2%
Kazakhstan	56.4	50.8	54.9	60.5	62.7	63.5	64.4	63.7	64.7	67.6	**76.4**	13.0%	2.3%	0.6%
Russian Federation	676.6	643.2	669.3	691.8	693.8	685.5	688.3	675.4	690.5	694.3	**720.7**	3.8%	0.3%	5.2%
Turkmenistan	12.2	19.9	21.5	23.8	26.0	23.1	23.9	28.6	27.5	28.7	**31.5**	9.8%	6.8%	0.2%
Uzbekistan	44.6	44.8	44.4	46.6	45.5	45.2	47.1	44.9	43.6	45.0	**43.9**	-2.4%	-0.5%	0.3%
Other CIS	16.2	15.6	15.9	17.0	18.0	17.1	17.5	17.4	17.5	18.0	**19.0**	5.9%	0.7%	0.1%
Total CIS	844.7	810.2	843.2	878.0	886.7	872.1	880.3	867.9	881.5	891.2	**930.5**	4.4%	0.5%	6.7%
Iran	205.8	212.7	213.4	224.9	226.2	237.9	249.0	249.2	257.2	272.0	**285.7**	5.0%	3.2%	2.1%
Iraq	29.2	32.6	34.7	36.7	39.0	42.0	40.2	40.1	46.2	47.1	**53.7**	14.1%	5.3%	0.4%
Israel	23.3	22.3	23.7	24.2	25.3	23.5	23.1	24.4	24.8	25.6	**25.6**	0.2%	1.1%	0.2%
Kuwait	29.7	31.1	33.5	33.6	37.3	38.7	35.4	38.5	38.9	38.7	**39.0**	0.7%	3.5%	0.3%
Oman	17.5	17.6	20.6	22.5	24.5	27.4	27.3	28.8	29.0	29.3	**30.7**	4.6%	7.0%	0.2%
Qatar	24.6	24.8	28.9	33.4	37.9	40.8	43.9	48.2	47.6	48.9	**48.3**	-1.2%	8.2%	0.3%
Saudi Arabia	184.3	194.3	213.0	219.8	233.1	234.0	250.8	259.0	262.2	262.8	**259.2**	-1.4%	4.5%	1.9%
United Arab Emirates	81.0	80.0	83.8	88.4	92.8	97.8	97.4	107.1	111.1	109.0	**112.2**	3.0%	4.4%	0.8%
Other Middle East	58.3	58.5	58.2	54.7	51.1	50.3	50.1	48.4	48.0	48.0	**47.9**	-0.2%	-1.6%	0.3%
Total Middle East	653.7	673.8	709.8	738.4	767.3	792.5	817.2	843.7	864.9	881.4	**902.3**	2.4%	3.8%	6.5%
Algeria	36.4	38.6	37.6	39.9	43.6	46.2	50.4	53.1	53.0	53.1	**56.7**	6.7%	4.5%	0.4%
Egypt	71.7	74.6	78.4	79.7	83.8	83.2	83.0	85.3	89.9	92.6	**94.5**	2.1%	3.2%	0.7%
Morocco	15.4	15.0	16.7	17.5	17.8	18.3	18.6	18.9	19.1	20.0	**21.0**	4.9%	3.7%	0.2%
South Africa	125.4	125.1	126.3	124.6	122.7	123.2	124.8	121.9	123.9	121.8	**121.5**	-0.2%	0.4%	0.9%
Other Africa	116.5	118.7	124.8	123.6	131.3	138.9	145.9	150.9	153.5	161.0	**167.8**	4.2%	3.8%	1.2%
Total Africa	365.4	372.0	383.8	385.3	399.2	409.7	422.6	430.1	439.4	448.6	**461.5**	2.9%	2.7%	3.3%
Australia	132.3	131.4	131.9	136.4	134.6	135.3	137.5	139.2	142.1	140.5	**144.3**	2.7%	0.8%	1.0%
Bangladesh	18.8	20.6	21.6	23.0	25.0	25.5	27.0	31.3	31.8	33.0	**35.8**	8.6%	6.4%	0.3%
China	2230.4	2330.1	2491.6	2690.5	2799.5	2907.5	2974.7	3009.6	3047.1	3139.0	**3273.5**	4.3%	3.9%	23.6%
China Hong Kong SAR	24.3	26.6	27.6	28.3	27.2	28.0	27.3	28.1	28.8	30.9	**31.1**	0.6%	1.7%	0.2%
India	477.9	514.3	539.2	571.4	601.0	624.5	667.5	689.8	719.3	750.1	**809.2**	7.9%	5.2%	5.8%
Indonesia	132.7	137.6	151.1	164.6	173.4	178.2	167.2	165.7	170.2	176.9	**185.5**	4.9%	2.8%	1.3%
Japan	517.8	473.1	504.7	479.1	475.7	472.3	460.3	453.3	450.8	455.2	**454.1**	-0.2%	-1.4%	3.3%
Malaysia	80.0	77.7	80.1	82.9	89.0	93.1	93.6	95.1	96.6	96.7	**99.3**	2.7%	2.3%	0.7%
New Zealand	19.3	19.2	19.9	19.7	20.0	20.2	21.2	21.4	21.6	22.2	**21.7**	-1.9%	1.4%	0.2%
Pakistan	62.4	63.2	63.4	63.5	64.1	64.9	66.9	70.4	76.6	81.0	**85.0**	5.0%	2.7%	0.6%
Philippines	28.0	28.3	29.3	29.9	30.9	33.1	34.9	38.3	41.8	45.7	**47.0**	2.9%	5.4%	0.3%
Singapore	59.3	63.8	68.6	71.3	71.6	73.6	75.8	80.6	83.8	86.5	**87.6**	1.2%	4.5%	0.6%
South Korea	241.4	242.6	261.3	273.4	276.3	276.7	279.5	285.3	292.2	297.1	**301.0**	1.3%	2.3%	2.2%
Sri Lanka	5.1	5.3	5.7	5.9	6.0	6.1	5.5	7.0	7.5	7.8	**8.1**	3.3%	3.7%	0.1%
Taiwan	106.6	104.7	110.9	109.3	109.1	111.1	113.8	112.9	115.0	117.0	**118.4**	1.2%	0.4%	0.9%
Thailand	95.2	98.5	104.8	108.9	116.5	118.3	121.6	124.7	127.3	130.2	**133.0**	2.1%	3.3%	1.0%
Vietnam	38.5	39.4	44.6	51.0	53.4	57.2	62.6	69.1	73.9	75.8	**85.8**	13.1%	9.4%	0.6%
Other Asia Pacific	46.2	42.2	45.4	45.2	48.3	48.8	52.7	53.9	60.5	62.4	**65.4**	4.8%	3.5%	0.5%
Total Asia Pacific	4316.2	4418.7	4701.5	4954.5	5121.6	5274.4	5389.6	5475.7	5587.0	5748.0	**5985.8**	4.1%	3.2%	43.2%
Total World	**11705.1**	**11540.3**	**12099.9**	**12403.7**	**12575.5**	**12819.4**	**12939.8**	**13045.6**	**13228.6**	**13474.6**	**13864.9**	**2.9%**	**1.5%**	**100.0%**
of which: OECD	5636.3	5365.1	5570.8	5517.5	5463.8	5522.7	5483.5	5495.7	5530.6	5586.9	**5669.0**	1.5%	-0.2%	40.9%
Non-OECD	6068.8	6175.2	6529.1	6886.2	7111.7	7296.8	7456.3	7549.9	7698.0	7887.7	**8195.9**	3.9%	3.0%	59.1%
European Union	1818.1	1714.8	1777.1	1719.1	1705.8	1694.4	1631.7	1652.9	1670.4	1691.8	**1688.2**	-0.2%	-0.8%	12.2%

*In this review, primary energy comprises commercially-traded fuels, including modern renewables used to generate electricity.
◆Less than 0.05%.

Table A2. Global primary energy consumption by fuel (Mtoe) (Source: BP Statistical Review of World Energy 2019)

Primary energy: consumption by fuel*

Million tonnes oil equivalent	2017 Oil	2017 Natural gas	2017 Coal	2017 Nuclear energy	2017 Hydro-electricity	2017 Renew-ables	2017 Total	2018 Oil	2018 Natural gas	2018 Coal	2018 Nuclear energy	2018 Hydro-electricity	2018 Renew-ables	2018 Total
Canada	108.8	94.3	18.6	22.7	89.7	9.5	343.7	110.0	99.5	14.4	22.6	87.6	10.3	**344.4**
Mexico	85.8	74.3	15.2	2.5	7.2	4.3	189.3	82.8	77.0	11.9	3.1	7.3	4.8	**186.9**
US	902.0	635.8	331.3	191.7	67.2	94.5	2222.5	919.7	702.6	317.0	192.2	65.3	103.8	**2300.6**
Total North America	1096.6	804.4	365.1	216.9	164.1	108.4	2755.5	1112.5	879.1	343.3	217.9	160.3	118.8	**2832.0**
Argentina	32.0	41.5	1.1	1.4	9.4	0.7	86.1	30.1	41.9	1.2	1.6	9.4	0.9	**85.1**
Brazil	136.1	32.4	16.6	3.6	83.9	21.4	293.9	135.9	30.9	15.9	3.5	87.7	23.6	**297.6**
Chile	17.7	4.8	7.7	–	4.8	3.3	38.3	18.1	5.5	7.7	–	5.2	3.5	**40.1**
Colombia	16.5	10.5	5.2	–	13.0	0.5	45.5	16.6	11.2	5.9	–	12.8	0.5	**46.9**
Ecuador	11.3	0.7	–	–	4.5	0.1	16.7	12.2	0.6	–	–	4.7	0.1	**17.6**
Peru	12.0	5.8	0.6	–	6.6	0.4	25.4	12.4	6.1	0.9	–	7.0	0.7	**27.0**
Trinidad & Tobago	2.1	13.1	–	–	–	†	15.2	2.1	13.2	–	–	–	†	**15.3**
Venezuela	22.1	33.4	0.1	–	18.0	†	73.6	19.5	28.7	0.1	–	16.3	†	**64.6**
Other S. & Cent. America	67.4	6.2	3.5	–	22.8	5.2	105.1	68.3	6.8	4.3	–	22.3	6.1	**107.8**
Total S. & Cent. America	317.2	148.4	34.8	4.9	163.0	31.5	699.8	315.3	144.8	36.0	5.1	165.5	35.4	**702.0**
Austria	13.1	7.8	3.1	–	8.7	2.8	35.5	13.4	7.5	2.9	–	8.5	2.8	**35.0**
Belgium	33.7	14.1	3.1	9.6	0.1	3.5	64.1	34.1	14.5	3.3	6.4	0.1	3.8	**62.2**
Czech Republic	10.4	7.2	15.6	6.4	0.4	1.8	41.8	10.6	6.9	15.7	6.8	0.4	1.7	**42.1**
Finland	10.3	1.6	4.0	5.1	3.3	3.8	28.1	10.7	1.8	4.3	5.2	3.0	4.3	**29.3**
France	79.1	38.5	9.3	90.1	11.1	9.4	237.5	78.9	36.7	8.4	93.5	14.5	10.6	**242.6**
Germany	119.0	77.2	71.5	17.3	4.6	44.4	333.9	113.2	75.9	66.4	17.2	3.8	47.3	**323.9**
Greece	16.0	4.1	4.8	–	0.9	2.2	28.0	16.0	4.1	4.7	–	1.3	2.4	**28.3**
Hungary	8.3	8.5	2.2	3.6	†	0.7	23.5	8.8	8.3	2.2	3.6	0.1	0.8	**23.7**
Italy	62.0	61.5	9.6	–	7.8	15.3	156.3	60.8	59.5	8.9	–	10.4	14.9	**154.5**
Netherlands	39.6	31.0	9.1	0.8	†	3.9	84.5	40.9	30.7	8.2	0.8	†	4.2	**84.8**
Norway	10.1	3.9	0.8	–	32.1	0.7	47.6	10.4	3.9	0.8	–	31.3	0.9	**47.4**
Poland	31.7	16.5	49.8	–	0.6	4.9	103.4	32.8	17.0	50.5	–	0.4	4.4	**105.2**
Portugal	12.0	5.5	3.2	–	1.3	3.8	25.8	11.5	5.0	2.7	–	2.8	3.9	**26.0**
Romania	10.3	9.6	5.4	2.6	3.3	2.2	33.4	10.2	9.3	5.3	2.6	4.0	2.0	**33.4**
Spain	65.0	27.3	13.4	13.1	4.2	15.7	138.8	66.6	27.1	11.1	12.6	8.0	16.0	**141.4**
Sweden	15.4	0.7	2.0	14.9	14.7	6.8	54.4	14.8	0.7	2.0	15.5	14.0	6.6	**53.6**
Switzerland	10.9	2.7	0.1	4.6	7.7	0.8	26.9	10.5	2.6	0.1	5.8	7.9	0.9	**27.8**
Turkey	49.2	44.3	39.5	–	13.2	6.6	152.7	48.6	40.7	42.3	–	13.5	8.5	**153.5**
Ukraine	9.9	26.0	25.7	19.4	2.0	0.4	83.4	9.6	26.3	26.2	19.1	2.2	0.6	**84.0**
United Kingdom	78.0	67.8	9.1	15.9	1.3	21.1	193.2	77.0	67.8	7.6	14.7	1.2	23.9	**192.3**
Other Europe	62.5	26.1	34.1	8.4	14.9	11.4	157.3	62.4	25.9	33.6	8.3	17.9	11.7	**159.8**
Total Europe	746.2	481.9	315.5	211.8	132.3	162.3	2050.0	742.0	472.0	307.1	212.1	145.3	172.2	**2050.7**
Azerbaijan	4.7	9.1	†	–	0.4	†	14.3	4.6	9.3	†	–	0.4	†	**14.4**
Belarus	6.7	15.7	0.8	–	0.1	0.1	23.4	6.8	16.6	1.0	–	0.1	0.1	**24.6**
Kazakhstan	15.0	13.7	36.4	–	2.5	0.1	67.6	16.4	16.7	40.8	–	2.3	0.1	**76.4**
Russian Federation	151.5	370.7	83.9	46.0	41.9	0.3	694.3	152.3	390.8	88.0	46.3	43.0	0.3	**720.7**
Turkmenistan	6.9	21.8	–	–	–	†	28.7	7.1	24.4	–	–	–	†	**31.5**
Uzbekistan	2.7	37.1	3.5	–	1.7	–	45.0	2.6	36.6	3.1	–	1.6	–	**43.9**
Other CIS	3.6	4.3	1.8	0.6	7.7	†	18.0	3.7	4.9	2.0	0.5	8.0	†	**19.0**
Total CIS	191.1	472.3	126.4	46.6	54.3	0.5	891.2	193.5	499.4	134.9	46.7	55.4	0.6	**930.5**
Iran	84.5	180.5	1.4	1.6	3.9	0.1	272.0	86.2	193.9	1.5	1.6	2.4	0.1	**285.7**
Iraq	35.6	11.0	–	–	0.5	†	47.1	38.4	14.7	–	–	0.7	†	**53.7**
Israel	11.7	8.5	5.0	–	†	0.4	25.6	11.5	9.0	4.7	–	†	0.5	**25.6**
Kuwait	20.4	18.1	0.2	–	–	†	38.7	20.0	18.7	0.2	–	–	†	**39.0**
Oman	9.2	20.0	0.1	–	–	†	29.3	9.2	21.4	0.1	–	–	†	**30.7**
Qatar	11.8	37.0	–	–	–	†	48.9	12.2	36.0	–	–	–	†	**48.3**
Saudi Arabia	168.8	93.9	0.1	–	–	†	262.8	162.6	96.4	0.1	–	–	†	**259.2**
United Arab Emirates	43.8	64.0	1.0	–	–	0.1	109.0	45.1	65.8	1.1	–	–	0.2	**112.2**
Other Middle East	26.6	20.1	0.4	–	0.3	0.5	48.0	26.8	19.5	0.4	–	0.3	0.8	**47.9**
Total Middle East	412.5	453.2	8.2	1.6	4.7	1.3	881.4	412.1	475.6	7.9	1.6	3.4	1.7	**902.3**
Algeria	19.4	33.4	0.2	–	†	0.1	53.1	19.6	36.7	0.2	–	†	0.1	**56.7**
Egypt	39.2	48.1	1.6	–	3.0	0.6	92.6	36.7	51.2	2.8	–	3.1	0.8	**94.5**
Morocco	13.5	1.0	4.5	–	0.3	0.8	20.0	13.2	0.9	5.4	–	0.4	1.1	**21.0**
South Africa	27.5	3.8	84.3	3.6	0.2	2.4	121.8	26.3	3.7	86.0	2.5	0.2	2.8	**121.5**
Other Africa	92.4	34.7	7.0	–	24.7	2.2	161.0	95.5	36.4	7.0	–	26.4	2.4	**167.8**
Total Africa	192.1	121.0	97.6	3.6	28.2	6.1	448.6	191.3	129.0	101.4	2.5	30.1	7.2	**461.5**
Australia	51.1	35.5	45.1	–	3.1	5.8	140.5	53.3	35.6	44.3	–	3.9	7.2	**144.3**
Bangladesh	7.9	22.9	1.9	–	0.2	0.1	33.0	9.0	24.4	2.1	–	0.2	0.1	**35.8**
China	610.7	206.7	1890.4	56.1	263.6	111.4	3139.0	641.2	243.3	1906.7	66.6	272.1	143.5	**3273.5**
China Hong Kong SAR	21.9	2.7	6.3	–	–	†	30.9	22.2	2.6	6.3	–	–	†	**31.1**
India	227.1	46.2	415.9	8.5	30.7	21.7	750.1	239.1	49.9	452.2	8.8	31.6	27.5	**809.2**
Indonesia	79.3	33.1	57.2	–	4.2	3.0	176.9	83.4	33.5	61.6	–	3.7	3.3	**185.5**
Japan	187.8	100.6	119.9	6.6	17.9	22.4	455.2	182.4	99.5	117.5	11.1	18.3	25.4	**454.1**
Malaysia	36.0	35.9	19.3	–	5.2	0.3	96.7	36.9	35.5	21.1	–	5.5	0.3	**99.3**
New Zealand	8.5	4.3	1.2	–	5.7	2.4	22.2	8.4	3.7	1.3	–	6.0	2.4	**21.7**
Pakistan	29.2	35.0	7.1	1.9	6.9	0.9	81.0	24.3	37.5	11.6	2.2	8.1	1.2	**85.0**
Philippines	21.7	3.2	15.5	–	2.2	3.1	45.7	22.0	3.5	16.3	–	2.1	3.2	**47.0**
Singapore	74.8	10.6	0.9	–	–	0.2	86.5	75.8	10.6	0.9	–	–	0.3	**87.6**
South Korea	130.0	42.8	86.2	33.6	0.6	4.0	297.1	128.9	48.1	88.2	30.2	0.7	5.0	**301.0**
Sri Lanka	5.4	–	1.4	–	0.9	0.1	7.8	5.3	–	1.2	–	1.4	0.1	**8.1**
Taiwan	50.1	20.0	39.4	5.1	1.2	1.2	117.0	50.0	20.3	39.3	6.3	1.0	1.5	**118.4**
Thailand	64.4	43.1	18.3	–	1.1	3.4	130.2	65.8	42.9	18.5	–	1.7	4.0	**133.0**
Vietnam	23.6	8.2	27.9	–	16.0	0.1	75.8	24.9	8.3	34.3	–	18.3	0.1	**85.8**
Other Asia Pacific	21.9	9.8	16.9	–	13.6	0.2	62.4	22.5	10.3	18.0	–	14.2	0.3	**65.4**
Total Asia Pacific	1651.3	660.6	2770.8	111.7	373.2	180.2	5748.0	1695.4	709.6	2841.3	125.3	388.9	225.4	**5985.8**
Total World	**4607.0**	**3141.9**	**3718.4**	**597.1**	**919.9**	**490.2**	**13474.6**	**4662.1**	**3309.4**	**3772.1**	**611.3**	**948.8**	**561.3**	**13864.9**
of which: OECD	2196.5	1435.2	892.9	443.4	314.6	304.3	5586.9	2204.8	1505.2	861.3	446.1	321.3	330.4	**5669.0**
Non-OECD	2410.5	1706.7	2825.6	153.7	605.3	185.9	7887.7	2457.3	1804.2	2910.8	165.2	627.5	230.8	**8195.9**
European Union	649.5	400.4	234.2	187.8	67.4	152.4	1691.8	646.8	394.2	222.4	187.2	78.0	159.6	**1688.2**

*In this review, primary energy comprises commercially-traded fuels, including modern renewables used to generate electricity.
†Less than 0.05.

Table A3. Global primary energy consumption per capita (Source: BP Statistical Review of World Energy 2019)

Primary energy: consumption per capita*

Gigajoules per capita	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Growth rate per annum 2018	2007-17
Canada	403.0	377.8	382.3	396.6	389.6	400.2	401.9	394.9	390.2	392.9	**390.2**	-0.7%	-0.4%
Mexico	62.9	61.5	62.3	64.4	63.8	63.2	62.1	61.2	61.2	61.4	**59.8**	-2.5%	-0.2%
US	311.7	293.9	301.6	296.7	287.1	293.0	294.2	289.6	287.5	286.8	**294.8**	2.8%	-1.2%
Total North America	255.7	241.2	246.6	244.6	237.2	241.5	241.9	237.8	235.8	235.3	**239.8**	1.9%	-1.1%
Argentina	77.4	75.2	78.4	79.1	80.6	83.2	81.9	83.0	82.0	81.4	**79.7**	-2.1%	0.6%
Brazil	52.1	51.3	56.0	58.1	58.7	60.5	61.4	60.2	58.4	58.8	**59.1**	0.5%	1.6%
Chile	80.8	78.5	78.1	84.2	85.4	85.6	83.4	84.7	88.1	88.8	**92.3**	3.8%	0.7%
Colombia	31.0	29.3	31.1	32.2	34.2	34.4	35.9	35.9	38.1	38.8	**39.7**	2.3%	3.0%
Ecuador	35.1	33.8	37.1	38.7	40.2	41.0	42.4	41.7	41.0	42.0	**43.8**	4.3%	2.3%
Peru	24.3	24.6	26.7	29.5	29.6	30.1	30.5	32.3	33.6	33.1	**34.7**	5.1%	3.8%
Trinidad & Tobago	505.0	508.2	551.8	551.6	521.8	534.6	517.8	521.1	473.0	466.2	**465.5**	-0.1%	-1.1%
Venezuela	125.9	123.6	114.9	118.5	121.8	117.3	111.9	106.6	95.8	96.4	**83.6**	-13.3%	-2.5%
Other S. & Cent. America	37.5	36.2	36.7	37.3	37.1	36.7	36.5	37.5	39.0	38.7	**39.3**	1.4%	0.1%
Total S. & Cent. America	53.6	52.4	54.7	56.5	57.2	57.9	57.9	57.5	56.6	56.7	**56.4**	-0.6%	0.8%
Austria	177.9	171.8	177.0	164.7	171.9	169.1	161.7	161.3	166.1	170.3	**167.4**	-1.7%	-0.3%
Belgium	263.0	244.4	258.5	239.6	229.3	233.7	217.1	219.3	235.4	234.8	**226.4**	-3.6%	-1.0%
Czech Republic	176.5	168.5	174.9	170.5	169.4	166.2	162.6	159.9	157.4	164.7	**166.0**	0.8%	-0.9%
Finland	247.5	229.2	248.7	230.8	223.1	224.2	215.7	213.8	218.7	212.9	**221.1**	3.8%	-1.9%
France	175.9	165.6	170.1	163.2	162.7	163.8	156.8	157.1	154.2	153.0	**155.7**	1.8%	-1.4%
Germany	173.2	162.9	169.7	163.5	165.5	169.9	162.6	165.3	167.7	170.2	**164.8**	-3.2%	◆
Greece	129.5	125.1	119.1	116.3	110.5	105.3	99.7	100.9	99.6	105.2	**106.4**	1.2%	-2.4%
Hungary	106.1	97.7	100.2	99.9	93.1	88.8	89.4	94.3	96.3	101.4	**102.5**	1.1%	-0.6%
Italy	127.4	118.7	122.3	119.5	116.2	111.0	105.2	107.7	109.0	110.2	**109.1**	-1.0%	-1.6%
Netherlands	237.0	232.8	245.6	234.3	226.0	218.7	206.0	208.0	211.1	207.7	**207.8**	0.1%	-1.5%
Norway	407.0	373.4	356.1	358.7	394.9	365.4	372.3	374.7	376.3	375.9	**370.6**	-1.4%	-0.6%
Poland	106.4	102.6	109.3	109.8	106.6	106.9	103.0	104.2	108.9	113.4	**115.5**	1.9%	0.8%
Portugal	95.8	96.4	101.4	97.1	89.2	98.4	99.8	99.6	105.7	104.4	**105.7**	1.2%	0.5%
Romania	77.6	68.5	69.7	72.1	69.8	65.5	68.6	69.0	69.5	71.0	**71.4**	0.6%	-0.8%
Spain	140.6	129.2	131.1	128.4	127.9	121.8	120.2	122.2	123.7	125.4	**127.6**	1.7%	-1.5%
Sweden	240.4	218.8	230.9	227.4	240.0	224.3	222.5	228.4	223.7	229.7	**224.8**	-2.1%	-0.7%
Switzerland	163.9	162.0	156.1	146.9	153.5	156.0	147.7	143.0	133.4	132.8	**136.3**	2.6%	-1.8%
Turkey	59.9	60.0	62.3	65.6	68.7	67.1	68.2	73.4	76.1	79.2	**78.5**	-0.9%	2.7%
Ukraine	121.0	103.3	111.1	116.1	113.7	108.9	96.3	80.3	84.6	78.9	**79.9**	1.3%	-4.2%
United Kingdom	148.4	139.8	141.9	132.7	133.5	132.2	124.0	124.9	123.1	122.2	**120.9**	-1.1%	-2.2%
Other Europe	108.1	102.6	106.5	104.4	100.2	101.9	98.8	101.3	104.1	105.9	**107.6**	1.6%	-0.1%
Total Europe	138.9	130.4	134.8	131.5	130.8	129.3	124.2	125.0	126.6	127.7	**127.4**	-0.2%	-0.9%
Azerbaijan	60.9	53.2	51.9	57.0	58.0	58.9	59.3	64.1	62.8	60.9	**60.7**	-0.3%	◆
Belarus	113.8	108.2	115.0	114.4	123.6	108.9	112.5	102.2	101.7	103.4	**108.8**	5.2%	-0.8%
Kazakhstan	147.7	131.5	140.2	152.1	155.1	154.5	154.3	150.1	150.6	155.5	**173.8**	11.8%	0.8%
Russian Federation	198.0	188.2	195.8	202.2	202.5	199.9	200.5	196.5	200.8	201.9	**209.6**	3.8%	0.3%
Turkmenistan	103.6	166.5	176.6	192.7	206.4	179.9	183.1	215.3	203.1	208.6	**225.4**	8.1%	5.0%
Uzbekistan	67.3	66.6	65.0	67.1	64.5	63.0	64.7	60.7	58.1	59.1	**56.8**	-3.8%	-2.1%
Other CIS	34.6	33.0	33.2	35.1	36.6	34.4	34.8	34.1	33.9	34.3	**35.9**	4.6%	-0.5%
Total CIS	154.0	147.1	152.3	157.7	158.4	154.8	155.3	152.2	153.8	154.8	**160.9**	3.9%	◆
Iran	118.3	120.9	119.8	124.8	123.9	128.6	132.9	131.5	134.1	140.3	**145.9**	4.0%	2.0%
Iraq	42.0	45.6	47.3	48.4	49.9	52.0	48.1	46.5	52.0	51.5	**57.2**	11.0%	2.2%
Israel	137.7	128.7	133.5	134.1	137.7	125.9	122.0	126.7	126.9	128.7	**127.0**	-1.3%	-0.8%
Kuwait	469.4	461.4	467.4	440.7	460.4	450.3	392.4	409.2	402.2	391.7	**388.5**	-0.8%	-1.5%
Oman	266.1	255.2	284.1	291.6	296.2	308.9	288.2	287.1	274.1	264.9	**266.0**	0.4%	1.2%
Qatar	740.8	653.7	680.1	717.2	753.2	759.7	773.5	813.8	775.0	775.1	**749.7**	-3.3%	-0.1%
Saudi Arabia	297.5	305.1	325.1	326.0	335.5	327.2	341.2	343.6	340.1	334.1	**323.4**	-3.2%	1.8%
United Arab Emirates	491.8	436.7	424.1	426.6	436.5	454.7	449.4	489.9	501.7	485.3	**492.3**	1.5%	-0.1%
Other Middle East	41.9	40.8	39.7	36.5	33.5	32.5	31.9	30.4	29.7	29.2	**28.7**	-1.8%	-3.5%
Total Middle East	132.3	132.8	136.5	138.8	141.1	142.7	144.3	146.2	147.2	147.5	**148.5**	0.7%	1.5%
Algeria	43.7	45.6	43.6	45.4	48.6	50.4	53.9	55.8	54.7	53.8	**56.5**	5.0%	2.5%
Egypt	37.1	37.9	39.0	38.8	39.9	38.8	37.8	38.1	39.4	39.8	**39.8**	0.2%	1.2%
Morocco	20.4	19.7	21.5	22.3	22.4	22.7	22.7	22.7	22.7	23.5	**24.3**	3.6%	2.3%
South Africa	104.1	102.7	102.5	99.8	97.0	95.9	95.8	92.3	92.6	89.9	**88.6**	-1.4%	-0.9%
Other Africa	6.1	6.0	6.2	6.0	6.2	6.3	6.5	6.5	6.4	6.6	**6.7**	1.4%	1.0%
Total Africa	15.3	15.2	15.3	15.0	15.1	15.1	15.2	15.1	15.0	15.0	**15.0**	0.3%	0.1%
Australia	259.5	253.0	249.7	254.0	247.0	244.7	245.2	244.9	246.7	240.6	**243.9**	1.4%	-0.8%
Bangladesh	5.3	5.7	5.9	6.3	6.7	6.8	7.1	8.1	8.2	8.4	**9.0**	7.5%	5.2%
China	69.5	72.2	76.7	82.4	85.2	88.0	89.6	90.2	90.9	93.2	**96.9**	3.9%	3.3%
China Hong Kong SAR	146.7	159.2	164.6	167.8	160.4	163.8	159.0	162.3	165.2	175.6	**175.1**	-0.2%	1.0%
India	16.7	17.7	18.3	19.2	19.9	20.5	21.6	22.1	22.7	23.5	**25.0**	6.7%	3.9%
Indonesia	23.5	24.1	26.1	28.1	29.2	29.6	27.4	26.9	27.3	28.1	**29.1**	3.8%	1.5%
Japan	168.6	154.1	164.4	156.1	155.1	154.1	150.4	148.3	147.7	149.5	**149.5**	◆	-1.3%
Malaysia	123.5	117.9	119.3	121.2	127.7	131.2	129.7	129.6	129.6	128.1	**129.7**	1.3%	0.5%
New Zealand	189.1	186.4	190.5	187.1	187.2	187.3	194.4	193.7	193.7	197.2	**191.6**	-2.8%	0.4%
Pakistan	16.0	15.8	15.6	15.3	15.1	14.9	15.1	15.6	16.6	17.2	**17.7**	3.0%	0.6%
Philippines	12.9	12.9	13.1	13.1	13.3	14.1	14.6	15.8	17.0	18.2	**18.5**	1.4%	3.7%
Singapore	512.1	538.0	565.8	576.7	568.7	574.8	582.6	609.7	624.3	634.3	**633.0**	-0.2%	2.5%
South Korea	205.4	205.7	220.8	230.1	231.6	230.9	232.3	236.1	240.9	244.0	**246.3**	1.0%	1.9%
Sri Lanka	10.7	11.0	11.7	12.2	12.3	12.5	11.2	14.2	15.0	15.7	**16.2**	2.9%	3.2%
Taiwan	194.6	190.5	201.1	197.4	196.3	199.2	203.4	201.3	204.4	207.4	**209.2**	0.9%	◆
Thailand	59.9	61.7	65.3	67.5	71.9	72.7	74.4	76.1	77.4	79.0	**80.5**	1.9%	2.9%
Vietnam	18.6	18.8	21.1	23.9	24.7	26.2	28.3	30.9	32.7	33.2	**37.2**	12.0%	8.2%
Other Asia Pacific	11.9	10.7	11.4	11.2	11.8	11.7	12.5	12.6	13.9	14.1	**14.6**	3.5%	2.1%
Total Asia Pacific	47.8	48.4	51.0	53.2	54.4	55.5	56.2	56.6	57.2	58.3	**60.2**	3.3%	2.2%
Total World	**72.2**	**70.3**	**72.8**	**73.7**	**73.8**	**74.4**	**74.2**	**74.0**	**74.2**	**74.7**	**76.0**	**1.8%**	**0.3%**
of which: OECD	192.8	182.2	187.9	184.9	182.0	182.9	180.6	180.0	180.1	181.0	**182.6**	0.9%	-0.8%
Non-OECD	45.6	45.8	47.8	49.7	50.7	51.3	51.8	51.8	52.1	52.8	**54.2**	2.7%	1.7%
European Union	152.0	142.9	147.7	142.6	141.2	140.1	134.8	136.4	137.6	139.2	**138.7**	-0.4%	-1.0%

*Primary energy comprises commercially-traded fuels, including modern renewables used to generate electricity.
◆Less than 0.05%.

31 APPENDIX B - GLOBAL ELECTRICITY GENERATION

Table B1. Global electricity generation (Terawatt-hours) (Source: BP Statistical Review of World Energy 2019)

Terawatt-hours	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Growth rate per annum 2018	Growth rate per annum 2007-17	Share 2018
Canada	638.4	614.0	606.9	638.3	636.5	662.5	660.5	663.7	663.9	662.7	**654.4**	-1.3%	0.4%	2.5%
Mexico	269.3	267.8	275.6	292.1	296.4	297.1	303.3	310.3	320.3	329.1	**332.1**	0.9%	2.3%	1.2%
US	4390.1	4206.5	4394.3	4363.4	4310.6	4330.3	4363.3	4348.7	4347.9	4302.5	**4460.8**	3.7%	-0.3%	16.8%
Total North America	5297.8	5088.3	5276.7	5293.8	5243.5	5289.9	5327.1	5322.7	5332.1	5294.4	**5447.3**	2.9%	-0.1%	20.5%
Argentina	121.9	122.3	126.0	129.5	136.0	139.4	138.6	145.4	147.2	145.6	**146.6**	0.7%	2.5%	0.6%
Brazil	462.9	466.2	515.8	531.8	552.5	570.8	590.5	581.2	578.9	588.0	**588.0**	♦	2.8%	2.2%
Chile	59.7	59.7	61.3	65.2	69.7	73.0	71.6	74.5	77.7	78.6	**80.2**	2.0%	3.0%	0.3%
Colombia	61.4	63.2	64.7	66.2	67.7	69.8	72.7	75.0	74.4	75.1	**77.4**	3.0%	2.2%	0.3%
Ecuador	18.6	18.3	19.5	20.5	22.8	23.3	24.3	26.0	27.3	28.0	**29.4**	4.8%	4.9%	0.1%
Peru	32.5	32.9	35.9	38.8	41.0	43.3	45.5	48.3	51.7	52.7	**54.0**	2.5%	5.8%	0.2%
Trinidad & Tobago	7.7	7.8	8.5	8.8	9.1	9.5	9.9	10.3	10.7	10.2	**10.3**	1.2%	2.9%	♦
Venezuela	119.3	124.8	116.7	122.9	127.9	130.0	128.3	123.8	113.8	117.3	**99.2**	-15.4%	0.3%	0.4%
Other S. & Cent. America	186.7	186.7	191.0	196.4	203.6	207.5	205.0	211.4	222.9	216.1	**220.1**	1.8%	1.5%	0.8%
Total S. & Cent. America	1070.7	1082.0	1139.5	1180.1	1230.4	1266.7	1286.5	1295.9	1304.8	1311.6	**1305.3**	-0.5%	2.4%	4.9%
Austria	66.9	69.1	71.1	65.9	72.4	68.0	65.1	64.9	67.9	70.8	**68.2**	-3.7%	0.9%	0.3%
Belgium	84.9	91.2	95.2	90.2	82.9	83.5	72.7	69.8	85.7	86.5	**74.6**	-13.7%	-0.3%	0.3%
Czech Republic	83.5	82.3	85.9	87.6	87.6	87.1	86.0	83.9	83.3	87.0	**88.0**	1.1%	-0.1%	0.3%
Finland	77.8	72.5	81.1	73.7	70.5	71.4	68.2	68.8	68.8	67.1	**69.6**	3.7%	-1.9%	0.3%
France	573.8	535.9	569.3	565.0	564.5	573.8	564.2	570.3	556.2	554.1	**574.2**	3.6%	-0.3%	2.2%
Germany	640.7	595.6	633.1	613.1	630.1	638.7	627.8	648.1	650.7	653.7	**648.7**	-0.8%	0.2%	2.4%
Greece	63.7	61.4	57.4	59.4	61.0	57.2	50.5	51.9	54.4	55.3	**54.2**	-2.0%	-1.4%	0.2%
Hungary	40.0	35.9	37.4	36.0	34.6	30.3	29.4	30.4	31.9	32.9	**32.0**	-2.7%	-1.9%	0.1%
Italy	319.1	292.6	302.1	302.6	299.3	289.8	279.8	283.0	289.8	295.8	**290.6**	-1.8%	-0.6%	1.1%
Netherlands	108.2	113.5	118.1	113.0	102.5	100.9	103.4	110.1	115.2	117.3	**117.5**	0.2%	1.1%	0.4%
Norway	142.1	131.8	123.6	127.6	147.7	134.0	142.0	144.5	149.0	149.4	**147.0**	-1.6%	0.9%	0.6%
Poland	155.3	151.7	157.7	163.5	162.1	164.6	159.1	164.9	166.6	170.5	**170.1**	-0.2%	0.7%	0.6%
Portugal	46.0	50.2	54.1	52.5	46.6	51.7	52.8	52.4	60.3	59.4	**59.9**	0.8%	2.3%	0.2%
Romania	65.0	58.0	61.0	62.2	59.0	58.9	63.3	66.3	65.1	64.3	**65.2**	1.4%	0.4%	0.2%
Spain	313.8	296.3	300.4	291.8	297.6	285.3	278.8	281.0	274.6	275.6	**275.0**	-0.2%	-1.0%	1.0%
Sweden	149.7	136.7	148.3	151.2	166.3	153.2	153.7	162.1	156.1	164.3	**163.5**	-0.4%	1.0%	0.6%
Switzerland	68.7	68.3	68.0	64.8	70.0	70.4	72.0	67.9	63.3	63.3	**69.8**	10.3%	-0.7%	0.3%
Turkey	198.4	194.8	211.2	229.4	239.5	240.2	252.0	261.8	274.4	297.3	**302.5**	1.8%	4.5%	1.1%
Ukraine	192.6	173.6	188.8	194.9	198.9	194.4	182.8	163.7	164.6	155.4	**159.4**	2.5%	-2.3%	0.6%
United Kingdom	388.9	376.8	382.1	368.0	363.9	358.3	338.1	338.9	339.3	338.6	**333.9**	-1.4%	-1.6%	1.3%
Other Europe	309.3	306.4	320.0	307.1	295.3	309.0	297.0	298.1	305.7	303.3	**313.4**	3.3%	0.2%	1.2%
Total Europe	4088.5	3894.7	4065.7	4019.4	4052.3	4020.4	3938.4	3982.8	4023.0	4061.8	**4077.3**	0.4%	♦	15.3%
Azerbaijan	21.6	18.9	18.7	20.3	23.0	23.4	24.7	24.7	25.0	24.3	**25.2**	3.6%	1.1%	0.1%
Belarus	35.1	30.4	34.9	32.2	30.8	31.5	34.7	34.2	33.6	34.5	**38.8**	12.4%	0.8%	0.1%
Kazakhstan	80.3	78.7	82.6	86.6	90.6	92.6	94.6	91.6	94.6	103.1	**107.1**	3.8%	3.0%	0.4%
Russian Federation	1040.0	993.1	1038.0	1054.9	1069.3	1059.1	1064.2	1067.5	1091.0	1089.6	**1110.8**	1.9%	0.7%	4.2%
Turkmenistan	15.0	16.0	16.7	17.2	17.8	18.9	20.1	21.5	22.6	22.8	**24.2**	6.1%	4.4%	0.1%
Uzbekistan	50.2	50.1	51.9	52.8	53.0	54.9	55.4	57.3	58.3	60.3	**62.4**	3.6%	2.1%	0.2%
Other CIS	39.7	39.1	41.1	44.6	46.0	43.3	44.1	44.0	43.5	47.1	**48.9**	3.9%	0.6%	0.2%
Total CIS	1282.0	1226.2	1284.0	1308.5	1330.4	1323.7	1337.9	1340.9	1368.5	1381.7	**1417.4**	2.6%	0.9%	5.3%
Iran	210.5	221.8	235.7	235.6	248.8	258.9	275.6	280.2	286.1	305.2	**310.8**	1.8%	4.2%	1.2%
Iraq	35.3	41.3	41.7	42.2	47.8	62.1	71.2	75.3	86.3	93.3	**103.3**	10.8%	11.2%	0.4%
Israel	55.8	55.3	58.5	59.3	63.0	61.4	61.3	64.3	67.3	67.7	**69.6**	2.9%	2.1%	0.3%
Kuwait	51.7	53.2	57.1	57.5	62.7	61.0	65.1	68.3	70.2	72.9	**74.2**	1.8%	4.1%	0.3%
Oman	16.0	18.4	19.8	21.9	25.0	26.2	29.1	32.8	34.2	36.1	**37.3**	3.2%	9.6%	0.1%
Qatar	21.6	24.2	28.1	30.7	34.8	34.7	38.7	41.5	42.3	43.8	**39.5**	-10.0%	8.5%	0.1%
Saudi Arabia	216.4	229.2	251.4	262.2	284.7	299.3	333.7	359.7	370.4	382.1	**383.8**	0.4%	6.5%	1.4%
United Arab Emirates	80.5	85.7	93.9	99.1	106.2	110.0	116.5	127.4	129.6	134.6	**136.9**	1.8%	5.5%	0.5%
Other Middle East	87.1	90.7	98.7	93.4	88.3	83.7	81.8	79.3	79.2	83.7	**84.9**	1.4%	0.3%	0.3%
Total Middle East	775.0	819.8	885.0	901.9	961.2	997.2	1073.2	1128.7	1165.7	1219.3	**1240.4**	1.7%	5.2%	4.7%
Algeria	40.2	43.1	45.7	53.1	57.4	59.9	64.2	68.8	71.0	76.0	**76.4**	0.5%	7.4%	0.3%
Egypt	128.8	134.3	144.4	149.6	162.8	165.1	171.2	181.8	188.2	193.2	**200.0**	3.5%	4.9%	0.8%
Morocco	21.0	21.7	23.7	25.4	27.7	28.1	29.3	30.3	30.7	31.6	**34.4**	8.9%	4.5%	0.1%
South Africa	258.3	249.6	259.6	262.5	257.9	256.1	254.8	250.1	252.7	255.1	**256.0**	0.4%	-0.3%	1.0%
Other Africa	174.6	180.8	198.2	198.6	214.9	234.3	248.3	255.7	258.5	273.7	**286.9**	4.8%	4.9%	1.1%
Total Africa	622.9	629.4	671.7	689.1	720.7	743.5	767.8	786.8	801.2	829.6	**853.7**	2.9%	3.1%	3.2%
Australia	245.4	249.9	251.0	256.3	250.7	249.6	247.6	254.3	258.5	259.0	**261.4**	0.9%	0.6%	1.0%
Bangladesh	34.2	37.2	40.8	44.2	48.7	54.4	57.4	61.8	70.0	74.4	**79.1**	6.3%	9.1%	0.3%
China	3495.8	3714.7	4207.2	4713.0	4987.6	5431.6	5649.6	5814.6	6133.2	6604.5	**7111.8**	7.7%	7.2%	26.7%
China Hong Kong SAR	38.0	38.7	38.4	39.1	38.8	39.2	39.9	38.0	38.3	37.1	**36.7**	-1.2%	-0.5%	0.1%
India	828.4	879.7	937.5	1034.0	1091.8	1146.1	1262.2	1317.3	1401.7	1470.3	**1561.1**	6.2%	6.3%	5.9%
Indonesia	149.4	156.8	169.8	183.4	200.3	216.2	228.6	234.0	247.9	254.6	**267.3**	5.0%	6.0%	1.0%
Japan	1183.7	1114.0	1156.0	1104.2	1106.9	1087.8	1062.7	1030.1	1042.1	1050.1	**1051.6**	0.1%	-1.2%	4.0%
Malaysia	106.9	111.3	120.1	120.9	127.3	137.5	143.2	147.2	158.8	162.3	**168.4**	3.8%	4.6%	0.6%
New Zealand	43.8	43.4	44.9	44.4	44.2	43.3	43.5	44.2	43.6	44.2	**44.3**	0.2%	0.1%	0.2%
Pakistan	96.2	97.1	100.0	99.9	99.0	102.2	107.3	110.5	122.9	126.6	**140.6**	11.1%	2.6%	0.5%
Philippines	60.8	61.9	67.7	69.2	72.9	75.3	77.3	82.4	90.8	94.4	**99.8**	5.7%	4.7%	0.4%
Singapore	41.7	41.8	45.4	46.0	46.9	48.0	49.3	50.3	51.6	52.2	**52.9**	1.3%	2.4%	0.2%
South Korea	442.6	452.4	495.0	517.6	531.2	537.2	540.4	547.8	561.0	576.4	**594.3**	3.1%	3.1%	2.2%
Sri Lanka	10.0	10.0	10.8	11.6	11.9	12.0	12.9	13.2	14.4	14.9	**15.5**	4.0%	4.2%	0.1%
Taiwan	238.3	230.0	247.1	252.2	250.4	252.4	260.0	258.2	264.1	270.3	**273.6**	1.2%	1.1%	1.0%
Thailand	145.4	145.9	157.6	153.3	169.0	168.6	173.8	177.8	179.8	176.7	**177.6**	0.5%	2.2%	0.7%
Vietnam	71.0	80.6	91.7	101.5	115.1	124.5	141.3	157.9	175.7	192.5	**212.9**	10.6%	11.6%	0.8%
Other Asia Pacific	64.7	63.5	70.8	75.0	76.5	82.8	86.8	89.5	107.3	117.7	**124.7**	6.0%	6.7%	0.5%
Total Asia Pacific	7296.4	7529.0	8251.7	8865.8	9269.3	9808.4	10183.7	10429.1	10961.7	11578.2	**12273.6**	6.0%	5.2%	46.1%
Total World	**20433.3**	**20269.3**	**21574.3**	**22258.7**	**22807.8**	**23449.8**	**23914.6**	**24286.9**	**24956.9**	**25676.6**	**26614.8**	**3.7%**	**2.5%**	**100.0%**
of which: OECD	10999.0	10561.9	10992.3	10942.8	10950.2	10946.2	10891.4	10929.8	11013.7	11057.2	**11233.6**	1.6%	0.1%	42.2%
Non-OECD	9434.3	9707.4	10582.0	11315.9	11857.6	12503.6	13023.2	13357.1	13943.2	14619.4	**15381.2**	5.2%	4.9%	57.8%
European Union	3388.7	3224.4	3364.7	3299.2	3295.4	3269.6	3188.5	3236.7	3259.5	3290.4	**3282.2**	-0.2%	-0.3%	12.3%

*Based on gross output.
♦Less than 0.05%.

Table B2. Global electricity generation by fuel (Source: BP Statistical Review of World Energy 2019)

	2017								2018							
Terawatt-hours	Oil	Natural Gas	Coal	Nuclear energy	Hydro electric	Renew-ables	Other‡	Total	Oil	Natural Gas	Coal	Nuclear energy	Hydro electric	Renew-ables	Other‡	**Total**
Canada	3.2	59.6	60.1	100.4	396.5	42.1	0.8	662.7	3.2	58.7	59.3	100.0	387.3	45.3	0.6	**654.4**
Mexico	38.9	196.3	30.9	10.9	31.8	19.1	1.1	329.1	36.8	196.7	29.2	13.6	32.4	21.4	2.2	**332.1**
US	23.0	1394.0	1310.0	847.3	296.8	417.8	13.7	4302.5	26.4	1578.5	1245.8	849.6	288.7	458.5	13.3	**4460.8**
Total North America	65.1	1649.9	1401.0	958.6	725.2	479.0	15.6	5294.4	66.3	1833.9	1334.3	963.2	708.4	525.2	16.0	**5447.3**
Argentina	11.6	80.8	2.0	6.1	41.5	3.0	0.5	145.6	6.4	85.3	2.0	6.9	41.6	3.8	0.5	**146.6**
Brazil	15.5	65.6	25.8	15.7	370.9	94.5	–	588.0	11.5	46.8	21.9	15.6	387.7	104.5	–	**588.0**
Other S. & C. America	80.4	98.0	49.7	–	308.0	41.9	0.1	578.0	72.2	95.8	52.6	–	302.0	48.0	†	**570.6**
Total S. & C. America	107.5	244.3	77.5	21.8	720.4	139.4	0.6	1311.6	90.2	227.9	76.5	22.5	731.3	156.3	0.5	**1305.3**
Germany	5.6	86.7	241.9	76.3	20.2	196.2	26.7	653.7	5.2	83.0	229.0	76.1	16.9	209.2	29.3	**648.7**
Italy	11.5	140.3	35.1	–	34.4	67.7	6.8	295.8	10.9	127.2	36.6	–	45.9	66.0	4.1	**290.6**
Netherlands	1.2	57.9	31.3	3.4	0.1	17.4	6.1	117.3	0.6	57.3	30.0	3.5	0.1	18.6	7.4	**117.5**
Poland	2.0	10.0	133.8	–	2.6	21.6	0.5	170.5	1.2	12.4	134.7	–	2.0	19.5	0.4	**170.1**
Spain	15.8	64.0	46.3	58.1	18.8	69.5	3.1	275.6	15.6	57.2	38.4	55.6	35.2	70.7	2.3	**275.0**
Turkey	1.2	110.5	97.5	–	58.2	29.0	0.8	297.3	0.6	92.2	111.7	–	59.5	37.7	0.8	**302.5**
Ukraine	1.4	9.1	46.7	85.6	8.7	1.9	1.9	155.4	0.5	12.1	47.7	84.4	9.9	2.6	2.2	**159.4**
United Kingdom	1.6	136.8	22.5	70.3	5.9	93.4	8.0	338.6	1.7	131.5	16.8	65.1	5.5	105.6	7.8	**333.9**
Other Europe	21.6	172.0	233.3	642.4	436.1	220.4	31.9	1757.6	19.8	158.5	217.8	652.8	467.2	231.1	32.3	**1779.5**
Total Europe	61.9	787.5	888.5	936.1	584.9	717.1	85.8	4061.8	56.0	731.3	862.7	937.5	642.1	761.1	86.6	**4077.3**
Kazakhstan	1.9	19.8	69.9	–	11.2	0.4	–	103.1	1.7	24.2	70.2	–	10.3	0.7	–	**107.1**
Russian Federation	10.7	515.9	168.9	203.1	185.3	1.1	4.4	1089.6	11.4	521.5	177.5	204.5	190.2	1.3	4.4	**1110.8**
Other CIS	1.8	127.5	12.7	2.6	43.6	0.5	0.3	189.0	0.5	140.4	11.3	2.1	44.3	0.6	0.3	**199.5**
Total CIS	14.4	663.2	251.4	205.8	240.1	2.0	4.7	1381.7	13.7	686.1	259.0	206.6	244.8	2.5	4.7	**1417.4**
Iran	28.9	251.2	0.5	7.1	17.2	0.3	–	305.2	23.0	269.1	0.5	7.0	10.8	0.4	–	**310.8**
Saudi Arabia	156.9	225.1	–	–	–	0.1	–	382.1	150.6	233.0	–	–	–	0.2	–	**383.8**
United Arab Emirates	1.6	132.4	–	–	–	0.5	–	134.6	1.6	134.4	–	–	–	1.0	–	**136.9**
Other Middle East	134.8	232.3	22.3	–	3.6	4.5	†	397.5	135.7	241.9	20.8	–	4.4	5.9	0.1	**408.9**
Total Middle East	322.1	841.0	22.8	7.1	20.8	5.5	†	1219.3	310.9	878.5	21.3	7.0	15.2	7.4	0.1	**1240.4**
Egypt	27.7	149.4	–	–	13.4	2.7	–	193.2	22.1	160.9	–	–	13.5	3.5	–	**200.0**
South Africa	0.1	1.9	221.4	15.8	0.9	10.6	4.5	255.1	0.1	1.9	225.0	11.1	0.9	12.4	4.7	**256.0**
Other Africa	56.0	173.6	27.4	–	110.3	13.6	0.4	381.3	55.3	176.6	31.0	–	118.4	16.0	0.4	**397.7**
Total Africa	83.8	324.9	248.8	15.8	124.6	26.9	4.9	829.6	77.6	339.3	255.9	11.1	132.8	31.9	5.1	**853.7**
Australia	5.3	55.2	159.1	–	13.5	25.7	0.2	259.0	5.3	50.2	156.6	–	17.3	31.9	0.2	**261.4**
China	10.7	202.8	4445.5	248.1	1165.1	492.4	39.8	6604.5	10.7	223.6	4732.4	294.4	1202.4	634.2	14.0	**7111.8**
India	10.1	73.5	1117.6	37.4	135.7	95.8	0.3	1470.3	10.1	74.3	1176.3	39.1	139.7	121.5	0.2	**1561.1**
Indonesia	18.9	55.7	148.0	–	18.6	13.4	–	254.6	20.2	59.6	156.4	–	16.4	14.8	–	**267.3**
Japan	65.7	401.5	361.8	29.1	79.2	98.8	14.0	1050.1	60.0	386.9	347.2	49.1	81.0	112.1	15.3	**1051.6**
Malaysia	5.0	65.1	67.7	–	23.1	1.3	†	162.3	2.3	66.4	74.1	–	24.2	1.5	†	**168.4**
South Korea	13.1	128.0	261.7	148.4	2.8	17.6	4.8	576.4	9.1	160.4	261.3	133.5	2.9	21.9	5.1	**594.3**
Taiwan	12.8	93.4	125.9	22.4	5.4	5.3	5.0	270.3	8.4	94.8	126.6	27.7	4.5	6.4	5.2	**273.6**
Thailand	0.3	121.0	35.7	–	4.7	14.9	–	176.7	0.2	116.3	35.8	–	7.6	17.8	–	**177.6**
Vietnam	0.7	44.4	76.1	–	70.9	0.3	–	192.5	0.7	44.3	86.7	–	80.7	0.5	–	**212.9**
Other Asia Pacific	72.4	201.6	116.9	8.4	130.4	31.1	0.8	561.5	61.0	209.0	137.5	9.9	141.9	33.4	0.9	**593.6**
Total Asia Pacific	215.1	1442.1	6916.2	493.8	1649.4	796.6	65.0	11578.2	188.0	1485.8	7290.8	553.6	1718.5	996.0	40.9	**12273.6**
Total World	**870.0**	**5952.8**	**9806.2**	**2639.0**	**4065.4**	**2166.5**	**176.7**	**25676.6**	**802.8**	**6182.8**	**10100.5**	**2701.4**	**4193.1**	**2480.4**	**153.8**	**26614.8**
of which: OECD	202.9	3053.8	2989.8	1959.6	1390.4	1344.8	115.8	11057.2	188.2	3194.0	2881.1	1971.4	1419.8	1460.3	118.9	**11233.6**
Non-OECD	667.1	2899.0	6816.3	679.4	2675.1	821.7	60.9	14619.4	614.6	2988.8	7219.4	730.1	2773.3	1020.1	34.9	**15381.2**
EU	56.9	660.6	694.8	830.0	298.0	673.5	76.6	3290.4	52.5	619.7	655.2	827.4	344.8	705.5	77.1	**3282.2**

*Based on gross output.
‡Includes sources not specified elsewhere e.g. pumped hydro, non-renewable waste and statistical discrepancies.
†Less than 0.05.

32 APPENDIX C – OIL RESERVES, CONSUMPTION AND PRODUCTION

Table C1. Global total proved oil reserves (Billion tonnes) (Source: BP Statistical Review of World Energy 2019)

Total proved reserves

	At end 1998	At end 2008	At end 2017	At end 2018			
	Thousand million barrels	Thousand million barrels	Thousand million barrels	Thousand million barrels	Thousand million tonnes	Share of total	R/P ratio
Canada	49.8	176.3	168.9	**167.8**	**27.1**	9.7%	88.3
Mexico	21.6	11.9	7.7	**7.7**	**1.1**	0.4%	10.2
US	28.6	28.4	61.2	**61.2**	**7.3**	3.5%	11.0
Total North America	100.0	216.6	237.8	**236.7**	**35.4**	13.7%	28.7
Argentina	2.8	2.5	2.0	**2.0**	**0.3**	0.1%	9.3
Brazil	7.4	12.8	12.8	**13.4**	**2.0**	0.8%	13.7
Colombia	2.5	1.4	1.7	**1.8**	**0.3**	0.1%	5.6
Ecuador	4.1	4.3	3.0	**2.8**	**0.4**	0.2%	14.8
Peru	0.9	1.1	1.0	**1.0**	**0.1**	0.1%	17.6
Trinidad & Tobago	0.7	0.8	0.2	**0.2**	**†**	◆	7.6
Venezuela	76.1	172.3	302.8	**303.3**	**48.0**	17.5%	*
Other S. & Cent. America	1.1	0.8	0.5	**0.5**	**0.1**	◆	11.5
Total S. & Cent. America	95.6	196.0	324.0	**325.1**	**51.1**	18.8%	136.2
Denmark	0.9	0.8	0.4	**0.4**	**0.1**	◆	10.1
Italy	0.6	0.5	0.6	**0.6**	**0.1**	◆	16.2
Norway	11.7	7.5	7.9	**8.6**	**1.1**	0.5%	12.8
Romania	1.2	0.5	0.6	**0.6**	**0.1**	◆	22.2
United Kingdom	5.1	3.1	2.5	**2.5**	**0.3**	0.1%	6.3
Other Europe	1.9	1.9	1.6	**1.6**	**0.2**	0.1%	14.1
Total Europe	21.4	14.2	13.7	**14.3**	**1.9**	0.8%	11.1
Azerbaijan	1.2	7.0	7.0	**7.0**	**1.0**	0.4%	24.1
Kazakhstan	5.4	30.0	30.0	**30.0**	**3.9**	1.7%	42.7
Russian Federation	113.1	106.4	106.3	**106.2**	**14.6**	6.1%	25.4
Turkmenistan	0.5	0.6	0.6	**0.6**	**0.1**	◆	7.4
Uzbekistan	0.6	0.6	0.6	**0.6**	**0.1**	◆	25.4
Other CIS	0.3	0.3	0.3	**0.3**	**†**	◆	18.1
Total CIS	121.1	144.8	144.7	**144.7**	**19.6**	8.4%	27.4
Iran	93.7	137.6	155.6	**155.6**	**21.4**	9.0%	90.4
Iraq	112.5	115.0	147.2	**147.2**	**19.9**	8.5%	87.4
Kuwait	96.5	101.5	101.5	**101.5**	**14.0**	5.9%	91.2
Oman	5.4	5.6	5.4	**5.4**	**0.7**	0.3%	15.0
Qatar	13.5	26.8	25.2	**25.2**	**2.6**	1.5%	36.8
Saudi Arabia	261.5	264.1	296.0	**297.7**	**40.9**	17.2%	66.4
Syria	2.3	2.5	2.5	**2.5**	**0.3**	0.1%	284.8
United Arab Emirates	97.8	97.8	97.8	**97.8**	**13.0**	5.7%	68.0
Yemen	1.9	2.7	3.0	**3.0**	**0.4**	0.2%	121.4
Other Middle East	0.2	0.1	0.1	**0.2**	**†**	◆	2.1
Total Middle East	685.2	753.7	834.3	**836.1**	**113.2**	48.3%	72.1
Algeria	11.3	12.2	12.2	**12.2**	**1.5**	0.7%	22.1
Angola	4.0	9.5	8.4	**8.4**	**1.1**	0.5%	15.0
Chad	–	1.5	1.5	**1.5**	**0.2**	0.1%	40.9
Republic of Congo	1.7	1.6	1.6	**1.6**	**0.2**	0.1%	13.2
Egypt	3.8	4.2	3.3	**3.3**	**0.4**	0.2%	13.6
Equatorial Guinea	0.6	1.7	1.1	**1.1**	**0.1**	0.1%	15.8
Gabon	2.6	2.0	2.0	**2.0**	**0.3**	0.1%	28.2
Libya	29.5	44.3	48.4	**48.4**	**6.3**	2.8%	131.3
Nigeria	22.5	37.2	37.5	**37.5**	**5.1**	2.2%	50.0
South Sudan	n/a	n/a	3.5	**3.5**	**0.5**	0.2%	73.4
Sudan	0.3	5.0	1.5	**1.5**	**0.2**	0.1%	41.1
Tunisia	0.3	0.6	0.4	**0.4**	**0.1**	◆	23.2
Other Africa	0.7	0.7	3.9	**3.9**	**0.5**	0.2%	33.7
Total Africa	77.2	120.4	125.3	**125.3**	**16.6**	7.2%	41.9
Australia	4.8	4.2	4.0	**4.0**	**0.4**	0.2%	30.8
Brunei	1.0	1.1	1.1	**1.1**	**0.1**	0.1%	27.0
China	17.4	21.2	25.9	**25.9**	**3.5**	1.5%	18.7
India	5.4	5.8	4.5	**4.5**	**0.6**	0.3%	14.1
Indonesia	5.1	3.7	3.2	**3.2**	**0.4**	0.2%	10.7
Malaysia	3.4	5.5	3.0	**3.0**	**0.4**	0.2%	12.1
Thailand	0.4	0.5	0.3	**0.3**	**†**	◆	1.8
Vietnam	1.9	4.7	4.4	**4.4**	**0.6**	0.3%	43.9
Other Asia Pacific	1.3	1.3	1.2	**1.2**	**0.2**	0.1%	12.9
Total Asia Pacific	40.8	48.0	47.7	**47.6**	**6.3**	2.8%	17.1
Total World	**1141.2**	**1493.8**	**1727.5**	**1729.7**	**244.1**	**100.0%**	**50.0**
of which: OECD	124.5	234.0	254.4	**254.0**	**37.6**	14.7%	26.4
Non-OECD	1016.7	1259.8	1473.1	**1475.8**	**206.6**	85.3%	59.1
OPEC	827.9	1027.9	1240.2	**1242.2**	**174.8**	71.8%	86.5
Non-OPEC	313.3	465.9	487.3	**487.5**	**69.4**	28.2%	24.1
European Union	8.7	5.7	4.9	**4.8**	**0.6**	0.3%	8.6
Canadian oil sands: Total	43.1	170.3	163.4	**162.3**	**26.4**	9.4%	
of which: Under active development	8.4	27.0	22.0	**20.9**	**3.4**	1.2%	
Venezuela: Orinoco Belt	–	94.2	260.9	**261.4**	**41.9**	15.1%	

†Less than 0.05.
◆Less than 0.05%.
n/a not available.
*More than 500 years.

Notes: Total proved reserves of oil – Generally taken to be those quantities that geological and engineering information indicates with reasonable certainty can be recovered in the future from known reservoirs under existing economic and operating conditions. The data series for total proved oil reserves does not necessarily meet the definitions, guidelines and practices used for determining proved reserves at company level, for instance as published by the US Securities and Exchange Commission, nor does it necessarily represent BP's view of proved reserves by country.
Reserves-to-production (R/P) ratio – If the reserves remaining at the end of any year are divided by the production in that year, the result is the length of time that those remaining reserves would last if production were to continue at that rate.
Source of data – The estimates in this table have been compiled using a combination of primary official sources, third-party data from the OPEC Secretariat, World Oil, Oil & Gas Journal and Chinese reserves based on official data and information in the public domain.
Canadian oil sands 'under active development' are an official estimate. Venezuelan Orinoco Belt reserves are based on the OPEC Secretariat and government announcements.
Reserves include gas condensate and natural gas liquids (NGLs) as well as crude oil. Saudi Arabia's oil reserves include NGLs from 2017.
Shares of total and R/P ratios are calculated using thousand million barrels figures.

Table C2. Global oil production (thousands of barrels a day) (Source: BP Statistical Review of World Energy 2019)

Oil: Production in thousands of barrels per day*

												Growth rate per annum		Share
Thousand barrels daily	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	**2018**	2018	2007-17	2018
Canada	3207	3202	3332	3515	3740	4000	4271	4388	4451	4798	**5208**	8.5%	3.8%	5.5%
Mexico	3165	2978	2959	2940	2911	2875	2784	2587	2456	2224	**2068**	-7.0%	-4.4%	2.2%
US	6783	7259	7552	7870	8910	10073	11773	12773	12340	13135	**15311**	16.6%	6.7%	16.2%
Total North America	13156	13440	13843	14326	15561	16948	18828	19748	19247	20157	**22587**	12.1%	4.0%	23.8%
Argentina	802	730	712	667	657	645	638	647	610	591	**592**	0.2%	-3.2%	0.6%
Brazil	1887	2019	2125	2173	2132	2096	2341	2525	2591	2721	**2683**	-1.4%	4.1%	2.8%
Colombia	588	671	786	915	944	1010	990	1006	886	854	**866**	1.4%	4.9%	0.9%
Ecuador	507	488	488	501	505	527	557	543	548	531	**517**	-2.7%	0.3%	0.5%
Peru	122	155	165	159	157	171	175	153	141	137	**154**	12.4%	1.6%	0.2%
Trinidad & Tobago	149	150	145	136	117	116	114	109	97	99	**87**	-11.5%	-4.4%	0.1%
Venezuela	3228	3038	2842	2755	2704	2680	2692	2631	2347	2096	**1514**	-27.8%	-4.3%	1.6%
Other S. & Cent. America	143	136	144	144	147	152	155	146	135	132	**124**	-5.6%	-1.2%	0.1%
Total S. & Cent. America	7426	7387	7407	7450	7362	7397	7663	7759	7355	7160	**6537**	-8.7%	-0.2%	6.9%
Denmark	287	265	249	225	204	178	167	158	142	138	**116**	-15.9%	-7.8%	0.1%
Italy	108	95	106	110	112	114	120	113	78	86	**97**	12.9%	-3.4%	0.1%
Norway	2458	2342	2132	2033	1911	1832	1881	1940	1991	1963	**1844**	-6.0%	-2.6%	1.9%
Romania	99	94	90	89	83	86	84	83	79	76	**74**	-2.2%	-2.7%	0.1%
United Kingdom	1549	1469	1356	1112	946	864	852	963	1013	999	**1085**	8.6%	-4.9%	1.1%
Other Europe	374	357	342	335	335	344	339	329	313	303	**306**	1.1%	-2.6%	0.3%
Total Europe	4876	4621	4274	3903	3592	3419	3443	3587	3616	3565	**3523**	-1.2%	-3.6%	3.7%
Azerbaijan	916	1027	1037	932	882	888	861	851	838	792	**795**	0.4%	-1.0%	0.8%
Kazakhstan	1485	1609	1676	1684	1664	1737	1710	1695	1655	1838	**1927**	4.8%	2.7%	2.0%
Russian Federation	9965	10152	10379	10533	10656	10807	10860	11007	11269	11255	**11438**	1.6%	1.1%	12.1%
Turkmenistan	208	205	210	223	234	254	257	262	244	232	**222**	-4.7%	1.9%	0.2%
Uzbekistan	102	95	78	77	68	63	61	59	58	61	**64**	5.0%	-5.2%	0.1%
Other CIS	37	36	36	36	35	35	35	36	36	37	**38**	2.6%	-0.1%	♦
Total CIS	12712	13125	13415	13485	13539	13784	13784	13909	14099	14215	**14483**	1.9%	1.1%	15.3%
Iran	4415	4285	4421	4452	3810	3609	3714	3853	4586	5024	**4715**	-6.1%	1.4%	5.0%
Iraq	2428	2446	2469	2773	3079	3103	3239	3986	4423	4533	**4614**	1.8%	7.8%	4.9%
Kuwait	2781	2495	2556	2909	3164	3125	3097	3061	3141	3001	**3049**	1.6%	1.2%	3.2%
Oman	757	813	865	885	918	942	943	981	1004	971	**978**	0.8%	3.2%	1.0%
Qatar	1432	1415	1630	1824	1928	1991	1975	1933	1938	1874	**1879**	0.3%	4.0%	2.0%
Saudi Arabia	10665	9709	9865	11079	11622	11393	11519	11998	12406	11892	**12287**	3.3%	1.5%	13.0%
Syria	406	401	385	353	171	59	33	27	25	25	**24**	-2.2%	-24.4%	♦
United Arab Emirates	3113	2795	2937	3303	3440	3577	3603	3898	4038	3910	**3942**	0.8%	2.4%	4.2%
Yemen	316	308	306	220	178	197	153	63	43	60	**68**	12.8%	-15.9%	0.1%
Other Middle East	193	192	192	201	184	209	214	213	214	208	**207**	-0.7%	0.7%	0.2%
Total Middle East	26506	24859	25626	28001	28493	28205	28490	30012	31818	31497	**31762**	0.8%	2.2%	33.5%
Algeria	1951	1775	1689	1642	1537	1485	1589	1558	1577	1540	**1510**	-2.0%	-2.5%	1.6%
Angola	1876	1754	1812	1670	1734	1738	1701	1796	1745	1676	**1534**	-8.5%	0.1%	1.6%
Chad	127	118	122	114	101	91	89	111	103	104	**101**	-3.1%	-3.2%	0.1%
Republic of Congo	237	276	314	301	280	243	253	234	232	269	**333**	23.6%	1.9%	0.4%
Egypt	715	730	725	714	715	710	714	726	691	660	**670**	1.4%	-0.6%	0.7%
Equatorial Guinea	369	332	306	301	320	282	284	260	223	195	**190**	-2.6%	-6.3%	0.2%
Gabon	240	241	233	236	221	213	211	214	221	210	**194**	-7.6%	-1.5%	0.2%
Libya	1875	1739	1799	516	1539	1048	518	437	412	929	**1010**	8.7%	-6.9%	1.1%
Nigeria	2172	2211	2533	2461	2412	2279	2276	2201	1900	1991	**2051**	3.0%	-1.0%	2.2%
South Sudan	n/a	n/a	n/a	n/a	31	100	155	148	117	111	**131**	17.5%	n/a	0.1%
Sudan	457	475	462	291	103	118	120	109	104	95	**100**	5.7%	-15.0%	0.1%
Tunisia	96	91	83	77	82	76	71	64	60	48	**50**	4.3%	-7.4%	0.1%
Other Africa	184	181	149	198	196	225	234	276	259	304	**320**	5.4%	4.7%	0.3%
Total Africa	10299	9923	10227	8520	9270	8607	8216	8133	7643	8133	**8193**	0.7%	-2.3%	8.6%
Australia	538	507	548	483	479	407	436	384	361	348	**356**	2.2%	-4.5%	0.4%
Brunei	175	168	172	165	159	135	126	127	121	113	**112**	-1.5%	-5.3%	0.1%
China	3814	3805	4077	4074	4155	4216	4246	4309	3999	3846	**3798**	-1.3%	0.3%	4.0%
India	818	838	901	937	926	926	905	893	874	884	**869**	-1.7%	1.2%	0.9%
Indonesia	1006	994	1003	952	917	883	847	838	876	838	**808**	-3.5%	-1.5%	0.9%
Malaysia	727	688	733	659	663	627	649	696	704	683	**682**	-0.1%	-0.6%	0.7%
Thailand	368	383	391	428	468	462	461	478	486	483	**485**	0.3%	3.3%	0.5%
Vietnam	309	341	323	327	358	359	336	365	333	298	**275**	-7.9%	-1.1%	0.3%
Other Asia Pacific	341	330	315	299	287	272	307	308	292	281	**249**	-11.2%	-1.3%	0.3%
Total Asia Pacific	8095	8055	8463	8324	8411	8287	8313	8399	8044	7774	**7633**	-1.8%	-0.2%	8.1%
Total World	**83069**	**81410**	**83255**	**84009**	**86228**	**86647**	**88736**	**91547**	**91822**	**92502**	**94718**	**2.4%**	**1.2%**	**100.0%**
of which: OECD	18417	18424	18531	18571	19487	20621	22565	23583	23090	23940	**26329**	10.0%	2.3%	27.8%
Non-OECD	64652	62986	64724	65438	66742	66026	66171	67964	68731	68561	**68389**	-0.3%	0.8%	72.2%
OPEC	37290	34999	35894	36724	38292	37293	37228	38601	39736	39673	**39338**	-0.8%	0.9%	41.5%
Non-OPEC	45779	46412	47361	47285	47936	49354	51508	52946	52086	52828	**55380**	4.8%	1.3%	58.5%
European Union	2258	2119	1981	1712	1518	1425	1405	1499	1483	1464	**1533**	4.7%	-4.9%	1.6%

*Includes crude oil, shale oil, oil sands, condensates (both lease condensate and gas plant condensate) and NGLs (natural gas liquids – ethane, LPG and naphtha separated from the production of natural gas). Excludes liquid fuels from other sources such as biomass and derivatives of coal and natural gas.
♦Less than 0.05%.
n/a not available.
Note: Annual changes and shares of total are calculated using thousand barrels daily figures.

Table C3. Global oil production (million tonnes) (Source: BP Statistical Review of World Energy 2019)

Oil: Production in million tonnes*

Million tonnes	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Growth rate per annum 2018	Growth rate per annum 2007-17	Share 2018
Canada	152.9	152.8	160.3	169.8	182.6	195.1	209.4	215.6	218.0	235.4	**255.5**	8.5%	4.2%	5.7%
Mexico	156.9	146.7	145.6	144.5	143.9	141.8	137.1	127.5	121.4	109.5	**102.3**	-6.6%	-4.4%	2.3%
US	302.2	322.2	332.8	345.4	394.2	447.2	523.0	566.6	541.9	573.9	**669.4**	16.6%	6.5%	15.0%
Total North America	612.0	621.7	638.7	659.8	720.6	784.1	869.5	909.7	881.3	918.7	**1027.1**	11.8%	3.8%	23.0%
Argentina	37.8	34.0	33.3	31.2	30.8	30.2	29.8	30.1	28.7	27.3	**27.6**	1.1%	-3.3%	0.6%
Brazil	98.8	105.7	111.3	113.8	111.9	109.7	122.5	132.2	136.2	142.3	**140.3**	-1.4%	4.1%	3.1%
Colombia	31.0	35.3	41.4	48.2	49.9	53.2	52.2	53.0	46.8	45.0	**45.6**	1.4%	4.9%	1.0%
Ecuador	27.2	26.1	26.1	26.8	27.1	28.2	29.8	29.1	29.5	28.5	**27.7**	-2.7%	0.4%	0.6%
Peru	5.7	6.9	7.3	7.0	6.9	7.3	7.5	6.5	5.8	5.7	**6.4**	12.2%	0.4%	0.1%
Trinidad & Tobago	6.9	6.8	6.2	5.9	5.2	5.1	5.1	4.8	4.3	4.4	**3.9**	-10.9%	-4.8%	0.1%
Venezuela	165.8	155.9	145.8	141.5	139.3	137.8	138.5	135.4	121.0	107.6	**77.3**	-28.1%	-4.2%	1.7%
Other S. & Cent. America	7.3	6.9	7.3	7.3	7.4	7.6	7.8	7.3	6.8	6.6	**6.2**	-5.5%	-1.2%	0.1%
Total S. & Cent. America	380.5	377.6	378.7	381.7	378.6	379.2	393.1	398.4	379.2	367.3	**335.1**	-8.8%	-0.2%	7.5%
Denmark	14.0	12.9	12.2	10.9	10.0	8.7	8.1	7.7	6.9	6.7	**5.7**	-15.9%	-7.8%	0.1%
Italy	5.2	4.6	5.1	5.3	5.4	5.5	5.8	5.5	3.8	4.1	**4.7**	12.9%	-3.4%	0.1%
Norway	114.2	108.1	98.4	93.2	86.9	82.8	84.8	87.5	90.2	88.6	**83.1**	-6.2%	-2.8%	1.9%
Romania	4.7	4.5	4.3	4.2	4.0	4.1	4.1	4.0	3.8	3.6	**3.6**	-2.0%	-2.6%	0.1%
United Kingdom	72.0	68.3	63.2	52.1	44.7	40.7	40.0	45.4	47.5	46.6	**50.8**	9.0%	-4.9%	1.1%
Other Europe	18.5	17.6	16.9	16.6	16.7	17.1	16.9	16.4	15.6	15.0	**15.2**	1.0%	-2.6%	0.3%
Total Europe	228.7	216.0	200.0	182.3	167.6	158.9	159.7	166.5	167.8	164.7	**162.9**	-1.1%	-3.7%	3.6%
Azerbaijan	45.3	50.9	51.3	46.1	43.7	43.8	42.5	42.0	41.4	39.1	**39.2**	0.3%	-1.0%	0.9%
Kazakhstan	70.7	76.5	79.7	80.1	79.3	82.3	81.1	80.2	78.6	87.0	**91.2**	4.9%	2.6%	2.0%
Russian Federation	494.3	501.4	512.3	519.5	526.7	532.2	535.1	541.8	555.9	554.3	**563.3**	1.6%	1.1%	12.6%
Turkmenistan	10.2	10.0	10.3	10.9	11.5	12.4	12.5	12.8	11.9	11.2	**10.6**	-5.3%	1.7%	0.2%
Uzbekistan	4.8	4.5	3.6	3.6	3.2	2.9	2.8	2.7	2.6	2.8	**2.9**	4.5%	-5.6%	0.1%
Other CIS	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	**1.9**	2.6%	-0.1%	◆
Total CIS	627.2	645.0	659.1	662.0	666.1	675.4	675.8	681.3	692.2	696.1	**709.1**	1.9%	1.1%	15.8%
Iran	215.4	207.2	212.0	212.5	180.5	169.7	174.0	180.2	216.3	235.6	**220.4**	-6.5%	1.0%	4.9%
Iraq	119.3	119.7	120.8	135.8	151.3	152.0	158.8	195.6	217.6	222.2	**226.1**	1.8%	7.8%	5.1%
Kuwait	136.0	120.9	123.2	140.7	153.8	151.2	150.0	148.1	152.5	144.8	**146.8**	1.4%	1.1%	3.3%
Oman	37.1	39.7	42.2	43.2	45.0	46.1	46.2	48.0	49.3	47.6	**47.8**	0.5%	3.2%	1.1%
Qatar	64.5	62.4	70.9	77.7	82.2	84.2	83.5	81.2	81.6	78.5	**78.5**	◆	3.2%	1.8%
Saudi Arabia	510.0	459.0	463.3	522.7	549.2	538.4	543.8	568.0	586.7	559.3	**578.3**	3.4%	1.4%	12.9%
Syria	19.6	19.3	18.5	16.9	8.1	2.7	1.5	1.2	1.1	1.1	**1.1**	-2.5%	-25.1%	◆
United Arab Emirates	145.2	129.3	135.2	150.6	156.9	163.3	163.4	176.1	182.4	176.2	**177.7**	0.8%	2.1%	4.0%
Yemen	14.8	14.4	14.3	10.2	8.1	9.0	6.9	2.6	1.6	2.4	**2.8**	14.7%	-17.2%	0.1%
Other Middle East	9.5	9.4	9.4	9.9	9.0	10.3	10.5	10.5	10.6	10.3	**10.2**	-1.0%	0.7%	0.2%
Total Middle East	1271.5	1181.4	1210.0	1320.3	1344.2	1326.9	1338.7	1411.6	1499.8	1477.9	**1489.7**	0.8%	2.0%	33.3%
Algeria	84.8	77.2	73.8	71.7	67.2	64.8	68.8	67.2	68.4	66.6	**65.3**	-2.0%	-2.6%	1.5%
Angola	92.3	86.0	88.9	82.0	85.3	85.2	83.3	88.2	85.8	81.9	**74.6**	-8.8%	0.1%	1.7%
Chad	6.7	6.2	6.4	6.0	5.3	4.8	4.7	5.8	5.4	5.4	**5.3**	-3.1%	-3.2%	0.1%
Republic of Congo	12.2	14.1	16.0	15.3	14.2	12.3	12.9	11.9	11.8	13.8	**17.0**	23.9%	1.8%	0.4%
Egypt	34.7	35.3	35.0	34.6	34.7	34.4	35.1	35.4	33.8	32.2	**32.7**	1.6%	-0.5%	0.7%
Equatorial Guinea	17.6	15.6	14.5	14.2	15.2	13.2	13.3	12.1	10.4	9.0	**8.7**	-3.1%	-6.6%	0.2%
Gabon	12.0	12.0	11.6	11.8	11.1	10.7	10.5	10.7	11.0	10.5	**9.7**	-7.6%	-1.5%	0.2%
Libya	88.2	81.7	84.6	24.3	72.6	49.4	24.4	20.5	19.3	43.8	**47.5**	8.7%	-6.9%	1.1%
Nigeria	105.8	106.9	122.1	118.4	116.4	109.5	109.3	105.7	91.3	95.5	**98.4**	3.0%	-1.1%	2.2%
South Sudan	n/a	n/a	n/a	n/a	1.5	4.9	7.7	7.3	5.8	5.5	**6.4**	17.5%	n/a	0.1%
Sudan	22.6	23.4	22.8	14.3	5.1	5.8	5.9	5.4	5.1	4.7	**4.9**	5.7%	-15.0%	0.1%
Tunisia	4.5	4.2	3.9	3.6	3.8	3.5	3.3	2.9	2.8	2.2	**2.3**	3.4%	-7.5%	0.1%
Other Africa	9.2	9.1	7.4	9.8	9.8	11.2	11.6	13.7	12.9	15.0	**15.7**	5.1%	4.6%	0.4%
Total Africa	490.4	471.8	487.0	406.0	442.2	409.5	390.6	386.8	363.9	386.0	**388.7**	0.7%	-2.3%	8.7%
Australia	24.1	22.4	24.5	21.5	21.4	17.8	19.1	17.0	15.6	14.9	**15.2**	1.5%	-4.8%	0.3%
Brunei	8.6	8.2	8.4	8.1	7.8	6.6	6.2	6.2	5.9	5.5	**5.4**	-1.4%	-5.3%	0.1%
China	190.4	189.5	203.0	202.9	207.5	210.0	211.4	214.6	199.7	191.5	**189.1**	-1.3%	0.3%	4.2%
India	37.8	38.0	41.3	42.9	42.5	42.5	41.6	41.2	40.2	40.4	**39.5**	-2.2%	1.0%	0.9%
Indonesia	49.4	48.4	48.6	46.3	44.6	42.7	41.0	40.6	42.8	41.0	**39.5**	-3.5%	-1.5%	0.9%
Malaysia	33.6	31.8	33.1	29.7	30.1	28.7	29.8	32.2	32.6	31.5	**31.5**	-0.2%	-0.6%	0.7%
Thailand	14.4	14.9	15.1	15.8	17.2	17.0	16.8	17.5	18.0	17.5	**17.3**	-1.0%	2.6%	0.4%
Vietnam	15.2	16.7	15.6	15.8	17.4	17.3	16.2	17.6	16.0	14.3	**13.0**	-9.1%	-1.3%	0.3%
Other Asia Pacific	14.9	14.4	13.8	13.1	12.6	12.0	13.7	13.8	13.1	12.5	**11.1**	-11.1%	-1.1%	0.2%
Total Asia Pacific	388.4	384.3	403.5	396.0	401.0	394.6	395.8	400.6	383.9	369.1	**361.6**	-2.0%	-0.3%	8.1%
Total World	**3998.7**	**3897.8**	**3976.9**	**4008.0**	**4120.3**	**4128.5**	**4223.2**	**4354.8**	**4368.0**	**4379.9**	**4474.3**	**2.2%**	**1.0%**	**100.0%**
of which: OECD	857.4	853.0	856.5	856.6	902.3	953.2	1041.2	1086.4	1058.1	1092.0	**1198.6**	9.8%	2.1%	26.8%
Non-OECD	3141.3	3044.8	3120.4	3151.4	3217.9	3175.3	3182.0	3268.5	3309.8	3287.9	**3275.8**	-0.4%	0.7%	73.2%
OPEC	1796.3	1674.2	1709.0	1746.2	1822.4	1769.8	1764.4	1830.1	1885.8	1873.7	**1854.3**	-1.0%	0.8%	41.4%
Non-OPEC	2202.3	2223.6	2267.9	2261.9	2297.9	2358.7	2458.8	2524.8	2482.2	2506.2	**2620.1**	4.5%	1.2%	58.6%
European Union	106.6	100.0	93.6	81.3	72.7	68.1	67.0	71.6	70.6	69.3	**72.7**	4.9%	-4.9%	1.6%

*Includes crude oil, shale oil, oil sands, condensates (both lease condensate and gas plant condensate) and NGLs (natural gas liquids – ethane, LPG and naphtha separated from the production of natural gas). Excludes liquid fuels from other sources such as biomass and derivatives of coal and natural gas.
◆Less than 0.05%.
n/a not available.
Note: Annual changes and shares of total are calculated using million tonnes figures.

Table C4. Global crude oil and condensate production (Source: BP Statistical Review of World Energy 2019)

Oil: Crude oil and condensate production in thousands of barrels per day*

Thousand barrels daily	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Growth rate per annum 2018	Growth rate per annum 2007-17	Share 2018
Canada	2581	2576	2724	2900	3131	3358	3610	3679	3678	3977	**4302**	8.2%	4.3%	5.2%
Mexico	2792	2601	2577	2553	2548	2522	2429	2267	2154	1948	**1833**	-5.9%	-4.5%	2.2%
US	5000	5349	5478	5654	6502	7467	8759	9431	8831	9352	**10962**	17.2%	6.3%	13.2%
Total North America	10372	10527	10779	11106	12180	13348	14797	15376	14662	15277	**17097**	11.9%	3.6%	20.6%
Argentina	679	604	589	553	549	540	532	532	511	480	**489**	2.1%	-3.6%	0.6%
Brazil	1812	1950	2055	2105	2061	2024	2255	2437	2510	2622	**2587**	-1.3%	4.1%	3.1%
Colombia	588	671	786	915	944	1010	990	1006	886	854	**866**	1.4%	4.9%	1.0%
Ecuador	505	486	486	500	504	526	557	543	548	531	**517**	-2.7%	0.4%	0.6%
Peru	98	117	123	117	112	118	121	104	91	88	**98**	11.2%	-0.7%	0.1%
Trinidad & Tobago	114	107	98	92	82	81	81	79	71	72	**63**	-11.6%	-5.1%	0.1%
Venezuela	3064	2879	2695	2623	2580	2564	2578	2514	2242	1992	**1425**	-28.4%	-4.2%	1.7%
Other S. & Cent. America	129	121	125	126	131	135	140	133	122	117	**111**	-5.6%	-0.9%	0.1%
Total S. & Cent. America	6988	6935	6957	7031	6963	6998	7255	7347	6982	6756	**6157**	-8.9%	-0.2%	7.4%
Denmark	287	265	249	225	204	178	167	158	142	138	**116**	-15.9%	-7.8%	0.1%
Italy	108	95	106	110	112	114	120	113	78	86	**97**	12.9%	-3.4%	0.1%
Norway	2175	2057	1871	1758	1612	1532	1562	1608	1648	1617	**1515**	-6.3%	-3.3%	1.8%
Romania	93	90	86	84	79	83	82	80	76	73	**71**	-1.8%	-2.5%	0.1%
United Kingdom	1404	1344	1245	1036	891	815	796	909	940	917	**1005**	9.5%	-4.9%	1.2%
Other Europe	347	331	319	315	317	327	324	315	297	284	**287**	1.1%	-2.6%	0.3%
Total Europe	4416	4182	3876	3527	3215	3050	3050	3183	3180	3116	**3092**	-0.8%	-4.0%	3.7%
Azerbaijan	895	1014	1023	919	872	877	849	840	826	781	**783**	0.2%	-0.9%	0.9%
Kazakhstan	1483	1609	1676	1684	1662	1720	1701	1672	1637	1813	**1900**	4.8%	2.5%	2.3%
Russian Federation	9784	9927	10150	10287	10395	10528	10595	10758	11003	11017	**11201**	1.7%	1.1%	13.5%
Turkmenistan	198	194	199	212	220	237	240	245	224	209	**196**	-6.3%	1.2%	0.2%
Uzbekistan	102	95	78	77	68	63	61	59	58	61	**64**	5.0%	-5.2%	0.1%
Other CIS	37	36	36	36	35	35	35	36	36	37	**38**	2.6%	-0.1%	♦
Total CIS	12498	12876	13162	13214	13252	13461	13481	13610	13785	13918	**14181**	1.9%	1.1%	17.1%
Iran	4173	4015	4068	4048	3398	3192	3273	3392	4090	4471	**4156**	-7.0%	0.7%	5.0%
Iraq	2394	2405	2424	2728	3037	3058	3198	3945	4375	4469	**4550**	1.8%	7.8%	5.5%
Kuwait	2574	2278	2307	2645	2890	2847	2830	2782	2860	2704	**2737**	1.2%	0.9%	3.3%
Oman	757	813	865	885	918	942	943	981	1004	971	**978**	0.8%	3.2%	1.2%
Qatar	1211	1151	1307	1399	1491	1520	1508	1463	1465	1416	**1408**	-0.6%	2.6%	1.7%
Saudi Arabia	9453	8411	8423	9566	9987	9875	9941	10420	10688	10175	**10534**	3.5%	1.2%	12.7%
Syria	371	366	350	319	146	45	23	19	17	17	**16**	-3.3%	-26.7%	♦
United Arab Emirates	2819	2495	2603	2856	2961	3095	3063	3284	3384	3280	**3301**	0.6%	1.7%	4.0%
Yemen	295	286	284	197	154	173	128	38	16	33	**40**	21.3%	-20.3%	♦
Other Middle East	183	182	182	191	173	199	204	203	204	199	**196**	-1.5%	0.8%	0.2%
Total Middle East	24230	22402	22813	24834	25155	24944	25113	26527	28104	27733	**27916**	0.7%	1.8%	33.6%
Algeria	1643	1517	1461	1416	1320	1275	1329	1290	1316	1287	**1258**	-2.2%	-2.7%	1.5%
Angola	1855	1734	1793	1656	1714	1716	1672	1780	1722	1637	**1483**	-9.5%	♦	1.8%
Chad	127	118	122	114	101	91	89	111	103	104	**101**	-3.1%	-3.2%	0.1%
Republic of Congo	235	269	307	292	268	234	245	227	225	263	**327**	24.3%	1.8%	0.4%
Egypt	651	665	663	649	649	643	667	662	631	603	**615**	2.0%	-0.6%	0.7%
Equatorial Guinea	349	310	286	280	299	261	266	242	204	174	**169**	-2.9%	-6.8%	0.2%
Gabon	240	241	233	236	221	213	211	214	221	210	**194**	-7.6%	-1.5%	0.2%
Libya	1808	1687	1748	508	1499	1025	510	422	397	909	**988**	8.7%	-6.8%	1.2%
Nigeria	2100	2138	2455	2373	2330	2193	2188	2119	1822	1912	**1967**	2.9%	-1.1%	2.4%
South Sudan	n/a	n/a	n/a	n/a	31	100	155	148	117	111	**131**	17.5%	n/a	0.2%
Sudan	457	475	462	291	103	118	120	109	104	95	**100**	5.7%	-15.0%	0.1%
Tunisia	87	82	79	70	70	64	59	54	51	43	**42**	-3.5%	-7.6%	0.1%
Other Africa	184	181	149	198	196	225	234	276	259	304	**319**	5.2%	4.7%	0.4%
Total Africa	9735	9418	9759	8083	8802	8158	7744	7653	7170	7651	**7693**	0.5%	-2.3%	9.3%
Australia	455	423	471	411	405	335	353	322	292	284	**295**	3.8%	-4.7%	0.4%
Brunei	161	155	159	153	146	122	114	115	109	101	**100**	-1.1%	-5.6%	0.1%
China	3814	3805	4077	4074	4155	4216	4246	4309	3999	3846	**3798**	-1.3%	0.3%	4.6%
India	703	690	762	793	786	789	778	771	744	744	**719**	-3.3%	0.5%	0.9%
Indonesia	977	949	945	902	859	825	789	786	831	801	**772**	-3.6%	-1.7%	0.9%
Malaysia	688	659	653	583	598	588	610	662	667	648	**646**	-0.2%	-0.5%	0.8%
Thailand	229	238	242	224	239	241	233	248	258	240	**228**	-4.8%	1.2%	0.3%
Vietnam	301	332	304	308	338	337	315	342	307	275	**243**	-11.6%	-1.6%	0.3%
Other Asia Pacific	289	279	267	253	242	235	272	276	262	249	**224**	-10.2%	-0.9%	0.3%
Total Asia Pacific	7617	7530	7880	7701	7769	7688	7711	7832	7469	7187	**7024**	-2.3%	-0.5%	8.4%
Total World	**75857**	**73869**	**75226**	**75498**	**77336**	**77647**	**79152**	**81528**	**81351**	**81639**	**83161**	**1.9%**	**0.8%**	**100.0%**
of which: OECD	15098	14990	14988	14904	15653	16578	18058	18745	18005	18551	**20352**	9.7%	1.7%	24.5%
Non-OECD	60759	58879	60238	60594	61683	61069	61094	62783	63346	63089	**62809**	-0.4%	0.6%	75.5%
OPEC	34423	32017	32597	33126	34499	33594	33370	34636	35558	35430	**35014**	-1.2%	0.6%	42.1%
Non-OPEC	41435	41852	42629	42371	42837	44053	45782	46892	45793	46209	**48147**	4.2%	1.0%	57.9%
European Union	2088	1971	1851	1617	1447	1361	1336	1432	1397	1369	**1441**	5.3%	-4.9%	1.7%

*Includes crude oil, shale oil, oil sands and condensates (both lease condensate and gas plant condensate). Excludes liquid fuels from other sources such as natural gas liquids, biomass and derivatives of coal and natural gas.
♦Less than 0.05%.
n/a not available.
Note: Annual changes and shares of total are calculated using thousand barrels daily figures.

Table C5. Global natural gas liquids production (Source: BP Statistical Review of World Energy 2019)

Oil: Natural gas liquids production in thousands of barrels per day*

Thousand barrels daily	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Growth rate per annum 2018	Growth rate per annum 2007-17	Share 2018
Canada	626	626	608	615	610	642	661	709	773	822	**906**	10.3%	1.9%	7.8%
Mexico	374	377	382	388	363	353	355	320	302	276	**235**	-14.8%	-3.7%	2.0%
US	1784	1910	2074	2216	2408	2606	3015	3342	3509	3783	**4349**	15.0%	7.8%	37.6%
Total North America	2783	2913	3064	3219	3381	3600	4031	4371	4584	4880	**5490**	12.5%	5.5%	47.5%
Argentina	123	126	123	114	107	105	106	114	100	111	**102**	-7.8%	-1.2%	0.9%
Brazil	74	69	70	68	70	72	87	88	81	99	**96**	-3.3%	3.3%	0.8%
Colombia	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	**n/a**	n/a	n/a	n/a
Ecuador	2	2	2	1	1	1	–	–	–	–	**–**	n/a	-100.0%	–
Peru	24	38	42	42	45	54	54	49	50	49	**56**	14.7%	8.3%	0.5%
Trinidad & Tobago	35	44	47	44	35	34	33	30	25	27	**24**	-11.3%	-2.3%	0.2%
Venezuela	165	159	147	132	124	116	114	117	105	104	**88**	-15.0%	-5.1%	0.8%
Other S. & Cent. America	14	15	19	19	16	17	14	13	12	14	**13**	-5.0%	-3.2%	0.1%
Total S. & Cent. America	438	453	451	419	399	399	408	411	373	404	**379**	-6.0%	-1.1%	3.3%
Denmark	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	**n/a**	n/a	n/a	n/a
Italy	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	**n/a**	n/a	n/a	n/a
Norway	283	285	261	275	300	300	318	332	343	345	**329**	-4.7%	2.2%	2.8%
Romania	6	4	4	5	4	3	3	3	4	3	**3**	-11.5%	-7.2%	◆
United Kingdom	144	125	110	76	55	49	56	55	73	82	**80**	-1.8%	-5.1%	0.7%
Other Europe	27	25	23	20	19	17	15	14	16	19	**19**	1.4%	-3.4%	0.2%
Total Europe	460	439	398	375	377	369	392	404	436	449	**431**	-3.9%	◆	3.7%
Azerbaijan	21	12	13	13	10	11	12	11	11	10	**12**	9.9%	-6.2%	0.1%
Kazakhstan	2	†	†	†	2	17	9	23	18	25	**27**	9.2%	30.5%	0.2%
Russian Federation	180	225	228	247	260	278	265	249	266	238	**237**	-0.2%	2.3%	2.1%
Turkmenistan	10	10	10	10	14	17	17	17	20	23	**26**	10.0%	11.3%	0.2%
Uzbekistan	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	**n/a**	n/a	n/a	n/a
Other CIS	–	–	–	–	–	–	–	–	–	–	**–**	n/a	n/a	–
Total CIS	214	248	252	271	286	323	303	299	315	296	**301**	1.7%	3.1%	2.6%
Iran	242	270	352	404	412	418	441	461	496	553	**559**	1.1%	11.5%	4.8%
Iraq	34	41	45	45	42	45	40	41	48	64	**64**	-0.1%	9.1%	0.6%
Kuwait	207	217	249	264	275	278	267	279	281	297	**312**	5.0%	4.7%	2.7%
Oman	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	**n/a**	n/a	n/a	n/a
Qatar	222	264	323	426	437	471	466	470	473	458	**471**	2.8%	10.9%	4.1%
Saudi Arabia	1211	1298	1442	1513	1635	1518	1577	1578	1718	1717	**1753**	2.1%	3.7%	15.2%
Syria	35	35	35	34	25	14	10	8	8	8	**8**	–	-13.7%	0.1%
United Arab Emirates	294	300	334	447	479	482	539	614	654	631	**641**	1.7%	7.3%	5.5%
Yemen	21	22	23	23	24	24	25	26	26	27	**28**	2.4%	2.1%	0.2%
Other Middle East	10	10	10	11	10	10	10	10	10	10	**11**	14.4%	◆	0.1%
Total Middle East	2275	2457	2812	3167	3338	3260	3377	3485	3714	3764	**3847**	2.2%	5.8%	33.3%
Algeria	308	258	228	225	216	210	260	268	261	254	**252**	-0.8%	-1.8%	2.2%
Angola	22	20	19	14	20	22	30	16	23	39	**51**	31.8%	6.0%	0.4%
Chad	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	**n/a**	n/a	n/a	n/a
Republic of Congo	2	7	7	9	12	9	8	7	7	6	**6**	-5.6%	7.7%	0.1%
Egypt	65	65	61	65	66	67	47	64	60	57	**55**	-3.9%	-0.6%	0.5%
Equatorial Guinea	21	22	20	21	20	21	19	17	19	21	**21**	-0.3%	-0.4%	0.2%
Gabon	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	**n/a**	n/a	n/a	n/a
Libya	67	51	50	8	40	22	8	15	15	20	**21**	5.9%	-11.2%	0.2%
Nigeria	72	73	78	88	82	86	88	82	78	80	**85**	6.0%	1.3%	0.7%
South Sudan	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	**n/a**	n/a	n/a	n/a
Sudan	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	**n/a**	n/a	n/a	n/a
Tunisia	8	9	4	7	13	12	12	10	9	5	**8**	74.4%	-5.4%	0.1%
Other Africa	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	**1**	n/a	n/a	◆
Total Africa	564	506	468	437	468	449	471	480	472	482	**500**	3.7%	-1.4%	4.3%
Australia	82	84	77	71	73	72	83	62	69	64	**61**	-4.7%	-3.4%	0.5%
Brunei	14	14	13	13	13	13	12	11	12	13	**12**	-4.8%	-1.6%	0.1%
China	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	**n/a**	n/a	n/a	n/a
India	115	148	140	144	140	136	128	122	129	141	**150**	6.7%	6.0%	1.3%
Indonesia	29	45	58	50	58	58	58	52	45	37	**36**	-1.6%	7.8%	0.3%
Malaysia	39	29	79	76	65	39	39	35	37	35	**36**	1.9%	-2.0%	0.3%
Thailand	139	145	149	204	229	222	228	230	228	244	**257**	5.4%	6.1%	2.2%
Vietnam	8	10	19	19	20	22	21	23	25	23	**32**	35.8%	7.9%	0.3%
Other Asia Pacific	52	51	48	46	45	37	35	32	30	31	**25**	-19.3%	-4.0%	0.2%
Total Asia Pacific	478	526	583	623	643	599	603	567	576	587	**609**	3.6%	3.0%	5.3%
Total World	**7212**	**7541**	**8029**	**8511**	**8892**	**9000**	**9584**	**10018**	**10471**	**10862**	**11557**	**6.4%**	**4.3%**	**100.0%**
of which: OECD	3319	3434	3543	3668	3834	4043	4507	4838	5086	5390	**5977**	10.9%	4.7%	51.7%
Non-OECD	3893	4107	4486	4843	5058	4956	5077	5181	5385	5473	**5580**	2.0%	4.0%	48.3%
OPEC	2867	2982	3296	3597	3793	3699	3858	3964	4178	4243	**4325**	1.9%	4.5%	37.4%
Non-OPEC	4345	4559	4733	4914	5099	5300	5726	6054	6293	6619	**7233**	9.3%	4.2%	62.6%
European Union	169	147	130	94	71	63	69	67	87	95	**92**	-3.3%	-5.2%	0.8%

*Includes ethane, LPG and naphtha separated from the production of natural gas. Excludes condensates.
†Less than 0.05.
◆Less than 0.05%.
n/a not available.
Note: Annual changes and shares of total are calculated using thousand barrels daily figures.

Source: Includes data from ICIS.

Table C6. Global oil consumption (thousand barrels per day) (Source: BP Statistical Review of World Energy 2019)

Oil: Consumption in thousands of barrels per day*

Thousand barrels daily	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Growth rate per annum 2018	Growth rate per annum 2007-17	Share 2018
Canada	2323	2209	2358	2436	2376	2398	2442	2401	2448	2448	**2447**	◆	0.4%	2.5%
Mexico	2080	2021	2040	2065	2083	2034	1960	1939	1950	1883	**1812**	-3.8%	-1.0%	1.8%
US	19490	18771	19180	18882	18490	18961	19106	19531	19687	19958	**20456**	2.5%	-0.4%	20.5%
Total North America	23894	23001	23578	23383	22949	23393	23507	23871	24086	24289	**24714**	1.8%	-0.3%	24.8%
Argentina	540	532	594	609	636	683	673	696	686	684	**648**	-5.3%	2.6%	0.6%
Brazil	2481	2498	2714	2832	2884	3100	3210	3140	2960	3052	**3081**	0.9%	2.8%	3.1%
Chile	390	383	343	371	376	362	353	355	377	369	**379**	2.7%	-0.2%	0.4%
Colombia	248	230	256	275	295	297	316	332	345	340	**342**	0.6%	3.9%	0.3%
Ecuador	188	191	220	226	233	247	260	254	240	237	**255**	7.6%	2.6%	0.3%
Peru	175	182	191	220	215	228	225	247	259	258	**267**	3.4%	5.1%	0.3%
Trinidad & Tobago	45	44	45	42	40	45	41	46	48	42	**42**	-1.2%	-0.1%	◆
Venezuela	716	726	725	737	792	782	720	637	537	463	**409**	-11.7%	-3.2%	0.4%
Other S. & Cent. America	1257	1229	1247	1267	1244	1219	1234	1294	1340	1352	**1373**	1.5%	0.5%	1.4%
Total S. & Cent. America	6041	6016	6335	6579	6715	6964	7034	7001	6792	6798	**6795**	◆	1.7%	6.8%
Austria	272	262	275	259	258	262	255	256	261	265	**272**	2.5%	-0.3%	0.3%
Belgium	731	678	706	662	645	665	665	684	694	696	**703**	1.0%	◆	0.7%
Czech Republic	209	204	195	201	198	190	202	196	182	217	**222**	2.2%	0.6%	0.2%
Finland	225	213	223	213	205	220	214	212	221	217	**229**	5.7%	-0.5%	0.2%
France	1889	1822	1763	1725	1673	1661	1613	1612	1597	1608	**1607**	-0.1%	-1.7%	1.6%
Germany	2502	2409	2441	2365	2352	2404	2344	2336	2374	2443	**2321**	-5.0%	0.3%	2.3%
Greece	440	419	382	362	321	303	302	313	314	324	**323**	-0.3%	-3.6%	0.3%
Hungary	164	154	146	155	143	142	159	168	166	177	**188**	6.5%	0.5%	0.2%
Italy	1661	1563	1532	1475	1384	1274	1204	1257	1266	1279	**1253**	-2.0%	-3.0%	1.3%
Netherlands	979	945	964	971	925	898	866	834	851	829	**860**	3.8%	-2.2%	0.9%
Norway	218	222	229	227	226	230	217	223	217	223	**234**	5.1%	0.1%	0.2%
Poland	567	567	594	592	571	538	538	559	606	662	**685**	3.4%	1.9%	0.7%
Portugal	293	274	272	256	231	241	241	246	240	246	**236**	-4.0%	-2.1%	0.2%
Romania	216	195	184	191	191	174	187	191	202	213	**211**	-1.0%	-0.3%	0.2%
Spain	1559	1474	1447	1383	1300	1203	1199	1243	1288	1301	**1335**	2.7%	-2.1%	1.3%
Sweden	340	325	328	309	309	306	304	302	319	321	**308**	-3.8%	-1.1%	0.3%
Switzerland	256	260	242	235	238	249	224	227	216	222	**215**	-3.2%	-0.8%	0.2%
Turkey	686	709	694	673	704	757	775	912	978	1013	**1003**	-1.0%	3.8%	1.0%
Ukraine	299	282	267	278	267	257	221	194	205	207	**200**	-3.0%	-3.9%	0.2%
United Kingdom	1738	1669	1652	1600	1546	1532	1536	1578	1623	1637	**1618**	-1.2%	-0.7%	1.6%
Other Europe	1313	1231	1216	1189	1140	1124	1123	1169	1214	1253	**1252**	-0.1%	-0.5%	1.3%
Total Europe	16558	15876	15752	15321	14826	14631	14389	14713	15032	15351	**15276**	-0.5%	-0.8%	15.3%
Azerbaijan	74	73	72	89	92	101	99	100	98	99	**98**	-1.0%	0.9%	0.1%
Belarus	160	182	150	173	211	144	164	139	137	135	**136**	1.0%	-1.9%	0.1%
Kazakhstan	240	198	211	243	245	260	262	295	305	317	**357**	12.4%	2.8%	0.4%
Russian Federation	2861	2775	2878	3074	3119	3134	3298	3146	3217	3207	**3228**	0.7%	1.4%	3.2%
Turkmenistan	114	106	118	125	129	137	143	145	143	147	**151**	3.2%	2.8%	0.2%
Uzbekistan	93	89	76	71	63	60	57	53	49	55	**52**	-4.0%	-5.3%	0.1%
Other CIS	60	63	63	65	75	78	76	78	86	73	**76**	3.0%	2.7%	0.1%
Total CIS	3602	3486	3567	3838	3935	3914	4099	3955	4034	4033	**4099**	1.6%	1.3%	4.1%
Iran	1925	1919	1788	1851	1882	2064	1959	1804	1749	1843	**1879**	2.0%	◆	1.9%
Iraq	481	536	570	629	666	716	681	683	760	732	**777**	6.1%	4.1%	0.8%
Israel	254	232	241	254	295	223	214	226	230	247	**242**	-1.9%	-0.6%	0.2%
Kuwait	406	455	470	444	490	508	446	461	453	455	**451**	-0.9%	1.7%	0.5%
Oman	123	119	135	146	157	178	185	184	187	193	**192**	-0.3%	7.9%	0.2%
Qatar	178	173	191	246	257	287	294	317	341	320	**328**	2.6%	8.0%	0.3%
Saudi Arabia	2622	2914	3206	3295	3460	3451	3764	3886	3875	3838	**3724**	-3.0%	4.8%	3.7%
United Arab Emirates	603	606	654	735	773	852	880	957	1023	964	**991**	2.8%	5.3%	1.0%
Other Middle East	795	774	720	701	650	630	631	579	553	547	**551**	0.8%	-3.5%	0.6%
Total Middle East	7386	7727	7974	8301	8631	8910	9053	9099	9172	9138	**9136**	◆	2.7%	9.2%
Algeria	309	327	327	349	370	387	401	425	412	408	**414**	1.6%	3.6%	0.4%
Egypt	686	725	766	720	747	756	806	834	857	806	**760**	-5.7%	2.3%	0.8%
Morocco	231	234	258	275	277	282	272	268	275	290	**286**	-1.6%	3.2%	0.3%
South Africa	511	507	538	542	552	561	555	578	555	556	**533**	-4.1%	0.3%	0.5%
Other Africa	1462	1530	1592	1512	1628	1719	1737	1751	1779	1901	**1996**	3.4%	3.5%	2.0%
Total Africa	3198	3322	3481	3398	3574	3705	3770	3857	3878	3962	**3959**	-0.1%	2.7%	4.0%
Australia	944	950	954	1001	1025	1034	1047	1005	1038	1055	**1094**	3.7%	1.2%	1.1%
Bangladesh	77	72	81	104	110	108	120	127	137	153	**176**	14.8%	7.2%	0.2%
China	7914	8295	9446	9808	10242	10750	11239	11986	12304	12840	**13525**	5.3%	5.1%	13.5%
China Hong Kong SAR	292	332	359	361	344	352	336	368	380	427	**434**	1.6%	2.9%	0.4%
India	3137	3300	3381	3550	3747	3789	3914	4245	4654	4870	**5156**	5.9%	5.0%	5.2%
Indonesia	1288	1321	1415	1590	1646	1677	1708	1571	1628	1696	**1785**	5.2%	2.5%	1.8%
Japan	4847	4390	4442	4442	4702	4516	4303	4151	4019	3975	**3854**	-3.1%	-2.3%	3.9%
Malaysia	672	679	688	724	757	802	796	790	807	793	**814**	2.6%	1.2%	0.8%
New Zealand	154	148	150	150	148	151	154	160	163	175	**173**	-1.2%	1.3%	0.2%
Pakistan	389	415	411	414	402	442	458	505	566	589	**498**	-15.4%	4.4%	0.5%
Philippines	283	300	313	298	309	326	347	397	427	459	**466**	1.5%	4.5%	0.5%
Singapore	973	1049	1157	1208	1202	1225	1268	1338	1385	1419	**1449**	2.1%	4.4%	1.5%
South Korea	2312	2345	2378	2401	2466	2464	2463	2587	2781	2811	**2793**	-0.6%	1.6%	2.8%
Sri Lanka	83	87	87	92	95	82	71	90	105	113	**112**	-1.3%	2.2%	0.1%
Taiwan	1010	1022	1043	950	950	981	1013	1021	1046	1069	**1075**	0.5%	-0.4%	1.1%
Thailand	1016	1075	1121	1184	1250	1299	1309	1360	1396	1444	**1478**	2.3%	3.4%	1.5%
Vietnam	300	305	332	361	368	398	409	445	471	498	**522**	4.9%	5.8%	0.5%
Other Asia Pacific	249	268	285	304	329	364	388	408	436	449	**461**	2.8%	6.0%	0.5%
Total Asia Pacific	25940	26351	28043	28942	30094	30759	31343	32551	33743	34835	**35863**	3.0%	2.9%	35.9%
Total World	**86619**	**85780**	**88730**	**89763**	**90724**	**92276**	**93194**	**95048**	**96737**	**98406**	**99843**	**1.5%**	**1.2%**	**100.0%**
of which: OECD	48187	46217	46776	46253	45752	45782	45455	46086	46688	47199	**47466**	0.6%	-0.5%	47.5%
Non-OECD	38432	39563	41954	43510	44973	46494	47739	48961	50049	51206	**52377**	2.3%	3.2%	52.5%
European Union	14786	14092	14012	13599	13101	12848	12663	12855	13091	13356	**13302**	-0.4%	-1.1%	13.3%

*Inland demand plus international aviation and marine bunkers and refinery fuel and loss. Consumption of biogasoline (such as ethanol), biodiesel and derivatives of coal and natural gas are also included.

◆Less than 0.05%.

Notes: Differences between these world consumption figures and world production statistics are accounted for by stock changes, consumption of non-petroleum additives and substitute fuels, and unavoidable disparities in the definition, measurement or conversion of oil supply and demand data.

Annual changes and shares of total are calculated using thousand barrels daily figures.

Table C7. Global oil consumption (MToe) (Source: BP Statistical Review of World Energy 2019)

Oil: Consumption in million tonnes oil equivalent*

Million tonnes oil equivalent	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Growth rate per annum 2018	Growth rate per annum 2007-17	Share 2018
Canada	105.7	99.8	107.1	110.4	107.5	107.8	109.6	107.0	108.7	108.8	**110.0**	1.1%	0.2%	2.4%
Mexico	96.2	92.9	93.3	94.9	96.4	93.8	89.5	88.5	89.1	85.8	**82.8**	-3.5%	-1.2%	1.8%
US	903.4	860.6	877.5	862.2	843.8	859.8	866.1	884.5	893.3	902.0	**919.7**	2.0%	-0.6%	19.7%
Total North America	1105.3	1053.3	1077.9	1067.4	1047.7	1061.3	1065.3	1080.0	1091.1	1096.6	**1112.5**	1.5%	-0.6%	23.9%
Argentina	25.5	25.0	28.6	28.9	30.1	32.4	31.9	32.9	32.3	32.0	**30.1**	-6.0%	2.6%	0.6%
Brazil	112.6	112.9	122.8	128.4	131.3	140.3	145.7	140.6	132.7	136.1	**135.9**	-0.1%	2.6%	2.9%
Chile	19.2	18.7	16.6	18.1	18.1	17.5	17.0	17.1	18.2	17.7	**18.1**	2.7%	-0.4%	0.4%
Colombia	12.0	11.0	12.3	13.2	14.3	14.4	15.3	16.2	16.8	16.5	**16.6**	0.7%	4.0%	0.4%
Ecuador	9.1	9.2	10.7	10.9	11.3	12.0	12.7	12.3	11.5	11.3	**12.2**	8.2%	2.5%	0.3%
Peru	8.4	8.7	9.1	10.5	10.2	10.7	10.5	11.6	12.2	12.0	**12.4**	3.2%	4.7%	0.3%
Trinidad & Tobago	2.3	2.2	2.3	2.1	2.0	2.3	2.1	2.3	2.4	2.1	**2.1**	-0.9%	-0.1%	♦
Venezuela	34.9	35.3	35.2	35.7	38.5	38.0	34.9	30.7	25.9	22.1	**19.5**	-11.9%	-3.2%	0.4%
Other S. & Cent. America	63.9	62.2	62.9	64.0	63.0	61.2	61.9	64.8	67.1	67.4	**68.3**	1.4%	0.4%	1.5%
Total S. & Cent. America	287.9	285.3	300.4	311.9	318.9	328.8	331.9	328.5	319.1	317.2	**315.3**	-0.6%	1.5%	6.8%
Austria	13.7	13.2	13.7	12.8	12.7	12.9	12.6	12.6	12.9	13.1	**13.4**	2.4%	-0.5%	0.3%
Belgium	36.9	33.4	34.8	32.5	31.5	32.3	32.0	32.9	33.7	33.7	**34.1**	1.0%	-0.4%	0.7%
Czech Republic	10.2	10.0	9.5	9.7	9.5	9.1	9.7	9.5	8.9	10.4	**10.6**	2.4%	0.3%	0.2%
Finland	11.0	10.4	10.9	10.3	9.9	10.4	10.0	10.0	10.5	10.3	**10.7**	4.8%	-0.8%	0.2%
France	93.8	90.3	87.3	85.4	83.0	82.0	79.6	79.2	78.7	79.1	**78.9**	-0.2%	-1.8%	1.7%
Germany	123.7	118.7	119.5	115.8	115.3	117.5	114.5	114.2	116.5	119.0	**113.2**	-4.9%	0.1%	2.4%
Greece	22.2	21.0	19.1	18.0	16.0	15.0	14.9	15.4	15.4	16.0	**16.0**	-0.1%	-3.7%	0.3%
Hungary	7.8	7.4	7.0	7.3	6.8	6.7	7.5	7.9	7.8	8.3	**8.8**	6.3%	0.3%	0.2%
Italy	82.5	77.2	75.3	72.6	67.8	61.9	58.5	61.1	61.6	62.0	**60.8**	-2.0%	-3.2%	1.3%
Netherlands	48.0	46.0	46.7	47.3	45.0	42.7	40.8	39.8	41.0	39.6	**40.9**	3.2%	-2.4%	0.9%
Norway	10.2	10.3	10.6	10.5	10.5	10.6	10.0	10.2	9.9	10.1	**10.4**	3.6%	-0.3%	0.2%
Poland	27.2	27.1	28.5	28.4	27.5	25.6	25.7	26.7	29.1	31.7	**32.8**	3.6%	2.0%	0.7%
Portugal	14.4	13.4	13.3	12.5	11.3	11.7	11.6	11.9	11.7	12.0	**11.5**	-3.4%	-2.2%	0.2%
Romania	10.5	9.5	9.0	9.3	9.3	8.5	9.1	9.3	9.8	10.3	**10.2**	-0.2%	-0.3%	0.2%
Spain	78.7	74.1	72.7	69.6	65.5	60.5	60.3	62.2	64.5	65.0	**66.6**	2.6%	-2.2%	1.4%
Sweden	16.6	15.9	16.1	15.0	14.9	14.7	14.6	14.5	15.3	15.4	**14.8**	-3.6%	-1.3%	0.3%
Switzerland	12.6	12.8	11.9	11.5	11.7	12.3	11.0	11.2	10.6	10.9	**10.5**	-3.3%	-0.8%	0.2%
Turkey	33.1	33.6	32.8	32.1	33.8	36.5	37.2	44.0	47.4	49.2	**48.6**	-1.2%	3.9%	1.0%
Ukraine	14.7	14.0	13.1	13.6	13.1	12.4	10.7	9.4	9.9	9.9	**9.6**	-3.6%	-4.0%	0.2%
United Kingdom	83.4	79.8	79.0	76.7	74.5	73.4	73.5	75.3	77.5	78.0	**77.0**	-1.2%	-0.8%	1.7%
Other Europe	65.9	61.7	61.0	59.5	57.3	56.1	56.0	58.4	60.7	62.5	**62.4**	-0.1%	-0.6%	1.3%
Total Europe	817.1	779.8	771.5	750.6	727.0	712.8	699.7	715.7	733.3	746.2	**742.0**	-0.6%	-1.0%	15.9%
Azerbaijan	3.7	3.5	3.4	4.2	4.4	4.8	4.7	4.7	4.7	4.7	**4.6**	-2.1%	0.3%	0.1%
Belarus	8.0	9.3	7.5	8.5	10.4	7.2	8.2	7.0	6.9	6.7	**6.8**	1.1%	-1.8%	0.1%
Kazakhstan	11.9	9.6	10.2	11.9	12.0	12.6	12.6	14.1	14.5	15.0	**16.4**	9.5%	2.3%	0.4%
Russian Federation	138.1	132.5	137.9	147.0	149.6	149.5	157.4	149.4	153.1	151.5	**152.3**	0.5%	1.2%	3.3%
Turkmenistan	5.4	5.2	5.7	6.0	6.2	6.4	6.7	6.8	6.7	6.9	**7.1**	2.8%	2.7%	0.2%
Uzbekistan	4.7	4.4	3.7	3.5	3.1	3.0	2.8	2.6	2.4	2.7	**2.6**	-3.9%	-5.3%	0.1%
Other CIS	2.9	3.1	3.1	3.2	3.5	3.7	3.6	3.7	4.0	3.6	**3.7**	3.1%	2.6%	0.1%
Total CIS	174.7	167.5	171.6	184.4	189.3	187.1	196.0	188.2	192.3	191.1	**193.5**	1.3%	1.1%	4.2%
Iran	94.7	93.9	85.6	89.3	90.7	99.9	93.9	85.6	81.8	84.5	**86.2**	2.0%	-0.7%	1.8%
Iraq	23.0	26.1	27.8	30.5	32.6	34.9	33.1	33.2	37.0	35.6	**38.4**	7.7%	4.4%	0.8%
Israel	12.3	11.1	11.5	12.2	14.3	10.6	10.1	10.7	10.9	11.7	**11.5**	-1.7%	-0.8%	0.2%
Kuwait	19.4	20.9	21.5	19.9	22.3	23.2	19.9	20.8	20.5	20.4	**20.0**	-1.9%	1.2%	0.4%
Oman	6.0	5.8	6.6	6.9	7.5	8.7	8.9	9.0	9.2	9.2	**9.2**	-0.4%	7.6%	0.2%
Qatar	6.8	6.5	7.0	8.8	9.0	10.2	10.7	11.7	12.8	11.8	**12.2**	3.5%	7.6%	0.3%
Saudi Arabia	118.6	130.2	141.3	144.4	151.8	152.2	167.0	173.5	171.5	168.8	**162.6**	-3.6%	4.5%	3.5%
United Arab Emirates	30.8	30.2	32.2	34.9	36.4	40.3	40.8	43.8	46.6	43.8	**45.1**	2.9%	4.1%	1.0%
Other Middle East	39.5	38.2	35.5	34.6	32.1	30.8	30.8	28.3	27.0	26.6	**26.8**	0.8%	-3.6%	0.6%
Total Middle East	351.1	362.8	368.9	381.5	396.8	410.8	415.2	416.6	417.4	412.5	**412.1**	-0.1%	2.2%	8.8%
Algeria	14.6	15.5	15.5	16.5	17.6	18.4	19.1	20.3	19.7	19.4	**19.6**	1.2%	3.7%	0.4%
Egypt	33.6	35.4	37.4	34.8	36.5	36.9	39.5	41.1	42.1	39.2	**36.7**	-6.4%	2.3%	0.8%
Morocco	11.0	11.1	12.3	13.2	13.3	13.4	12.8	12.5	12.8	13.5	**13.2**	-2.5%	3.1%	0.3%
South Africa	25.3	25.0	26.6	26.7	27.4	27.7	27.5	28.6	27.5	27.5	**26.3**	-4.5%	0.3%	0.6%
Other Africa	72.0	75.1	78.1	74.0	79.9	84.1	84.9	85.4	86.8	92.4	**95.5**	3.3%	3.3%	2.0%
Total Africa	156.5	162.2	169.9	165.3	174.5	180.4	183.7	187.9	189.0	192.1	**191.3**	-0.4%	2.6%	4.1%
Australia	45.2	45.4	45.6	48.2	49.6	49.9	50.6	48.5	50.3	51.1	**53.3**	4.4%	1.4%	1.1%
Bangladesh	3.9	3.6	4.1	5.2	5.6	5.5	6.1	6.5	7.1	7.9	**9.0**	14.6%	7.4%	0.2%
China	384.7	400.6	455.5	472.4	495.3	517.3	539.3	573.3	587.0	610.7	**641.2**	5.0%	4.9%	13.8%
China Hong Kong SAR	14.9	16.9	18.3	18.4	17.6	18.0	17.1	18.7	19.4	21.9	**22.2**	1.3%	2.9%	0.5%
India	149.3	157.0	160.6	168.3	178.3	179.5	184.7	199.8	219.5	227.1	**239.1**	5.3%	4.8%	5.1%
Indonesia	62.6	63.5	67.6	76.0	78.4	79.5	80.7	73.8	76.4	79.3	**83.4**	5.2%	2.1%	1.8%
Japan	232.4	208.2	210.5	211.0	224.9	214.7	204.0	196.5	191.0	187.8	**182.4**	-2.9%	-2.4%	3.9%
Malaysia	31.0	30.8	30.9	33.0	34.6	36.8	36.5	36.2	36.4	36.0	**36.9**	2.6%	1.1%	0.8%
New Zealand	7.5	7.2	7.3	7.3	7.2	7.4	7.5	7.8	7.9	8.5	**8.4**	-1.3%	1.4%	0.2%
Pakistan	19.8	21.2	21.0	21.1	20.5	22.4	23.2	25.3	28.3	29.2	**24.3**	-16.6%	4.1%	0.5%
Philippines	13.8	14.5	15.2	14.4	15.0	15.8	16.7	19.1	20.5	21.7	**22.0**	1.0%	4.2%	0.5%
Singapore	51.7	55.8	61.3	64.0	63.8	64.6	66.3	70.0	72.9	74.8	**75.8**	1.4%	4.4%	1.6%
South Korea	108.1	109.0	110.5	111.4	114.7	114.3	114.1	120.2	129.3	130.0	**128.9**	-0.8%	1.4%	2.8%
Sri Lanka	4.1	4.3	4.3	4.6	4.7	4.0	3.5	4.3	5.1	5.4	**5.3**	-1.6%	1.9%	0.1%
Taiwan	47.8	48.0	49.0	44.5	44.5	45.5	47.1	47.5	48.7	50.1	**50.0**	-0.1%	-0.6%	1.1%
Thailand	46.4	48.6	50.2	52.4	55.1	57.2	57.6	60.2	62.5	64.4	**65.8**	2.2%	3.1%	1.4%
Vietnam	14.6	14.8	16.0	17.4	17.6	19.0	19.5	21.2	22.5	23.6	**24.9**	5.1%	5.5%	0.5%
Other Asia Pacific	12.4	13.2	14.9	16.2	17.8	19.0	20.0	21.3	21.9	22.5	**22.5**	2.8%	5.8%	0.5%
Total Asia Pacific	1250.2	1262.6	1341.7	1384.7	1443.6	1469.1	1493.4	1548.9	1606.2	1651.3	**1695.4**	2.7%	2.8%	36.4%
Total World	**4142.9**	**4073.4**	**4201.9**	**4245.7**	**4297.8**	**4350.3**	**4385.3**	**4465.8**	**4548.3**	**4607.0**	**4662.1**	**1.2%**	**1.0%**	**100.0%**
of which: OECD	2288.9	2177.5	2198.5	2172.9	2151.9	2139.3	2120.1	2147.8	2180.5	2196.5	**2204.8**	0.4%	-0.7%	47.3%
Non-OECD	1853.9	1896.0	2003.4	2072.8	2145.8	2211.0	2265.3	2317.9	2367.7	2410.5	**2457.3**	1.9%	3.0%	52.7%
European Union	730.5	693.2	687.5	667.2	643.1	626.4	616.3	625.7	639.0	649.5	**646.8**	-0.4%	-1.2%	13.9%

*Inland demand plus international aviation and marine bunkers and refinery fuel and loss. Consumption of biogasoline (such as ethanol), biodiesel and derivatives of coal and natural gas are also included.
♦Less than 0.05%.
Notes: Differences between these world consumption figures and world production statistics are accounted for by stock changes, consumption of non-petroleum additives and substitute fuels, and unavoidable disparities in the definition, measurement or conversion of oil supply and demand data.
Annual changes and shares of total are calculated using million tonnes oil equivalent figures.
Oil consumption data expressed in million tonnes is available at *bp.com/statisticalreview*.

Table C8. Regional oil consumption by product group (Source: BP Statistical Review of World Energy 2019)

Oil: Regional consumption – by product group

Thousand barrels daily	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Growth rate per annum 2018	2007-17	Share 2018
North America														
Light distillates	10859	10839	10950	10697	10572	10778	10841	11092	11287	11229	**11195**	-0.3%	♦	45.3%
Middle distillates	6934	6281	6567	6694	6409	6519	6792	6814	6757	6927	**7212**	4.1%	-0.5%	29.2%
Fuel oil	941	801	810	745	662	576	447	418	474	519	**498**	-4.1%	-7.1%	2.0%
Others	5160	5080	5251	5248	5306	5520	5427	5547	5567	5613	**5810**	3.5%	0.1%	23.5%
Total North America	23894	23001	23578	23383	22949	23393	23507	23871	24086	24289	**24714**	1.8%	-0.3%	100.0%
of which: US														
Light distillates	9253	9257	9263	9022	8932	9125	9164	9413	9547	9566	**9556**	-0.1%	♦	46.7%
Middle distillates	5801	5241	5464	5518	5278	5371	5632	5657	5603	5742	**5961**	3.8%	-0.8%	29.1%
Fuel oil	609	508	532	459	367	317	256	258	325	341	**321**	-5.9%	-7.2%	1.6%
Others	3827	3766	3921	3883	3913	4147	4054	4203	4212	4309	**4618**	7.2%	0.3%	22.6%
Total US	19490	18771	19180	18882	18490	18961	19106	19531	19687	19958	**20456**	2.5%	-0.4%	100.0%
S. & Cent. America														
Light distillates	1678	1768	1868	1946	1989	2091	2152	2212	2184	2246	**2245**	♦	3.5%	33.0%
Middle distillates	2178	2144	2367	2485	2602	2725	2744	2726	2645	2640	**2679**	1.4%	2.2%	39.4%
Fuel oil	833	783	763	739	739	712	736	724	665	610	**582**	-4.6%	-2.7%	8.6%
Others	1352	1320	1336	1409	1385	1435	1403	1339	1298	1302	**1290**	-1.0%	0.6%	19.0%
Total S. & Cent. America	6041	6016	6335	6579	6715	6964	7034	7001	6792	6798	**6795**	♦	1.7%	100.0%
Europe														
Light distillates	3648	3585	3533	3323	3173	3083	3010	2937	2948	2985	**2955**	-1.0%	-2.6%	19.3%
Middle distillates	8060	7767	7869	7749	7624	7684	7636	7987	8144	8404	**8399**	-0.1%	0.7%	55.0%
Fuel oil	1633	1481	1338	1291	1166	1041	969	923	965	967	**953**	-1.5%	-5.5%	6.2%
Others	3217	3044	3012	2958	2864	2823	2775	2866	2976	2995	**2970**	-0.9%	-0.8%	19.4%
Total Europe	16558	15876	15752	15321	14826	14631	14389	14713	15032	15351	**15276**	-0.5%	-0.8%	100.0%
CIS														
Light distillates	1118	1104	1161	1172	1204	1246	1254	1245	1246	1268	**1292**	1.9%	1.8%	31.5%
Middle distillates	1152	1051	1149	1250	1256	1244	1221	1173	1195	1248	**1326**	6.3%	1.4%	32.4%
Fuel oil	376	343	336	358	354	363	432	346	365	311	**330**	6.1%	-2.6%	8.0%
Others	957	989	921	1058	1121	1062	1192	1191	1228	1206	**1151**	-4.6%	2.1%	28.1%
Total CIS	3602	3486	3567	3838	3935	3914	4099	3955	4034	4033	**4099**	1.6%	1.3%	100.0%
Middle East														
Light distillates	1565	1627	1665	1757	1838	1911	1981	2026	2067	2181	**2239**	2.6%	4.1%	24.5%
Middle distillates	2303	2301	2279	2411	2497	2631	2537	2465	2371	2301	**2272**	-1.3%	0.2%	24.9%
Fuel oil	1747	1901	1937	1989	2021	2120	2164	2206	2094	1975	**1920**	-2.8%	2.3%	21.0%
Others	1772	1898	2093	2144	2275	2248	2370	2402	2639	2681	**2705**	0.9%	4.8%	29.6%
Total Middle East	7386	7727	7974	8301	8631	8910	9053	9099	9172	9138	**9136**	♦	2.7%	100.0%
Africa														
Light distillates	761	802	838	819	872	886	906	970	1029	1078	**1097**	1.7%	4.4%	27.7%
Middle distillates	1460	1514	1616	1611	1682	1797	1836	1865	1843	1896	**1922**	1.4%	3.2%	48.6%
Fuel oil	435	446	461	395	438	433	435	422	403	380	**320**	-15.9%	-1.1%	8.1%
Others	542	561	567	572	582	589	593	599	603	607	**621**	2.2%	1.4%	15.7%
Total Africa	3198	3322	3481	3398	3574	3705	3770	3857	3878	3962	**3959**	-0.1%	2.7%	100.0%
Asia Pacific														
Light distillates	7424	7711	8331	8537	8966	9489	9780	10571	10944	11251	**11636**	3.4%	4.3%	32.4%
Middle distillates	9394	9403	9926	10341	10800	11021	11146	11339	11585	11925	**12268**	2.9%	2.5%	34.2%
Fuel oil	3360	3043	3046	3113	3218	2983	2823	2805	2852	2791	**2646**	-5.2%	-2.5%	7.4%
Others	5762	6194	6740	6951	7110	7265	7594	7836	8362	8868	**9313**	5.0%	4.3%	26.0%
Total Asia Pacific	25940	26351	28043	28942	30094	30759	31343	32551	33743	34835	**35863**	3.0%	2.9%	100.0%
of which: China														
Light distillates	1941	2055	2416	2605	2787	3117	3338	3781	3952	4072	**4368**	7.3%	8.4%	32.3%
Middle distillates	3085	3134	3452	3667	3963	4070	4130	4206	4154	4287	**4386**	2.3%	4.1%	32.4%
Fuel oil	724	662	666	588	560	564	592	591	556	576	**587**	1.8%	-4.4%	4.3%
Others	2164	2443	2912	2948	2932	2998	3179	3408	3642	3906	**4185**	7.1%	5.9%	30.9%
Total China	7914	8295	9446	9808	10242	10750	11239	11986	12304	12840	**13525**	5.3%	5.1%	100.0%
of which: India														
Light distillates	581	569	573	607	644	665	688	797	868	887	**976**	10.1%	4.9%	18.9%
Middle distillates	1350	1439	1519	1601	1686	1685	1694	1774	1848	1879	**1955**	4.0%	4.1%	37.9%
Fuel oil	226	222	199	178	147	117	107	113	136	122	**118**	-3.0%	-6.2%	2.3%
Others	981	1070	1089	1163	1271	1322	1425	1560	1802	1982	**2106**	6.3%	7.4%	40.9%
Total India	3137	3300	3381	3550	3747	3789	3914	4245	4654	4870	**5156**	5.9%	5.0%	100.0%
of which: Japan														
Light distillates	1614	1634	1696	1635	1614	1631	1575	1621	1570	1578	**1518**	-3.8%	-0.9%	39.4%
Middle distillates	1502	1381	1391	1343	1361	1345	1319	1281	1291	1296	**1280**	-1.2%	-2.2%	33.2%
Fuel oil	707	450	442	577	824	646	532	433	371	284	**269**	-5.6%	-8.0%	7.0%
Others	1025	925	913	887	903	895	876	816	788	817	**787**	-3.7%	-2.0%	20.4%
Total Japan	4847	4390	4442	4442	4702	4516	4303	4151	4019	3975	**3854**	-3.1%	-2.3%	100.0%
World														
Light distillates	27053	27435	28346	28252	28614	29484	29923	31052	31705	32237	**32658**	1.3%	1.7%	32.7%
Middle distillates	31480	30462	31772	32542	32869	33620	33912	34370	34540	35342	**36078**	2.1%	1.2%	36.1%
Fuel oil	9324	8797	8691	8630	8598	8230	8006	7844	7820	7554	**7249**	-4.0%	-2.3%	7.3%
Others	18761	19086	19920	20340	20643	20942	21354	21781	22674	23272	**23859**	2.5%	2.0%	23.9%
Total World	**86619**	**85780**	**88730**	**89763**	**90724**	**92276**	**93194**	**95048**	**96737**	**98406**	**99843**	**1.5%**	**1.2%**	**100.0%**
OECD														
Light distillates	17388	17390	17568	17115	16919	17058	17052	17353	17561	17645	**17502**	-0.8%	-0.3%	36.9%
Middle distillates	17373	16301	16727	16720	16389	16562	16775	17175	17343	17775	**18094**	1.8%	♦	38.1%
Fuel oil	3528	2921	2786	2791	2846	2444	2091	1922	1984	1903	**1857**	-2.4%	-6.5%	3.9%
Others	9898	9605	9695	9626	9597	9718	9536	9636	9801	9875	**10014**	1.4%	-0.4%	21.1%
Total OECD	48187	46217	46776	46253	45752	45782	45455	46086	46688	47199	**47466**	0.6%	-0.5%	100.0%
Non-OECD														
Light distillates	9665	10045	10779	11136	11695	12425	12871	13699	14144	14592	**15156**	3.9%	4.8%	28.9%
Middle distillates	14108	14161	15045	15821	16480	17058	17136	17195	17197	17567	**17984**	2.4%	2.6%	34.3%
Fuel oil	5797	5877	5905	5839	5752	5786	5915	5922	5836	5651	**5392**	-4.6%	-0.3%	10.3%
Others	8863	9481	10225	10714	11046	11225	11817	12145	12872	13397	**13845**	3.3%	4.3%	26.4%
Total Non-OECD	38432	39563	41954	43510	44973	46494	47739	48961	50049	51206	**52377**	2.3%	3.2%	100.0%

♦Less than 0.05%.
Notes: 'Light distillates' consists of aviation and motor gasolines and light distillate feedstock (LDF).
'Middle distillates' consists of jet and heating kerosenes, and gas and diesel oils (including marine bunkers).
'Fuel oil' includes marine bunkers and crude oil used directly as fuel.
'Others' consists of refinery gas, liquefied petroleum gas (LPG), solvents, petroleum coke, lubricants, bitumen, wax, other refined products and refinery fuel and loss.
Annual changes and shares of total are calculated using thousand barrels daily figures
An extended breakdown of oil consumption by product group is available at *bp.com/statisticalreview*.

Table C9. Global oil refinery throughput (Source: BP Statistical Review of World Energy 2019)

Oil: Refinery throughput

Thousand barrels daily*	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Growth rate per annum 2018	Growth rate per annum 2007-17	Share 2018
Canada	1781	1731	1770	1681	1753	1769	1559	1640	1595	1756	**1656**	-5.7%	-0.5%	2.0%
Mexico	1295	1184	1184	1166	1199	1223	1155	1064	933	767	**609**	-20.6%	-4.9%	0.7%
US	14648	14336	14724	14799	14997	15306	15844	16183	16185	16581	**16962**	2.3%	0.9%	20.4%
Total North America	17724	17251	17678	17646	17949	18298	18557	18887	18713	19104	**19227**	0.6%	0.4%	23.2%
Argentina	578	532	531	516	530	527	526	536	511	500	**470**	-5.9%	-1.8%	0.6%
Brazil	1760	1781	1787	1813	1889	2035	2085	1972	1812	1741	**1733**	-0.5%	◆	2.1%
Chile	204	192	159	173	164	174	174	165	163	172	**172**	-0.2%	-1.5%	0.2%
Colombia	313	302	300	306	305	284	247	244	339	355	**382**	7.6%	1.3%	0.5%
Curacao	197	183	64	164	165	170	189	178	156	84	**29**	-66.0%	-8.7%	◆
Ecuador	155	156	137	156	152	141	125	121	150	156	**159**	2.1%	0.4%	0.2%
Peru	174	199	201	193	190	186	188	188	194	213	**209**	-2.0%	1.9%	0.3%
Trinidad & Tobago	150	152	126	137	107	132	105	125	148	131	**99**	-24.5%	-1.6%	0.1%
Venezuela	1010	961	969	991	936	952	920	863	654	544	**306**	-43.7%	-5.9%	0.4%
Other S. & Cent. America	961	801	702	711	329	293	282	279	274	235	**254**	8.0%	-13.2%	0.3%
Total S. & Cent. America	5502	5258	4976	5160	4767	4895	4841	4670	4402	4132	**3813**	-7.7%	-2.8%	4.6%
Austria	176	169	158	168	170	174	173	179	164	162	**180**	11.0%	-0.7%	0.2%
Belgium	675	629	668	598	634	555	645	644	640	685	**663**	-3.1%	0.3%	0.8%
Bulgaria	143	125	110	102	118	113	104	121	125	136	**118**	-13.1%	-0.4%	0.1%
Czech Republic	165	148	159	143	145	134	151	145	109	158	**151**	-4.5%	0.6%	0.2%
Denmark	156	157	146	137	153	144	139	147	140	151	**152**	1.0%	-0.4%	0.2%
Finland	222	220	211	225	215	227	225	197	226	226	**233**	3.0%	0.4%	0.3%
France	1676	1449	1314	1313	1138	1117	1096	1152	1122	1149	**1086**	-5.5%	-3.6%	1.3%
Germany	2151	2026	1915	1876	1901	1857	1833	1875	1887	1870	**1775**	-5.1%	-1.6%	2.1%
Greece	360	346	393	331	410	399	416	436	464	483	**489**	1.2%	2.3%	0.6%
Hungary	140	127	128	132	122	120	131	130	133	131	**141**	8.0%	-0.8%	0.2%
Italy	1741	1614	1673	1570	1475	1259	1198	1347	1293	1399	**1346**	-3.8%	-2.8%	1.6%
Lithuania	195	174	190	189	181	192	160	170	187	197	**195**	-1.3%	5.2%	0.2%
Netherlands	1120	1104	1156	1115	1110	1065	1090	1157	1172	1180	**1192**	1.0%	0.4%	1.4%
Norway	279	278	259	289	287	292	274	293	230	281	**286**	1.7%	-0.8%	0.3%
Poland	417	408	458	482	505	488	486	532	517	508	**540**	6.3%	2.4%	0.7%
Portugal	241	209	227	206	221	239	217	278	279	284	**251**	-11.7%	1.4%	0.3%
Romania	282	247	217	194	182	189	194	208	228	225	**232**	2.8%	-2.1%	0.3%
Slovakia	117	114	110	120	108	116	105	119	115	112	**109**	-2.3%	-0.7%	0.1%
Spain	1174	1057	1060	1051	1186	1168	1185	1306	1302	1326	**1365**	2.9%	1.4%	1.6%
Sweden	413	394	406	374	417	332	380	401	395	392	**406**	3.6%	0.6%	0.5%
Turkey	490	375	392	394	398	421	406	526	531	542	**478**	-11.7%	0.4%	0.6%
Ukraine	243	255	249	206	108	85	69	64	64	77	**60**	-21.5%	-12.1%	0.1%
United Kingdom	1533	1440	1395	1433	1348	1197	1125	1118	1071	1073	**1054**	-1.8%	-3.5%	1.3%
Other Europe	343	349	334	304	262	291	281	265	270	287	**285**	-0.7%	-2.2%	0.3%
Total Europe	14454	13414	13327	12953	12793	12173	12082	12810	12665	13033	**12786**	-1.9%	-1.1%	15.4%
Azerbaijan	147	121	124	127	124	132	135	130	120	118	**125**	6.2%	-2.4%	0.2%
Belarus	427	434	330	411	434	425	448	462	372	364	**376**	3.3%	-1.6%	0.5%
Kazakhstan	236	235	257	326	331	341	361	342	339	355	**374**	5.4%	4.5%	0.5%
Russian Federation	4742	4765	5018	5185	5438	5636	5926	5773	5715	5703	**5833**	2.3%	2.2%	7.0%
Turkmenistan	148	152	170	164	156	146	136	127	118	125	**117**	-5.8%	-1.5%	0.1%
Uzbekistan	93	88	73	69	62	61	50	57	57	58	**70**	19.2%	-4.8%	0.1%
Other CIS	3	3	3	3	2	2	4	7	8	9	**10**	15.9%	10.6%	◆
Total CIS	5797	5798	5975	6286	6548	6742	7060	6899	6730	6732	**6905**	2.6%	1.8%	8.3%
Bahrain	257	256	265	259	263	264	257	266	258	262	**261**	-0.2%	◆	0.3%
Iran	1779	1826	1829	1873	1932	1999	1932	1867	1882	1968	**2026**	2.9%	1.4%	2.4%
Iraq	476	417	520	543	579	598	487	409	440	527	**596**	13.2%	4.4%	0.7%
Israel	215	220	226	218	219	221	231	232	219	218	**231**	6.0%	1.4%	0.3%
Kuwait	906	869	892	852	916	873	879	905	841	686	**679**	-1.0%	-2.9%	0.8%
Oman	214	203	167	201	193	187	180	190	178	232	**282**	21.8%	12.9%	0.3%
Qatar	145	158	294	278	292	270	261	253	280	379	**397**	4.8%	9.7%	0.5%
Saudi Arabia	2018	1928	1922	1884	1953	1876	2201	2447	2753	2802	**2770**	-1.1%	3.8%	3.3%
United Arab Emirates	493	492	571	635	638	650	643	1098	1077	1008	**1044**	3.6%	6.6%	1.3%
Other Middle East	391	386	381	349	268	238	230	181	144	161	**144**	-10.7%	-8.6%	0.2%
Total Middle East	6894	6754	7067	7091	7253	7176	7301	7846	8072	8242	**8431**	2.3%	2.4%	10.2%
Algeria	429	475	548	520	478	492	615	591	584	573	**598**	4.5%	3.9%	0.7%
Egypt	617	598	580	523	534	514	530	530	509	508	**519**	2.2%	-2.5%	0.6%
Morocco	114	93	110	103	111	111	104	53	–	–	**–**	n/a	-100.0%	–
Nigeria	107	49	96	108	92	97	64	22	62	81	**44**	-46.1%	4.5%	0.1%
South Africa	408	388	389	383	403	413	431	443	464	447	**455**	1.7%	1.4%	0.5%
Other Africa	718	696	701	512	586	594	444	455	460	435	**423**	-2.7%	-5.0%	0.5%
Total Africa	2394	2299	2424	2150	2205	2220	2188	2093	2079	2044	**2039**	-0.2%	-1.4%	2.5%
Australia	570	577	606	627	600	588	538	427	433	419	**477**	13.8%	-3.8%	0.6%
China	6828	7452	8408	8686	9199	9599	10155	10684	11084	11656	**12441**	6.7%	5.9%	15.0%
India	3213	3641	3899	4085	4302	4462	4475	4561	4930	5010	**5154**	2.9%	4.9%	6.2%
Indonesia	910	900	853	880	820	822	848	836	885	885	**916**	3.4%	-0.2%	1.1%
Japan	3946	3627	3619	3410	3400	3453	3289	3258	3280	3215	**3059**	-4.8%	-2.2%	3.7%
Malaysia	560	554	470	516	575	558	553	514	574	599	**596**	-0.5%	0.7%	0.7%
New Zealand	99	95	99	108	109	105	101	109	108	108	**103**	-4.1%	1.7%	0.1%
Pakistan	226	209	190	193	192	223	232	257	242	261	**275**	5.5%	0.9%	0.3%
Philippines	184	147	181	190	170	158	168	212	216	211	**237**	12.1%	0.3%	0.3%
Singapore	1161	844	979	1035	1020	936	871	937	973	1068	**1047**	-2.0%	-0.8%	1.3%
South Korea	2365	2297	2390	2533	2582	2484	2516	2784	2928	3061	**3030**	-1.0%	2.4%	3.7%
Taiwan	900	956	876	809	897	847	850	838	861	848	**889**	4.9%	-1.6%	1.1%
Thailand	927	938	963	934	986	1056	1005	1107	1056	1093	**1131**	3.4%	1.7%	1.4%
Vietnam	10	28	121	137	130	140	121	146	145	144	**266**	85.0%	30.5%	0.3%
Other Asia Pacific	118	115	122	126	113	126	120	113	125	128	**129**	1.2%	0.7%	0.2%
Total Asia Pacific	22017	22380	23775	24267	25094	25556	25841	26783	27840	28707	**29751**	3.6%	2.7%	35.9%
Total World	**74782**	**73154**	**75222**	**75552**	**76609**	**77060**	**77870**	**79989**	**80501**	**81992**	**82953**	**1.2%**	**0.9%**	**100.0%**
of which: OECD	38532	36673	37154	36818	37096	36780	36833	37968	37758	38528	**38316**	-0.5%	-0.2%	46.2%
Non-OECD	36250	36482	38068	38735	39513	40280	41037	42021	42742	43465	**44637**	2.7%	2.1%	53.8%
European Union	13246	12307	12237	11885	11861	11202	11154	11788	11698	11980	**11808**	-1.4%	-1.0%	14.2%

*Atmospheric distillation capacity on a calendar-day basis.
◆Less than 0.05%.
n/a not available.

Source: Includes data from ICIS.

Table C10. Global oil refining capacity (Source: BP Statistical Review of World Energy 2019)

Oil: Refining capacity

Thousand barrels daily*	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Growth rate per annum 2018	Growth rate per annum 2007-17	Share 2018
Canada	1951	1976	1913	2005	2015	1929	1929	1931	1934	1970	**2025**	2.8%	0.3%	2.0%
Mexico	1463	1463	1463	1606	1606	1606	1522	1522	1522	1546	**1546**	–	0.6%	1.5%
US	17672	17597	17736	17367	17823	17925	17967	18317	18617	18567	**18762**	1.1%	0.5%	18.8%
Total North America	21086	21036	21112	20977	21443	21460	21418	21770	22073	22082	**22333**	1.1%	0.5%	22.3%
Argentina	628	625	625	625	657	657	657	657	657	657	**580**	-11.7%	0.5%	0.6%
Brazil	1977	1992	1992	2014	2004	2097	2238	2281	2289	2285	**2285**	–	1.5%	2.3%
Chile	242	242	242	250	254	254	258	258	258	258	**258**	–	0.6%	0.3%
Colombia	326	336	336	336	336	336	336	421	421	421	**421**	–	2.7%	0.4%
Curacao	320	320	320	320	320	320	320	320	320	320	**320**	–	–	0.3%
Ecuador	175	175	175	175	175	175	175	175	175	175	**175**	–	–	0.2%
Peru	230	252	252	252	252	253	253	253	253	253	**253**	–	1.3%	0.3%
Trinidad & Tobago	165	165	165	165	165	165	165	165	165	165	**–**	-100.0%	–	♦
Venezuela	1303	1303	1303	1303	1303	1303	1303	1303	1303	1303	**1303**	–	–	1.3%
Other S. & Cent. America	1176	900	901	1013	356	361	376	384	384	384	**384**	–	-10.7%	0.4%
Total S. & Cent. America	6542	6310	6311	6453	5822	5921	6081	6217	6225	6221	**5979**	-3.9%	-0.5%	6.0%
Austria	201	201	201	193	193	193	193	193	193	193	**193**	–	-0.4%	0.2%
Belgium	786	786	787	788	753	776	776	776	776	776	**776**	–	-0.1%	0.8%
Bulgaria	175	180	195	195	195	195	195	195	195	195	**195**	–	1.1%	0.2%
Czech Republic	193	193	193	193	175	175	175	175	175	175	**175**	–	-1.0%	0.2%
Denmark	189	189	189	181	181	181	180	180	180	181	**181**	–	-0.4%	0.2%
Finland	261	261	261	261	261	261	261	261	261	261	**261**	–	–	0.3%
France	1971	1847	1702	1610	1513	1375	1375	1375	1245	1245	**1245**	–	-4.4%	1.2%
Germany	2366	2362	2091	2077	2097	2061	2077	2049	2051	2069	**2085**	0.8%	-1.4%	2.1%
Greece	425	425	490	495	498	498	498	528	528	528	**528**	–	2.2%	0.5%
Hungary	165	165	165	165	165	165	165	165	165	165	**165**	–	–	0.2%
Italy	2396	2396	2396	2276	2098	1861	1900	1900	1900	1900	**1900**	–	-2.2%	1.9%
Lithuania	241	241	241	241	241	241	241	241	241	241	**241**	–	–	0.2%
Netherlands	1280	1280	1274	1276	1274	1274	1274	1293	1293	1294	**1294**	–	0.5%	1.3%
Norway	316	316	316	329	342	342	342	342	342	342	**342**	–	0.8%	0.3%
Poland	492	491	560	580	582	582	582	581	581	568	**581**	2.3%	1.4%	0.6%
Portugal	306	306	306	306	330	330	330	330	330	330	**330**	–	0.7%	0.3%
Romania	358	283	247	229	214	235	228	239	256	247	**254**	3.0%	-4.5%	0.3%
Slovakia	122	122	122	122	122	122	122	122	122	122	**122**	–	–	0.1%
Spain	1362	1362	1421	1542	1546	1546	1546	1562	1562	1562	**1564**	0.1%	1.4%	1.6%
Sweden	454	454	454	454	454	454	454	454	454	454	**454**	–	–	0.5%
Turkey	613	613	613	596	596	596	596	596	596	596	**818**	37.2%	-0.3%	0.8%
Ukraine	566	582	484	484	258	272	250	250	250	250	**250**	–	-7.2%	0.2%
United Kingdom	1827	1757	1757	1787	1526	1498	1337	1337	1227	1227	**1227**	–	-3.9%	1.2%
Other Europe	613	635	635	619	607	591	591	519	519	501	**501**	–	-2.0%	0.5%
Total Europe	17679	17447	17102	17000	16220	15824	15688	15664	15443	15421	**15681**	1.7%	-1.3%	15.7%
Azerbaijan	205	205	205	205	205	205	205	205	205	205	**120**	-41.5%	–	0.1%
Belarus	460	460	460	460	460	460	460	460	460	490	**520**	6.1%	0.6%	0.5%
Kazakhstan	330	330	330	330	330	350	350	350	350	360	**390**	8.3%	0.9%	0.4%
Russian Federation	5387	5425	5563	5721	5816	6279	6417	6523	6594	6596	**6596**	–	1.9%	6.6%
Turkmenistan	251	251	251	251	251	251	251	271	271	271	**271**	–	0.8%	0.3%
Uzbekistan	232	232	232	232	232	232	232	232	232	232	**232**	–	–	0.2%
Other CIS	10	10	14	10	10	11	28	37	37	37	**37**	–	14.0%	♦
Total CIS	6875	6913	7055	7209	7304	7788	7943	8078	8149	8191	**8166**	-0.3%	1.6%	8.2%
Bahrain	260	260	260	260	260	260	260	260	260	260	**260**	–	–	0.3%
Iran	1805	1860	1860	1860	1952	1985	1985	1985	1985	2105	**2225**	5.7%	1.7%	2.2%
Iraq	738	853	914	935	971	823	791	763	779	779	**859**	10.3%	0.5%	0.9%
Israel	275	275	280	292	292	294	301	301	301	301	**301**	–	1.0%	0.3%
Kuwait	936	936	936	936	936	936	936	936	936	736	**736**	–	-2.4%	0.7%
Oman	222	222	222	222	222	222	222	222	222	304	**334**	9.9%	3.5%	0.3%
Qatar	137	283	283	283	283	283	283	283	429	429	**429**	–	12.1%	0.4%
Saudi Arabia	2102	2109	2109	2107	2107	2507	2899	2899	2901	2826	**2835**	0.3%	3.0%	2.8%
United Arab Emirates	682	702	702	707	712	712	728	1149	1149	1229	**1229**	–	7.0%	1.2%
Other Middle East	496	496	496	496	496	382	382	382	382	496	**496**	–	–	0.5%
Total Middle East	7653	7996	8062	8098	8231	8404	8787	9180	9344	9465	**9704**	2.5%	2.3%	9.7%
Algeria	444	554	554	652	652	647	651	651	651	657	**657**	–	4.0%	0.7%
Egypt	810	810	810	810	810	810	810	810	810	810	**795**	-1.9%	–	0.8%
Morocco	131	131	131	131	201	201	201	201	201	201	**201**	–	2.6%	0.2%
Nigeria	250	110	211	336	336	336	339	339	339	339	**344**	1.5%	8.5%	0.3%
South Africa	520	520	520	520	520	520	520	520	520	520	**520**	–	–	0.5%
Other Africa	958	958	959	780	910	930	932	932	932	912	**917**	0.5%	-0.5%	0.9%
Total Africa	3113	3083	3185	3229	3429	3443	3453	3453	3453	3439	**3434**	-0.1%	1.3%	3.4%
Australia	734	734	740	742	663	662	536	443	452	454	**454**	–	-4.7%	0.5%
China	10360	11334	12323	13015	13643	14503	15253	15024	14855	15231	**15655**	2.8%	4.9%	15.6%
India	2992	3574	3703	3795	4279	4319	4319	4307	4620	4699	**4972**	5.8%	4.6%	5.0%
Indonesia	1094	1099	1099	1099	1099	1099	1099	1111	1111	1111	**1116**	0.5%	0.1%	1.1%
Japan	4650	4630	4291	4274	4254	4123	3749	3721	3600	3343	**3343**	–	-3.2%	3.3%
Malaysia	568	572	582	601	606	612	612	612	618	625	**625**	–	1.6%	0.6%
New Zealand	103	136	136	136	136	136	136	136	136	136	**136**	–	2.8%	0.1%
Pakistan	274	276	279	279	275	390	390	389	389	401	**401**	0.1%	3.9%	0.4%
Philippines	270	267	264	261	261	270	271	271	271	271	**271**	–	♦	0.3%
Singapore	1427	1427	1427	1427	1422	1414	1514	1514	1514	1514	**1514**	–	0.6%	1.5%
South Korea	2712	2746	2774	2864	2878	2878	3123	3128	3259	3298	**3346**	1.4%	2.1%	3.3%
Taiwan	1197	1197	1197	1197	1197	1197	1197	988	988	1083	**1083**	–	-1.0%	1.1%
Thailand	1165	1236	1230	1230	1230	1237	1252	1252	1235	1235	**1235**	–	1.2%	1.2%
Vietnam	11	159	159	159	159	159	159	159	163	167	**367**	119.8%	31.3%	0.4%
Other Asia Pacific	208	216	216	217	218	227	234	234	234	234	**234**	–	1.3%	0.2%
Total Asia Pacific	27766	29602	30418	31296	32320	33225	33843	33288	33443	33802	**34752**	2.8%	2.4%	34.7%
Total World	**90713**	**92387**	**93245**	**94262**	**94769**	**96065**	**97214**	**97650**	**98129**	**98621**	**100049**	**1.4%**	**1.0%**	**100.0%**
of which: OECD	45743	45539	45089	44983	44806	44311	43919	44120	44202	44002	**44553**	1.3%	-0.3%	44.5%
Non-OECD	44970	46848	48156	49279	49964	51754	53295	53530	53927	54618	**55496**	1.6%	2.2%	55.5%
European Union	15818	15548	15301	15219	14664	14270	14156	14204	13983	13979	**14017**	0.3%	-1.2%	14.0%

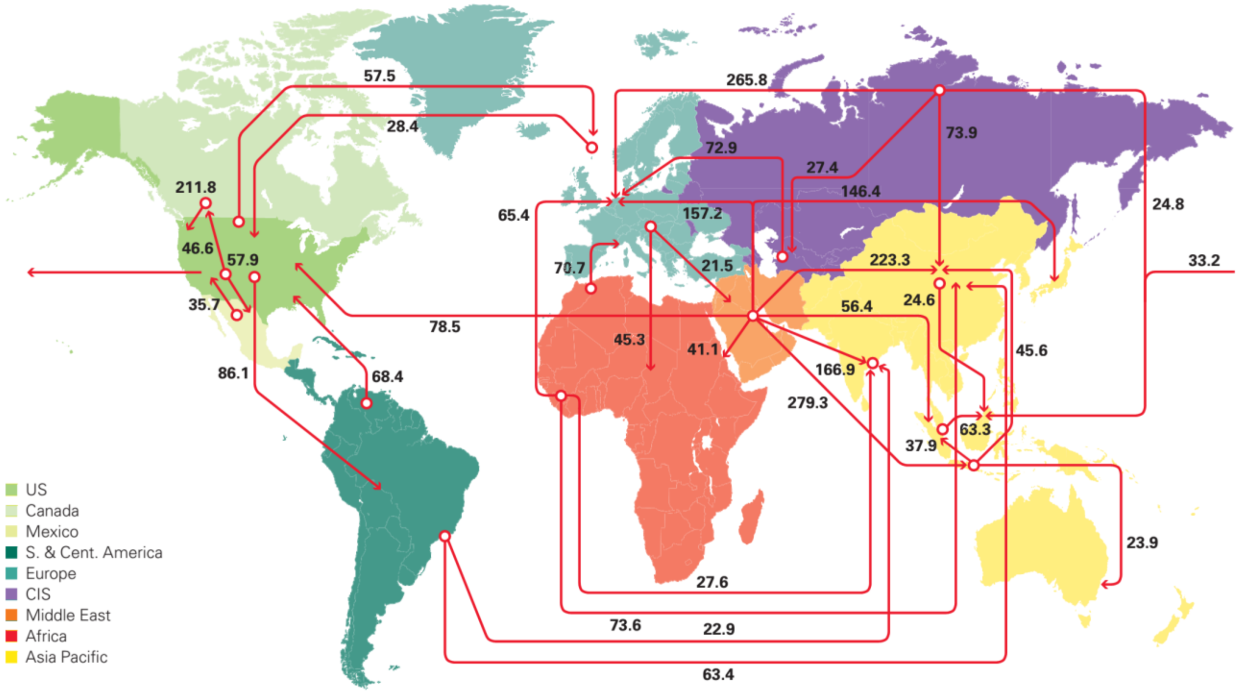
*Atmospheric distillation capacity at year end on a calendar-day basis.
♦Less than 0.05%.

Source: Includes data from ICIS.

Table C11. Global oil trade movements 1 (Source: BP Statistical Review of World Energy 2019)

Major trade movements 2018

Trade flows worldwide (million tonnes)



Oil trade in 2017 and 2018

Million tonnes	2017 Crude imports	2017 Product imports	2017 Crude exports	2017 Product exports	2018 Crude imports	2018 Product imports	2018 Crude exports	2018 Product exports
Canada	31.4	33.2	174.7	35.3	29.1	37.0	190.9	33.3
Mexico	†	57.3	57.8	6.7	0.1	64.4	61.7	5.8
US	396.9	104.1	46.9	235.1	386.3	103.9	93.2	251.6
S. & Cent. America	23.7	103.6	168.4	29.2	27.0	106.9	156.7	28.6
Europe	515.8	207.7	23.5	139.4	519.2	224.7	31.2	134.0
Russia	0.6	9.0	272.9	167.4	0.5	9.4	275.9	173.1
Other CIS	18.2	10.7	90.0	19.3	18.6	10.1	85.9	21.3
Iraq	†	2.5	187.2	5.4	†	3.7	200.9	8.5
Kuwait	†	0.7	102.9	26.8	†	0.7	103.0	23.5
Saudi Arabia	†	6.8	357.6	55.1	†	10.9	367.4	56.2
United Arab Emirates	8.1	22.8	128.3	73.0	9.8	27.8	125.9	75.8
Other Middle East	26.2	17.0	218.4	57.1	30.9	16.2	192.1	64.3
North Africa	5.2	29.3	82.5	26.7	7.0	28.8	95.6	27.1
West Africa	0.4	36.5	219.0	8.8	0.5	39.4	219.9	7.5
East & S. Africa	17.8	36.0	8.0	3.6	21.6	33.4	7.7	3.4
Australasia	21.9	31.3	9.6	2.8	23.6	33.6	10.9	3.7
China	422.1	84.4	3.8	50.5	464.5	81.9	2.7	55.7
India	211.1	33.9	0.1	54.1	227.5	31.3	0.1	53.4
Japan	162.5	42.1	0.2	18.7	150.8	43.7	†	17.6
Singapore	53.6	132.9	2.7	96.9	52.2	115.5	0.6	89.7
Other Asia Pacific	280.1	220.0	41.2	109.7	293.8	215.5	40.8	104.7
Total World	**2195.6**	**1221.8**	**2195.6**	**1221.8**	**2263.1**	**1238.8**	**2263.1**	**1238.8**

Thousand barrels daily	2017 Crude imports	2017 Product imports	2017 Crude exports	2017 Product exports	2018 Crude imports	2018 Product imports	2018 Crude exports	2018 Product exports
Canada	630	694	3509	739	584	774	3834	696
Mexico	‡	1198	1161	139	3	1345	1239	121
US	7972	2177	943	4915	7757	2172	1872	5259
S. & Cent. America	476	2167	3381	611	542	2235	3147	598
Europe	10357	4342	472	2915	10426	4698	627	2801
Russia	13	188	5480	3499	10	196	5540	3619
Other CIS	365	224	1807	403	373	211	1725	445
Iraq	‡	53	3760	113	‡	78	4035	177
Kuwait	‡	15	2066	561	‡	15	2068	491
Saudi Arabia	‡	142	7181	1152	‡	228	7379	1175
United Arab Emirates	163	476	2577	1526	198	581	2528	1586
Other Middle East	526	355	4385	1194	621	338	3858	1344
North Africa	103	613	1656	558	141	602	1920	566
West Africa	9	763	4399	183	10	825	4415	157
East & S. Africa	356	752	160	76	435	698	154	72
Australasia	439	654	192	59	475	703	219	77
China	8477	1763	77	1055	9328	1711	54	1164
India	4240	708	1	1131	4569	655	1	1117
Japan	3263	879	4	392	3028	913	‡	369
Singapore	1077	2779	55	2027	1048	2414	13	1874
Other Asia Pacific	5626	4600	827	2294	5901	4504	820	2188
Total World	**44093**	**25541**	**44093**	**25541**	**45448**	**25896**	**45448**	**25896**

†Less than 0.05.
‡Less than 0.5.
Notes: Does not include biofuels trade. Bunker fuel use is not included as exports. Intra-area movements (for example, between countries within Europe) are excluded. Crude imports and exports include condensates.

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Table C12. Global oil trade movements 2 (Source: BP Statistical Review of World Energy 2019)

Oil: Trade movements

Thousand barrels daily	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Growth rate per annum 2018	Growth rate per annum 2007-17	Share 2018
Imports														
US	12872	11453	11689	11338	10587	9859	9241	9451	10056	10148	**9929**	-2.2%	-2.9%	13.9%
Europe	14066	12802	12407	12489	12721	12920	12957	13993	14354	14699	**15124**	2.9%	0.3%	21.2%
China	4494	5100	5886	6295	6675	6978	7398	8333	9214	10240	**11039**	7.8%	9.4%	15.5%
India	3066	3491	3749	3823	4168	4370	4155	4380	4945	4947	**5223**	5.6%	5.4%	7.3%
Japan	4925	4263	4567	4494	4743	4637	4383	4332	4180	4142	**3941**	-4.8%	-1.9%	5.5%
Rest of World	17138	17211	17048	17634	17812	20012	21193	22026	23776	25457	**26087**	2.5%	3.9%	36.6%
Total World	**56561**	**54320**	**55346**	**56072**	**56706**	**58776**	**59328**	**62515**	**66526**	**69633**	**71344**	**2.5%**	**1.9%**	**100.0%**
Exports														
Canada	2498	2518	2599	2798	3056	3296	3536	3836	3890	4248	**4530**	6.6%	5.6%	6.3%
Mexico	1609	1449	1539	1487	1366	1347	1293	1323	1380	1300	**1360**	4.7%	-4.1%	1.9%
US	1967	1947	2154	2495	2682	3563	4033	4521	5078	5858	**7131**	21.7%	15.1%	10.0%
S. & Cent. America	3616	3748	3568	3755	3830	3790	3939	4107	4147	3992	**3745**	-6.2%	1.1%	5.2%
Europe	2073	2076	1966	2139	2181	2545	2467	2926	3082	3387	**3428**	1.2%	3.9%	4.8%
Russia	7540	7257	7397	7448	7457	7948	7792	8313	8814	8979	**9159**	2.0%	1.4%	12.8%
Other CIS	1730	1861	2039	2180	1962	2166	2092	2100	2096	2210	**2170**	-1.8%	3.5%	3.0%
Saudi Arabia	8357	7276	7595	8120	8468	8365	7911	7968	8606	8333	**8553**	2.6%	0.3%	12.0%
Middle East (ex S. Arabia)	12415	11744	11976	12188	11742	12242	12699	13537	15321	16183	**16087**	-0.6%	2.9%	22.5%
North Africa	3268	2943	2878	1951	2602	2127	1743	1701	1727	2214	**2486**	12.3%	-4.0%	3.5%
West Africa	4712	4531	4755	4759	4724	4590	4849	4880	4401	4582	**4572**	-0.2%	-0.8%	6.4%
Asia Pacific (ex Japan)	5392	5631	6226	6088	6299	6307	6450	6780	7356	7716	**7527**	-2.5%	2.5%	10.6%
Rest of World	1385	1340	653	663	338	491	524	525	625	632	**594**	-5.9%	-9.3%	0.8%
Total World	**56561**	**54320**	**55346**	**56072**	**56706**	**58776**	**59328**	**62515**	**66526**	**69633**	**71344**	**2.5%**	**1.9%**	**100.0%**

Notes: Unless otherwise stated, this table shows inter-regional trade based on the regional classification in the table 'Oil trade in 2017 and 2018' (see page 29).
Does not include biofuels trade. Bunker fuel use is not included as exports.
Annual changes and shares of total are calculated using thousand barrels daily figures.

Table C13. Global oil price (Source: BP Statistical Review of World Energy 2019)

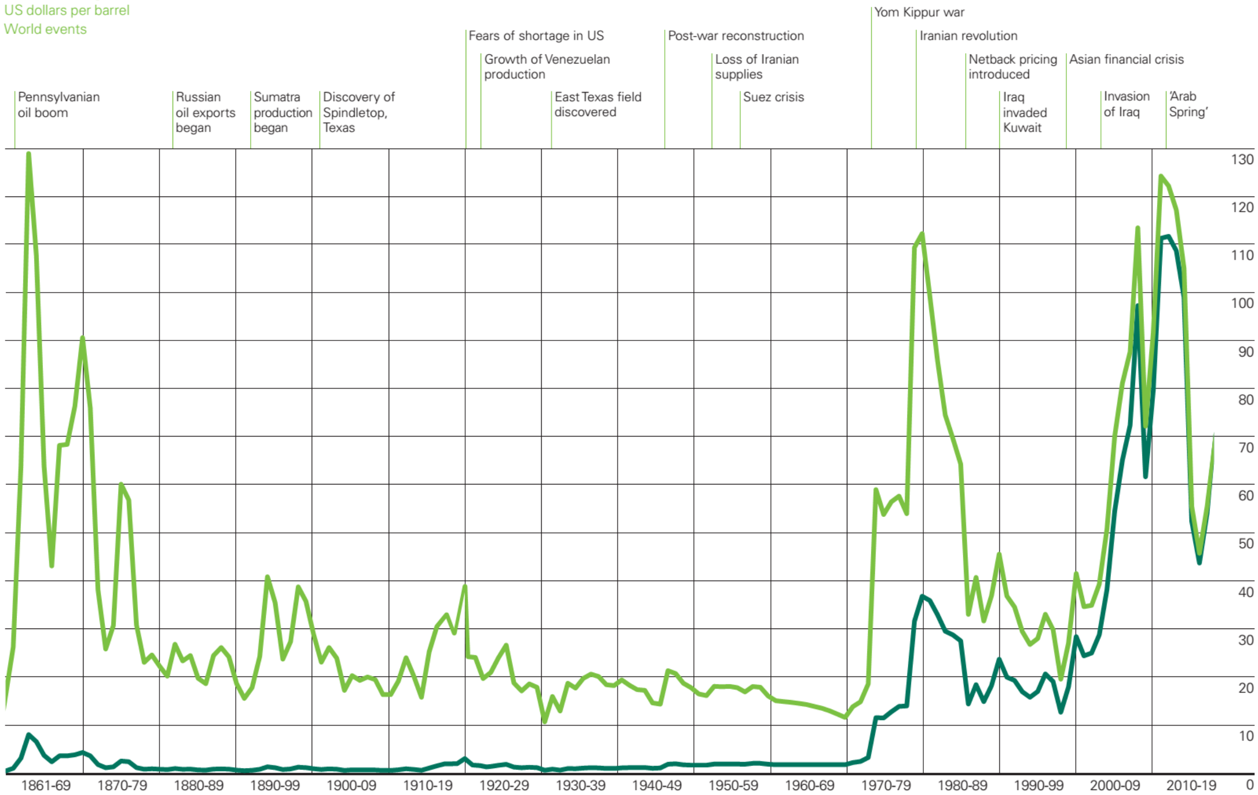
Spot crude prices

US dollars per barrel	Dubai $/bbl*	Brent $/bbl†	Nigerian Forcados $/bbl	West Texas Intermediate $/bbl‡
1983	28.78	29.55	29.54	30.30
1984	28.06	28.78	28.14	29.39
1985	27.53	27.56	27.75	27.98
1986	13.10	14.43	14.46	15.05
1987	16.95	18.44	18.39	19.19
1988	13.18	14.92	15.00	15.98
1989	15.65	18.23	18.30	19.67
1990	20.26	23.73	23.85	24.46
1991	16.63	20.00	20.11	21.53
1992	17.17	19.32	19.61	20.57
1993	14.93	16.97	17.41	18.45
1994	14.74	15.82	16.25	17.21
1995	16.10	17.02	17.26	18.42
1996	18.52	20.67	21.16	22.16
1997	18.23	19.09	19.33	20.61
1998	12.21	12.72	12.62	14.39
1999	17.25	17.97	18.00	19.31
2000	26.20	28.50	28.42	30.37
2001	22.81	24.44	24.23	25.93
2002	23.74	25.02	25.04	26.16
2003	26.78	28.83	28.66	31.06
2004	33.64	38.27	38.13	41.49
2005	49.35	54.52	55.69	56.59
2006	61.50	65.14	67.07	66.04
2007	68.19	72.39	74.48	72.20
2008	94.34	97.26	101.43	100.06
2009	61.39	61.67	63.35	61.92
2010	78.06	79.50	81.05	79.45
2011	106.18	111.26	113.65	95.04
2012	109.08	111.67	114.21	94.13
2013	105.47	108.66	111.95	97.99
2014	97.07	98.95	101.35	93.28
2015	51.20	52.39	54.41	48.71
2016	41.19	43.73	44.54	43.34
2017	53.13	54.19	54.31	50.79
2018	69.51	71.31	72.47	65.20

*1983-1985 Arabian Light, 1986-2018 Dubai dated.
†1983 Forties, 1984-2018 Brent dated.
‡1983 Posted WTI prices, 1984-2018 Spot WTI (Cushing) prices.

Crude oil prices 1861-2018

US dollars per barrel
World events



■ $ 2018 (deflated using the Consumer Price Index for the US)
■ $ money of the day

1861-1944 US average.
1945-1983 Arabian Light posted at Ras Tanura.
1984-2018 Brent dated.

Table C13.1. Crude oil production in EU, US and China
(Source: BP Statistical Review of World Energy 2019 and BP Statistical Review of World Energy 2011)

Year	European Union (kbbls/day)	United States (kbbls/day)	China (kbbls/day)	India (kbbls/day)
1965	707	9014	227	62
1966	706	9579	292	96
1967	713	10219	278	117
1968	711	10600	320	120
1969	707	10828	436	139
1970	702	11297	615	140
1971	685	11156	790	148
1972	676	11185	913	152
1973	681	10946	1075	148
1974	693	10461	1301	155
1975	720	10008	1545	171
1976	933	9736	1743	178
1977	1462	9863	1878	210
1978	1771	10274	2087	233
1979	2240	10136	2129	265
1980	2277	10170	2119	193
1981	2471	10181	2030	309
1982	2819	10199	2048	412
1983	3130	10247	2127	525
1984	3362	10509	2292	583
1985	3430	10580	2505	627
1986	3443	10231	2621	658
1987	3382	9944	2690	639
1988	3196	9765	2741	672
1989	2714	9159	2760	719
1990	2667	8914	2774	715
1991	2651	9076	2828	677
1992	2707	8868	2841	615
1993	2839	8583	2888	590
1994	3437	8389	2930	684
1995	3495	8322	2989	774
1996	3477	8295	3170	736
1997	3454	8269	3211	754
1998	3553	8011	3212	737
1999	3684	7731	3213	736
2000	3493	7733	3252	726
2001	3285	7669	3306	727
2002	3339	7626	3346	753
2003	3128	7400	3401	756
2004	2902	7228	3481	773
2005	2659	6895	3637	738
2006	2422	6841	3705	762
2007	2388	6847	3737	769
2008	2258	6783	3814	818
2009	2119	7259	3805	838
2010	1981	7552	4077	901
2011	1712	7870	4074	937
2012	1518	8910	4155	926
2013	1425	10073	4216	926
2014	1405	11773	4246	905
2015	1499	12773	4309	893
2016	1483	12340	3999	874
2017	1464	13135	3846	884
2018	1533	15311	3798	869

Table C13.2. Crude oil consumption in EU, US and China
(Source: BP Statistical Review of World Energy 2019 and BP Statistical Review of World Energy 2011)

Year	European Union (kbbls/day)	United States (kbbls/day)	China (kbbls/day)	India (kbbls/day)
1965	7792	11522	216	253
1966	8563	12100	277	282
1967	9298	12567	274	290
1968	10177	13405	299	325
1969	11413	14153	402	393
1970	12636	14710	556	391
1971	13238	15223	755	417
1972	14154	16381	867	448
1973	15168	17318	1061	474
1974	14255	16631	1220	465
1975	13752	16334	1346	477
1976	14653	17461	1539	503
1977	14531	18443	1630	543
1978	15227	18756	1823	589
1979	15600	18438	1831	634
1980	14542	17062	1690	644
1981	13619	16060	1612	698
1982	12958	15295	1597	728
1983	12665	15235	1638	766
1984	12756	15725	1695	824
1985	12982	15726	1820	897
1986	13372	16281	1934	945
1987	13421	16665	2055	975
1988	13546	17283	2203	1071
1989	13632	17325	2338	1165
1990	13807	16988	2320	1213
1991	13908	16713	2520	1234
1992	13925	17033	2736	1298
1993	13808	17236	3047	1314
1994	13829	17719	3115	1413
1995	14048	17725	3394	1581
1996	14338	18309	3722	1701
1997	14479	18621	4120	1832
1998	14765	18917	4216	1968
1999	14743	19519	4452	2141
2000	14585	19701	4766	2261
2001	14754	19649	4859	2288
2002	14679	19761	5262	2376
2003	14769	20033	5771	2420
2004	14953	20732	6738	2574
2005	15101	20802	6944	2567
2006	15103	20687	7437	2571
2007	14801	20680	7817	2835
2008	14786	19490	7914	3137
2009	14092	18771	8295	3300
2010	14012	19180	9446	3381
2011	13599	18882	9808	3550
2012	13101	18490	10242	3747
2013	12848	18961	10750	3789
2014	12663	19106	11239	3914
2015	12855	19531	11986	4245
2016	13091	19687	12304	4654
2017	13356	19958	12840	4870
2018	13302	20456	13525	5156

Table C13.3 Crude oil deficit consumption subtracted from production in EU, US and China
(Source: BP Statistical Review of World Energy 2019 and BP Statistical Review of World Energy 2011)

Year	European Union (kbbls/day)	United States (kbbls/day)	China (kbbls/day)	India (kbbls/day)
1965	-7085	-2508	11	-190
1966	-7858	-2521	14	-186
1967	-8585	-2348	4	-173
1968	-9466	-2805	21	-204
1969	-10706	-3325	34	-254
1970	-11935	-3413	59	-250
1971	-12553	-4067	35	-269
1972	-13478	-5196	46	-296
1973	-14487	-6372	14	-326
1974	-13562	-6170	80	-310
1975	-13032	-6326	200	-307
1976	-13720	-7725	205	-325
1977	-13069	-8580	248	-333
1978	-13457	-8482	264	-357
1979	-13360	-8302	298	-369
1980	-12265	-6892	429	-451
1981	-11147	-5879	418	-388
1982	-10139	-5096	451	-317
1983	-9535	-4988	489	-241
1984	-9393	-5216	597	-241
1985	-9553	-5146	685	-270
1986	-9929	-6050	687	-288
1987	-10038	-6721	635	-336
1988	-10351	-7518	538	-399
1989	-10918	-8166	423	-446
1990	-11140	-8074	454	-498
1991	-11257	-7637	307	-557
1992	-11219	-8165	105	-682
1993	-10969	-8653	-158	-724
1994	-10392	-9330	-185	-730
1995	-10553	-9403	-406	-807
1996	-10862	-10014	-552	-965
1997	-11025	-10352	-909	-1078
1998	-11212	-10906	-1004	-1231
1999	-11059	-11788	-1239	-1404
2000	-11092	-11968	-1513	-1536
2001	-11469	-11980	-1554	-1561
2002	-11339	-12135	-1916	-1622
2003	-11641	-12633	-2370	-1663
2004	-12051	-13504	-3257	-1801
2005	-12443	-13907	-3307	-1829
2006	-12680	-13846	-3732	-1809
2007	-12413	-13833	-4080	-2066
2008	-12528	-12707	-4100	-2319
2009	-11973	-11512	-4490	-2462
2010	-12031	-11628	-5369	-2480
2011	-11887	-11012	-5734	-2613
2012	-11583	-9580	-6087	-2821
2013	-11423	-8888	-6534	-2863
2014	-11258	-7333	-6993	-3009
2015	-11356	-6758	-7677	-3352
2016	-11608	-7347	-8305	-3780
2017	-11892	-6823	-8994	-3986
2018	-11769	-5145	-9727	-4287

33 APPENDIX D - REFINED PETROLEUM PRODUCTS

Table D1.1 (Part 1 of 5). Global refined petroleum products - consumption is the country's total consumption of refined petroleum products, in barrels per day (bbl/day). (Source: Central Intelligence Agnecy - World Fact Book)

(https://www.cia.gov/library/publications/the-world-factbook/rankorder/2246rank.html)

Rank	Nation State	Petroleum Conumption (Barrels/Day)	Global Market Share (%)	Date of estimate according to source
	GLOBAL TOTAL	**109 265 942**		
1	UNITED STATES	19 690 000	18,02 %	2015 EST.
2	EUROPEAN UNION	12 890 000	11,80 %	2015 EST.
3	CHINA	11 750 000	10,75 %	2015 EST.
4	INDIA	4 489 000	4,11 %	2016 EST.
5	JAPAN	4 026 000	3,68 %	2016 EST.
6	RUSSIA	3 594 000	3,29 %	2015 EST.
7	SAUDI ARABIA	3 237 000	2,96 %	2015 EST.
8	BRAZIL	3 018 000	2,76 %	2016 EST.
9	KOREA, SOUTH	2 630 000	2,41 %	2016 EST.
10	GERMANY	2 410 000	2,21 %	2016 EST.
11	CANADA	2 379 000	2,18 %	2016 EST.
12	MEXICO	2 027 000	1,86 %	2016 EST.
13	IRAN	1 922 000	1,76 %	2015 EST.
14	FRANCE	1 661 000	1,52 %	2016 EST.
15	INDONESIA	1 615 000	1,48 %	2016 EST.
16	UNITED KINGDOM	1 586 000	1,45 %	2016 EST.
17	SINGAPORE	1 582 000	1,45 %	2015 EST.
18	SPAIN	1 287 000	1,18 %	2016 EST.
19	THAILAND	1 272 000	1,16 %	2015 EST.
20	ITALY	1 253 000	1,15 %	2016 EST.
21	AUSTRALIA	1 100 000	1,01 %	2016 EST.
22	NETHERLANDS	973 000	0,89 %	2016 EST.
23	TAIWAN	955 300	0,87 %	2015 EST.
24	TURKEY	943 700	0,86 %	2016 EST.
25	UNITED ARAB EMIRATES	901 000	0,82 %	2015 EST.
26	IRAQ	850 000	0,78 %	2015 EST.
27	ARGENTINA	803 000	0,73 %	2015 EST.
28	EGYPT	802 000	0,73 %	2015 EST.
29	MALAYSIA	760 000	0,70 %	2015 EST.
30	VENEZUELA	747 000	0,68 %	2015 EST.
31	BELGIUM	662 400	0,61 %	2016 EST.
32	SOUTH AFRICA	660 000	0,60 %	2015 EST.
33	POLAND	578 200	0,53 %	2016 EST.
34	PAKISTAN	517 000	0,47 %	2015 EST.
35	KUWAIT	500 000	0,46 %	2016 EST.
36	PHILIPPINES	455 500	0,42 %	2017 EST.
37	ALGERIA	428 000	0,39 %	2015 EST.
38	VIETNAM	422 000	0,39 %	2015 EST.
39	HONG KONG	388 500	0,36 %	2015 EST.
40	COLOMBIA	345 000	0,32 %	2015 EST.
41	CHILE	337 400	0,31 %	2016 EST.
42	SWEDEN	320 200	0,29 %	2016 EST.
43	NIGERIA	316 000	0,29 %	2015 EST.
44	GREECE	299 600	0,27 %	2016 EST.
45	MOROCCO	286 000	0,26 %	2015 EST.
46	QATAR	280 000	0,26 %	2015 EST.
47	ECUADOR	274 000	0,25 %	2015 EST.

Table D1.2 (Part 2 of 5). Global refined petroleum products - consumption is the country's total consumption of refined petroleum products, in barrels per day (bbl/day). (Source: Central Intelligence Agnecy - World Fact Book)

(https://www.cia.gov/library/publications/the-world-factbook/rankorder/2246rank.html)

Rank	Nation State	Petroleum Conumption (Barrels/Day)	Global Market Share (%)	Date of estimate according to source
48	AUSTRIA	267 500	0,24 %	2016 EST.
49	LIBYA	262 000	0,24 %	2015 EST.
50	UKRAINE	248 000	0,23 %	2015 EST.
51	PERU	240 000	0,22 %	2015 EST.
52	PORTUGAL	234 700	0,21 %	2016 EST.
53	NORWAY	227 700	0,21 %	2016 EST.
54	SWITZERLAND	217 400	0,20 %	2016 EST.
55	FINLAND	200 700	0,18 %	2016 EST.
56	ISRAEL	199 900	0,18 %	2016 EST.
57	KAZAKHSTAN	186 300	0,17 %	2016 EST.
58	ROMANIA	182 000	0,17 %	2015 EST.
59	CZECHIA	180 400	0,17 %	2016 EST.
60	CUBA	180 000	0,16 %	2015 EST.
61	OMAN	176 000	0,16 %	2015 EST.
62	BELARUS	172 000	0,16 %	2015 EST.
63	NEW ZEALAND	167 700	0,15 %	2016 EST.
64	JORDAN	160 000	0,15 %	2015 EST.
65	DENMARK	158 200	0,14 %	2016 EST.
66	TURKMENISTAN	158 000	0,14 %	2015 EST.
67	HUNGARY	157 200	0,14 %	2016 EST.
68	PUERTO RICO	155 000	0,14 %	2015 EST.
69	IRELAND	151 700	0,14 %	2016 EST.
70	PANAMA	144 000	0,13 %	2015 EST.
71	LEBANON	143 000	0,13 %	2015 EST.
72	ANGOLA	142 000	0,13 %	2015 EST.
73	YEMEN	140 000	0,13 %	2015 EST.
74	SYRIA	140 000	0,13 %	2015 EST.
75	VIRGIN ISLANDS	132 000	0,12 %	2015 EST.
76	AFGHANISTAN	130 000	0,12 %	2015 EST.
77	DOMINICAN REPUBLIC	114 000	0,10 %	2015 EST.
78	SUDAN	110 000	0,101 %	2015 EST.
79	SRI LANKA	107 000	0,098 %	2015 EST.
80	BANGLADESH	107 000	0,098 %	2015 EST.
81	AZERBAIJAN	101 000	0,092 %	2015 EST.
82	TUNISIA	98 000	0,090 %	2015 EST.
83	GUATEMALA	94 770	0,087 %	2017 EST.
84	KENYA	93 000	0,085 %	2015 EST.
85	BURMA	91 000	0,083 %	2015 EST.
86	BULGARIA	89 000	0,081 %	2015 EST.
87	BOLIVIA	85 580	0,078 %	2017 EST.
88	SLOVAKIA	84 290	0,077 %	2016 EST.
89	SVALBARD	80 250	0,073 %	2013 EST.
90	CURACAO	72 000	0,066 %	2010 EST.
91	GIBRALTAR	70 000	0,064 %	2015 EST.
92	SERBIA	66 230	0,061 %	2016 EST.
93	ETHIOPIA	65 000	0,059 %	2015 EST.
94	GHANA	64 320	0,059 %	2016 EST.
95	CROATIA	63 850	0,058 %	2016 EST.
96	UZBEKISTAN	61 000	0,056 %	2015 EST.
97	TANZANIA	60 000	0,055 %	2015 EST.
98	BAHRAIN	58 000	0,053 %	2015 EST.
99	JAMAICA	57 600	0,053 %	2016 EST.

Table D1.3 (Part 3 of 5). Global refined petroleum products - consumption is the country's total consumption of refined petroleum products, in barrels per day (bbl/day). (Source: Central Intelligence Agnecy - World Fact Book)

(https://www.cia.gov/library/publications/the-world-factbook/rankorder/2246rank.html)

Rank	Nation State	Petroleum Conumption (Barrels/Day)	Global Market Share (%)	Date of estimate according to source
100	LUXEMBOURG	56 120	0,051 %	2016 EST.
101	URUGUAY	54 000	0,049 %	2015 EST.
102	COSTA RICA	54 000	0,049 %	2015 EST.
103	LITHUANIA	53 000	0,049 %	2015 EST.
104	SLOVENIA	52 300	0,048 %	2016 EST.
105	HONDURAS	52 000	0,048 %	2015 EST.
106	TRINIDAD AND TOBAGO	46 000	0,042 %	2015 EST.
107	CYPRUS	46 000	0,042 %	2015 EST.
108	BENIN	44 000	0,040 %	2015 EST.
109	SENEGAL	44 000	0,040 %	2015 EST.
110	COTE D'IVOIRE	43 000	0,039 %	2015 EST.
111	MALTA	42 000	0,038 %	2015 EST.
112	PAPUA NEW GUINEA	42 000	0,038 %	2015 EST.
113	CAMEROON	42 000	0,038 %	2015 EST.
114	CAMBODIA	39 000	0,036 %	2015 EST.
115	PARAGUAY	38 000	0,035 %	2015 EST.
116	LATVIA	37 680	0,034 %	2016 EST.
117	EL SALVADOR	36 230	0,033 %	2017 EST.
118	KYRGYZSTAN	33 000	0,030 %	2015 EST.
119	NEPAL	32 000	0,029 %	2015 EST.
120	BOSNIA AND HERZEGOVINA	31 000	0,028 %	2015 EST.
121	NICARAGUA	30 000	0,027 %	2015 EST.
122	CONGO, DEMOCRATIC REPUBLIC OF THE	30 000	0,027 %	2015 EST.
123	ESTONIA	29 140	0,027 %	2016 EST.
124	ZIMBABWE	29 000	0,027 %	2015 EST.
125	UGANDA	27 000	0,025 %	2015 EST.
126	ALBANIA	27 000	0,025 %	2014 EST.
127	MAURITIUS	26 000	0,024 %	2015 EST.
128	MONGOLIA	26 000	0,024 %	2015 EST.
129	NAMIBIA	25 000	0,023 %	2015 EST.
130	BAHAMAS, THE	24 000	0,022 %	2015 EST.
131	TAJIKISTAN	23 000	0,021 %	2015 EST.
132	BOTSWANA	23 000	0,021 %	2015 EST.
133	GEORGIA	23 000	0,021 %	2015 EST.
134	MOZAMBIQUE	23 000	0,021 %	2015 EST.
135	ZAMBIA	23 000	0,021 %	2015 EST.
136	BURKINA FASO	22 000	0,020 %	2015 EST.
137	GABON	22 000	0,020 %	2015 EST.
138	MOLDOVA	21 720	0,020 %	2017 EST.
139	MACEDONIA	20 700	0,019 %	2016 EST.
140	ICELAND	19 800	0,018 %	2016 EST.
141	WEST BANK	19 000	0,017 %	2015 EST.
142	HAITI	19 000	0,017 %	2015 EST.
143	BRUNEI	18 000	0,016 %	2015 EST.
144	CONGO, REPUBLIC OF THE	18 000	0,016 %	2015 EST.
145	KOREA, NORTH	18 000	0,016 %	2015 EST.
146	NEW CALEDONIA	17 000	0,016 %	2015 EST.
147	GUINEA	16 000	0,015 %	2015 EST.
148	FIJI	16 000	0,015 %	2015 EST.
149	MAURITANIA	16 000	0,015 %	2015 EST.
150	GUAM	15 400	0,014 %	2015 EST.

Table D1.4 (Part 4 of 5). Global refined petroleum products - consumption is the country's total consumption of refined petroleum products, in barrels per day (bbl/day). (Source: Central Intelligence Agnecy - World Fact Book)

(https://www.cia.gov/library/publications/the-world-factbook/rankorder/2246rank.html)

Rank	Nation State	Petroleum Conumption (Barrels/Day)	Global Market Share (%)	Date of estimate according to source
151	MADAGASCAR	15 000	0,014 %	2015 EST.
152	TOGO	14 000	0,013 %	2015 EST.
153	SURINAME	14 000	0,013 %	2015 EST.
154	KOSOVO	13 570	0,012 %	2017 EST.
155	NIGER	13 000	0,012 %	2015 EST.
156	GUYANA	13 000	0,012 %	2015 EST.
157	MACAU	12 700	0,012 %	2015 EST.
158	BARBADOS	12 000	0,01098 %	2015 EST.
159	MALDIVES	11 000	0,01007 %	2015 EST.
160	SOUTH SUDAN	11 000	0,01007 %	2015 EST.
161	ARMENIA	8 000	0,00732 %	2015 EST.
162	ARUBA	7 500	0,00686 %	2015 EST.
163	MONTENEGRO	7 500	0,00686 %	2016 EST.
164	MALI	7 500	0,00686 %	2015 EST.
165	SIERRA LEONE	7 500	0,00686 %	2015 EST.
166	MALAWI	7 000	0,00641 %	2015 EST.
167	FRENCH POLYNESIA	7 000	0,00641 %	2015 EST.
168	LIBERIA	6 600	0,00604 %	2015 EST.
169	SEYCHELLES	6 500	0,00595 %	2015 EST.
170	DJIBOUTI	6 000	0,00549 %	2015 EST.
171	GREENLAND	6 000	0,00549 %	2015 EST.
172	RWANDA	6 000	0,00549 %	2015 EST.
173	CABO VERDE	6 000	0,00549 %	2015 EST.
174	SOMALIA	5 700	0,00522 %	2015 EST.
175	EQUATORIAL GUINEA	5 200	0,00476 %	2015 EST.
176	ESWATINI	5 000	0,00458 %	2015 EST.
177	ANTIGUA AND BARBUDA	5 000	0,00458 %	2015 EST.
178	LESOTHO	5 000	0,00458 %	2015 EST.
179	CAYMAN ISLANDS	4 000	0,00366 %	2015 EST.
180	FAROE ISLANDS	3 947	0,00361 %	2015 EST.
181	BELIZE	3 700	0,00339 %	2015 EST.
182	ERITREA	3 600	0,00329 %	2015 EST.
183	GAMBIA, THE	3 600	0,00329 %	2015 EST.
184	LAOS	3 500	0,00320 %	2015 EST.
185	BERMUDA	3 300	0,00302 %	2015 EST.
186	SAINT LUCIA	3 100	0,00284 %	2015 EST.
187	TIMOR-LESTE	3 100	0,00284 %	2015 EST.
188	CENTRAL AFRICAN REPUBLIC	3 000	0,00275 %	2015 EST.
189	BHUTAN	3 000	0,00275 %	2015 EST.
190	GUINEA-BISSAU	2 500	0,00229 %	2015 EST.
191	AMERICAN SAMOA	2 375	0,00217 %	2015 EST.
192	CHAD	2 200	0,00201 %	2015 EST.
193	MARSHALL ISLANDS	2 000	0,00183 %	2015 EST.
194	SAINT KITTS AND NEVIS	1 900	0,00174 %	2015 EST.
195	WESTERN SAHARA	1 700	0,00156 %	2015 EST.
196	SOLOMON ISLANDS	1 600	0,00146 %	2015 EST.
197	SAINT VINCENT AND THE GRENADINES	1 600	0,00146 %	2015 EST.
198	TONGA	1 500	0,00137 %	2015 EST.
199	BURUNDI	1 500	0,00137 %	2015 EST.
200	TURKS AND CAICOS ISLANDS	1 340	0,00123 %	2015 EST.

Table D1.5 (Part 5 of 5). Global refined petroleum products - consumption is the country's total consumption of refined petroleum products, in barrels per day (bbl/day). (Source: Central Intelligence Agnecy - World Fact Book)

(https://www.cia.gov/library/publications/the-world-factbook/rankorder/2246rank.html)

Rank	Nation State	Petroleum Conumption (Barrels/Day)	Global Market Share (%)	Date of estimate according to source
201	COMOROS	1 300	0,00119 %	2015 EST.
202	BRITISH VIRGIN ISLANDS	1 200	0,00110 %	2015 EST.
203	SAMOA	1 100	0,00101 %	2015 EST.
204	SAO TOME AND PRINCIPE	1 000	0,00092 %	2015 EST.
205	VANUATU	1 000	0,00092 %	2015 EST.
206	DOMINICA	1 000	0,00092 %	2015 EST.
207	GRENADA	860	0,00079 %	2017 EST.
208	SAINT PIERRE AND MIQUELON	630	0,00058 %	2015 EST.
209	MONTSERRAT	570	0,00052 %	2015 EST.
210	COOK ISLANDS	530	0,00049 %	2015 EST.
211	KIRIBATI	400	0,00037 %	2015 EST.
212	NAURU	400	0,00037 %	2015 EST.
213	FALKLAND ISLANDS (ISLAS MALVINAS)	300	0,00027 %	2015 EST.
214	SAINT HELENA, ASCENSION, AND TRISTAN DA CUNHA	80	0,00007 %	2015 EST.
215	NIUE	60	0,00005 %	2015 EST.

Table D2.1 (Part 1 of 6). Petroleum Products Supplied by Type (Thousand Barrels per Day)
(Source: U.S. Energy Information Administration, July 2019 Monthly Energy Review)

Annual Average (year)	Asphalt and Road Oil Product Supplied ('000 bbls/day)	Aviation Gasoline Product Supplied ('000 bbls/day)	Distillate Fuel Oil Product Supplied ('000 bbls/day)	Propane Product Supplied ('000 bbls/day)	Propylene Product Supplied ('000 bbls/day)
1949	156 679	93 129	902 132	116 202	10 011
1950	179 655	108 266	1 081 877	145 606	12 544
1951	198 011	145 071	1 225 419	172 425	14 854
1952	212 989	169 391	1 303 240	183 927	15 845
1953	215 940	193 732	1 337 192	202 069	17 408
1954	229 570	177 995	1 442 047	218 756	18 845
1955	253 814	192 167	1 592 132	251 300	21 649
1956	271 675	203 833	1 682 667	274 326	23 633
1957	263 277	201 140	1 687 918	281 694	24 267
1958	280 260	223 249	1 790 208	302 598	26 068
1959	297 652	209 384	1 808 173	361 938	31 180
1960	302 120	161 240	1 872 317	385 996	33 253
1961	311 110	157 608	1 902 345	398 322	34 315
1962	331 745	142 693	2 006 589	435 026	37 477
1963	340 460	137 416	2 047 271	470 349	40 520
1964	346 175	127 208	2 050 339	501 144	43 173
1965	367 553	120 266	2 125 518	522 983	45 054
1966	386 252	105 340	2 184 603	551 630	47 522
1967	378 679	90 148	2 241 507	586 565	50 532
1968	405 003	83 672	2 389 451	659 369	47 784
1969	416 564	70 003	2 466 471	738 856	54 030
1970	446 899	54 529	2 540 304	726 791	55 041
1971	457 570	49 019	2 661 140	742 365	58 937
1972	468 104	46 243	2 912 869	832 748	68 372
1973	521 737	45 290	3 092 367	809 860	69 395
1974	481 134	44 425	2 947 715	769 313	68 918
1975	418 732	38 540	2 850 879	730 445	59 934
1976	410 956	36 508	3 133 046	766 733	70 071
1977	436 129	38 170	3 351 584	759 643	73 573
1978	478 759	38 781	3 431 660	714 566	77 156
1979	476 038	38 162	3 310 838	834 045	79 271
1980	396 169	34 828	2 866 052	741 815	71 525
1981	341 759	30 539	2 828 701	769 324	67 825
1982	342 427	25 497	2 670 863	831 017	52 836
1983	373 262	25 873	2 690 210	780 968	61 049
1984	408 475	23 750	2 844 858	766 940	66 396
1985	425 031	27 312	2 868 020	810 260	72 315
1986	448 254	31 981	2 914 358	750 537	80 085
1987	466 534	24 770	2 976 473	839 860	84 252
1988	467 859	26 516	3 121 611	830 228	92 578
1989	452 504	25 827	3 156 779	888 712	101 575
1990	483 123	24 411	3 020 557	811 737	105 184

Table D2.2 (Part 2 of 6). Petroleum Products Supplied by Type (Thousand Barrels per Day)
(Source: U.S. Energy Information Administration, July 2019 Monthly Energy Review)

Annual Average (year)	Asphalt and Road Oil Product Supplied ('000 bbls/day)	Aviation Gasoline Product Supplied ('000 bbls/day)	Distillate Fuel Oil Product Supplied ('000 bbls/day)	Propane Product Supplied ('000 bbls/day)	Propylene Product Supplied ('000 bbls/day)
1991	444 456	22 644	2 920 770	856 811	124 715
1992	453 817	22 221	2 978 887	896 377	135 929
1993	474 382	20 838	3 041 212	872 643	133 400
1994	484 248	20 699	3 162 239	939 696	142 353
1995	486 419	21 482	3 206 627	938 414	157 153
1996	484 167	20 219	3 365 243	978 366	157 227
1997	505 159	21 545	3 435 447	964 723	205 153
1998	521 255	19 266	3 461 444	929 405	190 296
1999	546 795	21 260	3 571 997	1 038 041	208 038
2000	525 235	19 639	3 722 172	1 010 710	224 098
2001	518 907	18 962	3 846 803	931 529	210 008
2002	511 926	18 307	3 775 907	1 014 964	233 000
2003	503 496	16 403	3 927 048	976 942	237 696
2004	536 833	16 910	4 058 262	1 021 082	254 822
2005	546 309	19 195	4 118 011	985 825	243 449
2006	520 682	18 153	4 169 125	947 181	267 655
2007	494 207	17 145	4 195 911	983 349	251 518
2008	416 659	15 309	3 945 420	923 858	230 347
2009	360 459	14 414	3 631 081	892 966	267 090
2010	362 394	14 679	3 800 314	851 621	308 019
2011	354 847	14 685	3 898 854	851 446	301 227
2012	340 376	13 593	3 741 416	862 377	312 404
2013	323 411	12 134	3 827 465	968 591	306 534
2014	327 246	11 775	4 037 248	869 645	297 178
2015	343 358	11 474	3 995 237	864 761	297 178
2016	351 356	11 077	3 877 252	833 043	296 773
2017	350 591	11 370	3 932 188	802 802	314 419
2018	329 090	12 151	4 133 572	856 660	304 540

Table D2.3 (Part 3 of 6). Petroleum Products Supplied by Type (Thousand Barrels per Day)
(Source: U.S. Energy Information Administration, July 2019 Monthly Energy Review)

Annual Average (year)	Propane/Propylene Product Supplied ('000 bbls/day)	Total Hydrocarbon Gas Liquids Product Supplied ('000 bbls/day)	Jet Fuel Product Supplied ('000 bbls/day)	Kerosene Product Supplied ('000 bbls/day)	Lubricants Product Supplied ('000 bbls/day)
1949	126 213	186 953	data not availavle	281 293	90 688
1950	158 150	234 260	data not availavle	322 860	106 447
1951	187 280	277 408	data not availavle	337 647	115 868
1952	199 772	295 913	54 989	331 292	104 276
1953	219 477	325 101	94 474	313 608	110 951
1954	237 602	351 948	125 622	324 140	105 581
1955	272 949	404 307	154 208	320 022	116 375
1956	297 959	441 352	197 145	320 557	120 036
1957	305 961	453 205	215 534	279 430	112 918
1958	328 667	486 838	274 630	293 742	108 142
1959	393 118	582 307	325 096	261 608	117 474
1960	419 249	621 014	371 481	271 421	116 601
1961	432 637	640 844	415 405	266 430	113 792
1962	472 503	699 896	489 137	268 584	119 493
1963	510 869	756 726	521 844	265 688	119 455
1964	544 317	806 270	558 068	253 383	125 104
1965	568 037	841 405	601 732	267 348	129 096
1966	599 152	887 496	669 551	277 033	134 107
1967	637 097	943 701	824 027	274 189	120 885
1968	707 153	1 053 937	954 585	281 243	132 423
1969	792 886	1 220 893	991 044	274 981	133 649
1970	781 832	1 224 153	967 063	262 942	136 145
1971	801 302	1 251 375	1 010 200	249 088	135 126
1972	901 119	1 420 355	1 045 055	234 566	144 298
1973	879 255	1 453 781	1 059 252	216 205	162 112
1974	838 231	1 422 441	993 425	176 307	155 260
1975	790 380	1 351 721	1 000 795	158 877	137 449
1976	836 804	1 406 811	987 317	169 180	152 273
1977	833 216	1 421 562	1 039 060	175 238	159 753
1978	791 722	1 412 751	1 056 586	175 458	171 559
1979	913 317	1 664 099	1 075 888	187 863	179 518
1980	813 340	1 590 148	1 067 557	158 388	159 421
1981	837 149	1 582 226	1 007 444	126 865	153 309
1982	883 853	1 599 648	1 012 552	128 666	139 805
1983	842 017	1 537 184	1 045 981	126 992	146 373
1984	833 336	1 701 544	1 175 479	115 259	155 661
1985	882 575	1 721 451	1 218 362	113 882	145 468
1986	830 622	1 628 617	1 307 342	98 251	142 236
1987	924 112	1 749 285	1 384 987	94 556	160 806
1988	922 806	1 779 530	1 448 660	96 173	154 647
1989	990 288	1 789 909	1 489 440	84 256	159 056
1990	916 921	1 704 518	1 522 267	42 530	163 680

Table D2.4 (Part 4 of 6). Petroleum Products Supplied by Type (Thousand Barrels per Day)
(Source: U.S. Energy Information Administration, July 2019 Monthly Energy Review)

Annual Average (year)	Propane/Propylene Product Supplied ('000 bbls/day)	Total Hydrocarbon Gas Liquids Product Supplied ('000 bbls/day)	Jet Fuel Product Supplied ('000 bbls/day)	Kerosene Product Supplied ('000 bbls/day)	Lubricants Product Supplied ('000 bbls/day)
1991	981 526	1 862 944	1 471 441	46 295	146 429
1992	1 032 306	1 946 032	1 454 292	41 402	148 882
1993	1 006 043	1 931 066	1 469 339	49 627	152 016
1994	1 082 049	2 080 571	1 526 858	48 945	158 887
1995	1 095 568	2 099 778	1 514 422	54 041	156 159
1996	1 135 593	2 221 803	1 577 954	61 735	151 137
1997	1 169 877	2 232 868	1 598 529	65 879	160 096
1998	1 119 701	2 126 447	1 621 934	78 055	167 597
1999	1 246 079	2 411 436	1 672 605	72 937	169 351
2000	1 234 809	2 433 776	1 725 284	67 396	166 355
2001	1 141 537	2 200 386	1 655 401	72 340	152 836
2002	1 247 964	2 295 310	1 613 649	43 340	151 025
2003	1 214 638	2 205 068	1 577 834	54 625	139 625
2004	1 275 904	2 264 030	1 629 964	64 317	141 068
2005	1 229 274	2 146 050	1 678 990	69 809	140 716
2006	1 214 835	2 135 483	1 632 906	53 683	137 096
2007	1 234 866	2 191 323	1 622 386	32 140	141 575
2008	1 154 205	2 044 387	1 538 554	14 229	131 078
2009	1 160 057	2 126 941	1 393 190	17 548	118 171
2010	1 159 640	2 265 268	1 431 649	19 929	131 296
2011	1 152 674	2 241 453	1 425 343	12 241	124 572
2012	1 174 782	2 297 426	1 398 133	5 276	114 299
2013	1 275 125	2 501 189	1 434 398	5 197	121 267
2014	1 166 823	2 442 439	1 469 928	8 996	126 494
2015	1 161 939	2 551 652	1 548 242	6 386	137 753
2016	1 129 817	2 536 162	1 614 227	8 670	130 418
2017	1 117 221	2 642 863	1 682 176	5 177	120 556
2018	1 161 200	2 986 920	1 710 960	5 085	112 212

Table D2.5 (Part 5 of 6). Petroleum Products Supplied by Type (Thousand Barrels per Day)
(Source: U.S. Energy Information Administration, July 2019 Monthly Energy Review)

Annual Average (year)	Motor Gasoline Product Supplied ('000 bbls/day)	Petroleum Coke Product Supplied ('000 bbls/day)	Residual Fuel Oil Product Supplied ('000 bbls/day)	Other Petroleum Products Supplied ('000 bbls/day)	Total Petroleum Products Supplied ('000 bbls/day)
1949	2 410 195	39 526	1 358 962	243 482	**5 763 038**
1950	2 615 816	41 153	1 517 241	250 342	**6 457 918**
1951	2 840 041	39 674	1 546 293	290 699	**7 016 132**
1952	2 953 525	38 044	1 516 844	289 115	**7 269 617**
1953	3 109 762	48 216	1 535 545	315 107	**7 599 627**
1954	3 193 499	54 181	1 431 005	320 447	**7 756 033**
1955	3 463 189	66 858	1 526 184	366 093	**8 455 348**
1956	3 547 749	67 970	1 537 740	384 475	**8 775 199**
1957	3 615 170	74 044	1 503 564	402 811	**8 809 011**
1958	3 710 715	85 258	1 454 978	409 767	**9 117 789**
1959	3 859 868	97 397	1 543 737	423 805	**9 526 501**
1960	3 969 005	148 831	1 528 522	434 770	**9 797 322**
1961	4 042 866	183 929	1 503 227	438 553	**9 976 110**
1962	4 198 926	193 710	1 495 378	453 929	**10 400 079**
1963	4 334 099	189 926	1 476 504	554 074	**10 743 463**
1964	4 402 590	192 336	1 515 249	645 781	**11 022 503**
1965	4 592 614	201 718	1 608 249	656 937	**11 512 436**
1966	4 808 033	201 863	1 716 247	713 849	**12 084 373**
1967	4 958 310	205 836	1 785 986	737 077	**12 560 345**
1968	5 260 593	208 522	1 825 790	797 648	**13 392 866**
1969	5 526 014	221 452	1 977 874	837 849	**14 136 795**
1970	5 784 518	211 548	2 203 529	865 556	**14 697 186**
1971	6 014 433	218 896	2 296 014	869 633	**15 212 493**
1972	6 376 443	241 191	2 529 090	948 770	**16 366 984**
1973	6 674 400	260 701	2 822 403	999 430	**17 307 679**
1974	6 537 471	238 510	2 638 948	1 017 074	**16 652 710**
1975	6 674 600	246 707	2 461 841	981 819	**16 321 959**
1976	6 977 689	243 418	2 800 951	1 142 915	**17 461 066**
1977	7 176 822	267 764	3 071 033	1 294 304	**18 431 419**
1978	7 411 805	255 679	3 022 556	1 391 027	**18 846 622**
1979	7 034 447	246 197	2 826 184	1 473 307	**18 512 540**
1980	6 578 544	236 560	2 508 268	1 459 926	**17 055 861**
1981	6 587 526	251 693	2 087 753	1 059 881	**16 057 696**
1982	6 539 244	247 930	1 716 463	872 624	**15 295 720**
1983	6 622 149	228 661	1 420 834	1 013 615	**15 231 134**
1984	6 692 515	247 381	1 369 397	991 295	**15 725 615**
1985	6 831 126	264 487	1 202 301	908 978	**15 726 418**
1986	7 034 071	268 346	1 418 402	988 770	**16 280 627**
1987	7 205 722	298 752	1 264 394	1 038 767	**16 665 046**
1988	7 336 462	311 659	1 377 800	1 162 394	**17 283 310**
1989	7 327 861	307 253	1 370 047	1 162 220	**17 325 153**
1990	7 234 907	338 637	1 228 825	1 225 039	**16 988 496**

Table D2.6 (Part 6 of 6). Petroleum Products Supplied by Type (Thousand Barrels per Day)
(Source: U.S. Energy Information Administration, July 2019 Monthly Energy Review)

Annual Average (year)	Motor Gasoline Product Supplied ('000 bbls/day)	Petroleum Coke Product Supplied ('000 bbls/day)	Residual Fuel Oil Product Supplied ('000 bbls/day)	Other Petroleum Products Supplied ('000 bbls/day)	Total Petroleum Products Supplied ('000 bbls/day)
1991	7 187 518	328 357	1 157 875	1 125 107	**16 713 836**
1992	7 267 522	382 253	1 094 346	1 243 200	**17 032 855**
1993	7 476 302	365 706	1 080 171	1 176 071	**17 236 731**
1994	7 601 368	360 662	1 020 787	1 252 896	**17 718 159**
1995	7 788 644	364 740	851 811	1 180 467	**17 724 589**
1996	7 890 585	379 413	848 363	1 308 287	**18 308 904**
1997	8 016 844	377 077	796 699	1 410 160	**18 620**
1998	8 253 416	446 690	887 121	1 333 916	**18 917 140**
1999	8 430 800	476 803	830 132	1 315 220	**19 519 337**
2000	8 472 060	405 880	908 544	1 254 735	**19 701 077**
2001	8 610 027	437 060	811 173	1 324 815	**19 648 707**
2002	8 847 838	462 762	699 608	1 341 628	**19 761 304**
2003	8 934 896	454 658	772 131	1 447 722	**20 033 507**
2004	9 105 407	524 268	864 708	1 525 380	**20 731 150**
2005	9 159 264	515 212	919 976	1 488 630	**20 802 162**
2006	9 252 533	522 215	688 845	1 556 696	**20 687 418**
2007	9 285 669	490 027	722 906	1 487 089	**20 680 378**
2008	8 989 228	463 654	622 199	1 317 247	**19 497 964**
2009	8 996 521	426 538	511 118	1 175 419	**18 771 400**
2010	8 992 654	375 724	535 099	1 251 118	**19 180 123**
2011	8 752 750	361 209	461 076	1 239 669	**18 886 697**
2012	8 682 206	360 240	368 756	1 164 937	**18 486 659**
2013	8 842 984	353 716	318 555	1 226 551	**18 966 868**
2014	8 920 842	346 797	257 192	1 151 125	**19 100 082**
2015	9 178 372	349 173	259 326	1 152 538	**19 533 511**
2016	9 317 080	345 246	326 225	1 169 522	**19 687 234**
2017	9 326 536	316 227	341 710	1 228 328	**19 957 724**
2018	9 319 219	332 968	321 570	1 189 124	**20 452 870**

34 APPENDIX E – GAS RESERVES, PRODUCTION AND CONSUMPTION

Table E1. Global total proved gas reserves (BP Statistical Review of World Energy 2019)

Total proved reserves

	At end 1998	At end 2008	At end 2017	At end 2018			
	Trillion cubic metres	Trillion cubic metres	Trillion cubic metres	Trillion cubic metres	Trillion cubic feet	Share of total	R/P ratio
Canada	1.7	1.7	2.0	**1.9**	**65.4**	0.9%	10.0
Mexico	0.8	0.4	0.2	**0.2**	**6.5**	0.1%	4.9
US	4.4	6.6	11.9	**11.9**	**419.8**	6.0%	14.3
Total North America	7.0	8.7	14.1	**13.9**	**491.7**	7.1%	13.2
Argentina	0.7	0.4	0.3	**0.3**	**12.2**	0.2%	8.8
Bolivia	0.1	0.3	0.3	**0.3**	**10.3**	0.1%	18.3
Brazil	0.2	0.4	0.4	**0.4**	**13.4**	0.2%	15.1
Colombia	0.2	0.1	0.1	**0.1**	**3.7**	0.1%	8.3
Peru	0.2	0.3	0.4	**0.4**	**12.4**	0.2%	27.4
Trinidad & Tobago	0.5	0.4	0.3	**0.3**	**10.9**	0.2%	9.1
Venezuela	4.6	5.5	6.3	**6.3**	**223.8**	3.2%	190.7
Other S. & Cent. America	0.1	0.1	0.1	**0.1**	**2.2**	♦	18.5
Total S. & Cent. America	6.8	7.5	8.2	**8.2**	**289.0**	4.2%	46.3
Denmark	0.1	0.1	†	**†**	**1.0**	♦	6.6
Germany	0.2	0.1	†	**†**	**0.9**	♦	4.8
Italy	0.3	0.1	†	**†**	**1.6**	♦	8.9
Netherlands	1.7	1.2	0.6	**0.6**	**20.7**	0.3%	18.2
Norway	1.2	2.2	1.7	**1.6**	**56.8**	0.8%	13.3
Poland	0.1	0.1	0.1	**0.1**	**2.2**	♦	16.0
Romania	0.3	0.6	0.1	**0.1**	**3.6**	0.1%	10.7
Ukraine	0.8	0.8	1.0	**1.1**	**38.5**	0.6%	54.9
United Kingdom	0.8	0.3	0.2	**0.2**	**6.6**	0.1%	4.6
Other Europe	0.2	0.2	0.1	**0.1**	**5.0**	0.1%	16.2
Total Europe	5.6	5.5	3.9	**3.9**	**137.1**	2.0%	15.5
Azerbaijan	0.7	1.1	1.3	**2.1**	**75.2**	1.1%	113.6
Kazakhstan	1.3	1.3	1.0	**1.0**	**35.0**	0.5%	40.7
Russian Federation	33.4	34.0	38.9	**38.9**	**1375.0**	19.8%	58.2
Turkmenistan	2.5	8.2	19.5	**19.5**	**688.1**	9.9%	316.8
Uzbekistan	1.2	1.3	1.2	**1.2**	**42.7**	0.6%	21.4
Other CIS	†	†	†	**†**	**1.2**	♦	113.1
Total CIS	39.2	45.9	62.0	**62.8**	**2217.4**	31.9%	75.6
Bahrain	0.3	0.2	0.2	**0.2**	**6.4**	0.1%	12.3
Iran	22.8	28.0	31.9	**31.9**	**1127.7**	16.2%	133.3
Iraq	3.0	3.0	3.6	**3.6**	**125.6**	1.8%	273.8
Israel	†	†	0.5	**0.4**	**14.6**	0.2%	41.1
Kuwait	1.4	1.7	1.7	**1.7**	**59.9**	0.9%	97.0
Oman	0.5	0.9	0.7	**0.7**	**23.5**	0.3%	18.5
Qatar	11.3	26.3	24.7	**24.7**	**872.1**	12.5%	140.7
Saudi Arabia	5.8	7.1	5.7	**5.9**	**208.1**	3.0%	52.6
Syria	0.2	0.3	0.3	**0.3**	**9.5**	0.1%	75.4
United Arab Emirates	5.8	5.9	5.9	**5.9**	**209.7**	3.0%	91.8
Yemen	0.3	0.3	0.3	**0.3**	**9.4**	0.1%	480.7
Other Middle East	†	†	†	**†**	**0.2**	♦	48.4
Total Middle East	51.5	73.7	75.3	**75.5**	**2666.7**	38.4%	109.9
Algeria	3.9	4.3	4.3	**4.3**	**153.1**	2.2%	47.0
Egypt	1.0	2.1	2.1	**2.1**	**75.5**	1.1%	36.5
Libya	1.2	1.5	1.4	**1.4**	**50.5**	0.7%	145.9
Nigeria	3.3	5.0	5.3	**5.3**	**188.8**	2.7%	108.6
Other Africa	0.8	1.1	1.2	**1.2**	**41.7**	0.6%	44.3
Total Africa	10.3	14.0	14.4	**14.4**	**509.6**	7.3%	61.0
Australia	1.6	2.7	2.4	**2.4**	**84.4**	1.2%	18.4
Bangladesh	0.3	0.3	0.2	**0.2**	**5.7**	0.1%	5.9
Brunei	0.4	0.3	0.3	**0.3**	**9.5**	0.1%	21.4
China	1.4	2.7	6.1	**6.1**	**214.4**	3.1%	37.6
India	0.6	1.0	1.2	**1.3**	**45.5**	0.7%	46.9
Indonesia	2.2	3.2	2.9	**2.8**	**97.5**	1.4%	37.7
Malaysia	2.4	2.4	2.4	**2.4**	**84.5**	1.2%	33.0
Myanmar	0.3	0.3	1.2	**1.2**	**41.3**	0.6%	65.6
Pakistan	0.4	0.6	0.4	**0.4**	**12.9**	0.2%	10.7
Papua New Guinea	†	†	0.2	**0.2**	**6.4**	0.1%	17.8
Thailand	0.4	0.4	0.2	**0.2**	**6.6**	0.1%	5.0
Vietnam	0.2	0.6	0.6	**0.6**	**22.8**	0.3%	67.0
Other Asia Pacific	0.4	0.3	0.2	**0.2**	**8.8**	0.1%	14.4
Total Asia Pacific	10.5	15.0	18.2	**18.1**	**640.3**	9.2%	28.7
Total World	**130.8**	**170.2**	**196.1**	**196.9**	**6951.8**	**100.0%**	**50.9**
of which: OECD	13.0	15.7	19.7	**19.4**	**686.8**	9.9%	13.7
Non-OECD	117.7	154.5	176.4	**177.4**	**6265.1**	90.1%	72.5
European Union	3.5	2.5	1.1	**1.1**	**39.6**	0.6%	10.3

†Less than 0.05.
♦Less than 0.05%.
Notes: Total proved reserves of natural gas – Generally taken to be those quantities that geological and engineering information indicates with reasonable certainty can be recovered in the future from known reservoirs under existing economic and operating conditions. The data series for total proved natural gas does not necessarily meet the definitions, guidelines and practices used for determining proved reserves at a company level, for instance as published by the US Securities and Exchange Commission, nor does it necessarily represent BP's view of proved reserves by country.
Reserves-to-production (R/P) ratio – If the reserves remaining at the end of any year are divided by the production in that year, the result is the length of time that those remaining reserves would last if production were to continue at that rate.
Source of data – The estimates in this table have been compiled using a combination of primary official sources and third-party data from Cedigaz and the OPEC Secretariat.
As far as possible, the data above represents standard cubic metres (measured at 15°C and 1013 mbar) and have been standardized using a gross calorific value (GCV) of 40 MJ/m³.

Table E2. Global natural gas production (billion cubic meters) (BP Statistical Review of World Energy 2019)

Natural gas: Production in billion cubic metres*

Billion cubic metres	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Growth rate per annum 2018	Growth rate per annum 2007-17	Share 2018
Canada	166.5	155.1	149.6	151.1	150.3	151.9	159.0	160.8	171.8	177.6	**184.7**	4.0%	0.2%	4.8%
Mexico	47.2	52.6	51.2	52.1	50.9	52.5	51.3	47.9	43.7	38.3	**37.4**	-2.4%	-2.0%	1.0%
US	546.1	557.6	575.2	617.4	649.1	655.7	704.7	740.3	727.4	745.8	**831.8**	11.5%	3.6%	21.5%
Total North America	759.8	765.2	775.9	820.5	850.3	860.1	915.0	949.0	942.8	961.6	**1053.9**	9.6%	2.6%	27.2%
Argentina	42.8	40.3	39.0	37.7	36.7	34.6	34.5	35.5	37.3	37.1	**39.4**	6.1%	-1.6%	1.0%
Bolivia	13.8	11.9	13.7	15.0	17.1	19.6	20.3	19.6	17.6	17.1	**16.0**	-6.6%	2.5%	0.4%
Brazil	14.4	12.3	15.0	17.2	19.8	21.9	23.3	23.8	24.1	27.2	**25.2**	-7.4%	8.9%	0.7%
Colombia	8.7	10.1	10.8	10.5	11.5	13.2	12.3	11.6	12.0	12.3	**12.9**	4.6%	5.4%	0.3%
Peru	3.5	3.6	7.3	11.5	12.0	12.4	13.1	12.7	14.0	13.0	**12.8**	-1.7%	17.6%	0.3%
Trinidad & Tobago	37.4	38.6	40.3	38.7	38.5	38.7	38.1	36.0	31.3	31.9	**34.0**	6.6%	-1.7%	0.9%
Venezuela	33.4	31.8	30.5	30.2	31.9	30.6	31.8	36.1	37.2	38.6	**33.2**	-13.9%	0.4%	0.9%
Other S. & Cent. America	3.8	3.8	3.8	3.2	3.0	2.7	2.6	2.9	3.1	3.1	**3.3**	6.8%	-2.5%	0.1%
Total S. & Cent. America	157.9	152.3	160.4	164.1	170.6	173.8	176.0	178.0	176.7	180.3	**176.7**	-2.0%	1.4%	4.6%
Denmark	10.5	8.8	8.5	6.9	6.0	5.0	4.8	4.8	4.7	5.1	**4.3**	-15.0%	-6.2%	0.1%
Germany	13.6	12.7	11.1	10.5	9.5	8.6	8.1	7.5	6.9	6.4	**5.5**	-13.1%	-8.2%	0.1%
Italy	8.8	7.6	8.0	8.0	8.2	7.4	6.8	6.4	5.5	5.3	**5.2**	-1.6%	-5.5%	0.1%
Netherlands	70.9	65.5	75.3	69.5	68.4	72.4	60.4	45.9	44.3	38.6	**32.3**	-16.3%	-4.6%	0.8%
Norway	99.4	103.6	106.4	100.5	113.9	107.9	108.0	116.2	115.9	123.2	**120.6**	-2.1%	3.2%	3.1%
Poland	4.3	4.3	4.3	4.5	4.5	4.4	4.3	4.3	4.1	4.0	**4.0**	-1.5%	-1.1%	0.1%
Romania	10.5	10.4	10.0	10.1	10.1	10.0	10.2	10.2	9.1	9.9	**9.5**	-3.7%	-0.8%	0.2%
Ukraine	20.3	20.3	19.4	19.5	19.4	20.2	20.2	18.8	19.0	19.4	**19.9**	2.4%	-0.3%	0.5%
United Kingdom	72.8	61.2	57.9	46.1	39.2	37.0	37.4	40.7	41.7	41.9	**40.6**	-3.1%	-5.7%	1.0%
Other Europe	10.0	9.7	9.7	9.9	8.9	7.8	7.2	6.8	9.2	9.5	**8.7**	-7.9%	-1.1%	0.2%
Total Europe	321.0	304.1	310.7	285.5	288.1	280.6	267.5	261.7	260.5	263.2	**250.7**	-4.8%	-1.5%	6.5%
Azerbaijan	15.9	15.9	16.3	16.0	16.8	17.4	18.4	18.8	18.3	17.8	**18.8**	5.6%	5.3%	0.5%
Kazakhstan	18.3	19.0	20.4	20.1	19.8	21.4	21.7	22.0	22.9	23.4	**24.4**	4.1%	4.0%	0.6%
Russian Federation	611.5	536.2	598.4	616.8	601.9	614.5	591.2	584.4	589.3	635.6	**669.5**	5.3%	0.6%	17.3%
Turkmenistan	61.6	33.3	40.1	56.3	59.0	59.0	63.5	65.9	63.2	58.7	**61.5**	4.8%	-0.5%	1.6%
Uzbekistan	61.0	58.4	57.1	56.6	56.5	55.9	56.3	53.6	53.1	53.4	**56.6**	6.1%	-1.0%	1.5%
Other CIS	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	**0.3**	3.3%	◆	◆
Total CIS	768.6	663.2	732.7	766.2	754.3	768.5	751.4	745.0	747.2	789.1	**831.1**	5.3%	0.5%	21.5%
Bahrain	12.0	12.1	12.4	12.6	13.1	14.0	14.7	14.8	14.4	14.5	**14.8**	2.6%	2.6%	0.4%
Iran	123.6	135.7	143.9	151.0	156.9	157.5	175.5	183.5	199.3	220.2	**239.5**	8.8%	6.4%	6.2%
Iraq	6.5	6.9	7.1	6.3	6.3	7.1	7.5	7.3	9.9	10.1	**13.0**	28.4%	8.3%	0.3%
Kuwait	12.1	10.9	11.1	12.9	14.7	15.5	14.3	16.1	16.4	16.2	**17.5**	7.6%	4.3%	0.5%
Oman	24.1	23.9	25.7	27.1	28.3	30.8	29.3	30.7	31.5	32.3	**36.0**	11.4%	2.7%	0.9%
Qatar	79.7	92.4	123.1	150.4	162.5	168.2	169.6	175.0	173.8	172.4	**175.5**	1.8%	10.2%	4.5%
Saudi Arabia	76.4	74.5	83.3	87.6	94.4	95.0	97.3	99.2	105.3	109.3	**112.1**	2.6%	4.4%	2.9%
Syria	5.6	6.1	8.4	7.4	6.1	5.0	4.6	4.1	3.5	3.4	**3.6**	4.0%	-4.9%	0.1%
United Arab Emirates	49.0	47.6	50.0	51.0	52.9	53.2	52.9	58.7	60.3	62.0	**64.7**	4.4%	2.4%	1.7%
Yemen	–	0.8	6.3	9.4	7.6	10.4	9.8	2.9	0.5	0.5	**0.6**	1.9%	n/a	◆
Other Middle East	3.5	2.7	3.3	4.2	2.5	6.3	7.3	8.1	9.0	9.5	**10.1**	6.4%	13.0%	0.3%
Total Middle East	392.3	413.8	474.7	520.0	545.5	562.9	582.7	600.3	624.1	650.4	**687.3**	5.7%	6.0%	17.8%
Algeria	82.6	76.6	77.4	79.6	78.4	79.3	80.2	81.4	91.4	93.0	**92.3**	-0.7%	1.3%	2.4%
Egypt	56.8	60.3	59.0	59.1	58.6	54.0	47.0	42.6	40.3	48.8	**58.6**	20.0%	-0.9%	1.5%
Libya	15.1	15.1	16.0	7.5	11.6	12.2	11.8	11.0	9.4	9.6	**9.8**	2.2%	-4.1%	0.3%
Nigeria	32.8	23.2	30.9	36.4	39.2	33.1	40.0	48.0	46.2	48.1	**49.2**	2.4%	3.6%	1.3%
Other Africa	16.6	16.9	19.0	19.1	19.0	19.7	19.7	20.5	21.6	26.2	**26.7**	1.9%	7.8%	0.7%
Total Africa	203.8	192.1	202.3	201.7	206.8	198.3	198.6	203.6	208.8	225.7	**236.6**	4.8%	1.4%	6.1%
Australia	41.7	46.7	54.0	55.7	59.5	61.8	66.6	76.0	96.4	112.8	**130.1**	15.3%	10.2%	3.4%
Bangladesh	16.4	18.7	19.3	19.6	21.3	22.0	23.0	25.9	26.5	26.7	**27.5**	3.2%	5.7%	0.7%
Brunei	11.8	11.1	12.0	12.5	12.3	11.9	12.7	13.3	12.9	12.9	**12.6**	-2.3%	0.7%	0.3%
China	80.9	85.9	96.5	106.2	111.5	121.8	131.2	135.7	137.9	149.2	**161.5**	8.3%	7.9%	4.2%
India	29.4	36.1	47.4	42.9	37.3	31.1	29.4	28.1	26.6	27.7	**27.5**	-0.7%	-0.4%	0.7%
Indonesia	74.8	78.0	87.0	82.7	78.3	77.6	76.4	76.2	75.1	72.9	**73.2**	0.4%	◆	1.9%
Malaysia	69.2	66.9	65.8	67.0	69.3	72.9	72.0	73.9	72.4	74.5	**72.5**	-2.6%	1.0%	1.9%
Myanmar	12.2	11.4	12.2	12.6	12.5	12.9	16.5	19.2	18.3	17.8	**17.8**	–	3.0%	0.5%
Pakistan	34.6	34.7	35.3	35.3	36.6	35.6	35.0	35.0	34.7	34.7	**34.2**	-1.3%	0.2%	0.9%
Thailand	29.8	32.0	37.5	38.3	42.9	43.3	43.6	41.2	40.4	38.7	**37.7**	-2.6%	3.7%	1.0%
Vietnam	7.2	7.7	9.1	8.2	9.0	9.4	9.9	10.3	10.2	9.5	**9.6**	1.3%	3.4%	0.2%
Other Asia Pacific	18.2	18.5	18.1	18.3	18.0	18.7	23.6	29.4	30.2	30.3	**27.5**	-9.2%	5.8%	0.7%
Total Asia Pacific	426.3	447.9	494.3	499.1	508.4	518.9	539.8	564.1	581.6	607.5	**631.7**	4.0%	4.1%	16.3%
Total World	**3029.8**	**2938.6**	**3151.0**	**3257.0**	**3323.8**	**3363.1**	**3431.1**	**3501.7**	**3541.7**	**3677.7**	**3867.9**	**5.2%**	**2.3%**	**100.0%**
of which: OECD	1102.1	1095.3	1122.0	1142.5	1177.6	1185.4	1232.9	1272.1	1287.5	1325.4	**1422.5**	7.3%	2.1%	36.8%
Non-OECD	1927.7	1843.3	2029.0	2114.4	2146.3	2177.7	2198.2	2229.6	2254.2	2352.3	**2445.3**	4.0%	2.4%	63.2%
European Union	200.2	179.2	183.8	164.2	153.7	151.5	138.2	125.7	124.7	119.7	**109.2**	-8.8%	-4.8%	2.8%

*Excludes gas flared or recycled. Includes natural gas produced for gas-to-liquids transformation.

Source: Includes data from Cedigaz, FGE MENAgas service.

◆Less than 0.05%.

n/a not available.

Notes: As far as possible, the data above represents standard cubic metres (measured at 15°C and 1013 mbar); as they are derived directly from tonnes of oil equivalent using an average conversion factor and have been standardized using a gross calorific value (GCV) of 40 MJ/m³.

Annual changes and shares of total are calculated using billion cubic metres figures.

Natural gas production data expressed in billion cubic feet per day is available at *bp.com/statisticalreview.*

Table E3. Global natural gas production (Mtoe) (BP Statistical Review of World Energy 2019)

Natural gas: Production in million tonnes oil equivalent*

Million tonnes oil equivalent	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Growth rate per annum 2018	Growth rate per annum 2007-17	Share 2018
Canada	143.2	133.3	128.6	129.9	129.2	130.6	136.7	138.2	147.7	152.7	**158.8**	4.0%	0.2%	4.8%
Mexico	40.6	45.2	44.0	44.8	43.7	45.1	44.1	41.2	37.5	32.9	**32.1**	-2.4%	-2.0%	1.0%
US	469.5	479.4	494.5	530.8	558.1	563.8	606.0	636.5	625.4	641.2	**715.2**	11.5%	3.6%	21.5%
Total North America	653.3	658.0	667.2	705.5	731.1	739.6	786.8	816.0	810.7	826.8	**906.2**	9.6%	2.6%	27.2%
Argentina	36.8	34.7	33.5	32.4	31.5	29.7	29.7	30.5	32.1	31.9	**33.9**	6.1%	-1.6%	1.0%
Bolivia	11.9	10.2	11.8	12.9	14.7	16.8	17.4	16.8	15.1	14.7	**13.7**	-6.6%	2.5%	0.4%
Brazil	12.4	10.6	12.9	14.8	17.1	18.9	20.1	20.5	20.7	23.4	**21.6**	-7.4%	8.9%	0.7%
Colombia	7.5	8.7	9.3	9.1	9.9	11.4	10.6	10.0	10.3	10.6	**11.1**	4.6%	5.4%	0.3%
Peru	3.0	3.1	6.3	9.9	10.3	10.7	11.3	10.9	12.1	11.2	**11.0**	-1.7%	17.6%	0.3%
Trinidad & Tobago	32.2	33.2	34.6	33.3	33.1	33.3	32.7	30.9	26.9	27.4	**29.2**	6.6%	-1.7%	0.9%
Venezuela	28.7	27.3	26.2	26.0	27.4	26.3	27.3	31.0	32.0	33.2	**28.6**	-13.9%	0.4%	0.9%
Other S. & Cent. America	3.3	3.3	3.3	2.7	2.6	2.3	2.3	2.5	2.7	2.7	**2.8**	6.8%	-2.5%	0.1%
Total S. & Cent. America	135.8	131.0	137.9	141.1	146.7	149.4	151.4	153.1	151.9	155.0	**151.9**	-2.0%	1.4%	4.6%
Denmark	9.0	7.5	7.3	5.9	5.2	4.3	4.1	4.1	4.0	4.3	**3.7**	-15.0%	-6.2%	0.1%
Germany	11.7	11.0	9.6	9.0	8.1	7.4	6.9	6.5	6.0	5.5	**4.8**	-13.1%	-8.2%	0.1%
Italy	7.6	6.6	6.9	6.9	7.0	6.3	5.9	5.5	4.7	4.5	**4.5**	-1.6%	-5.5%	0.1%
Netherlands	61.0	56.3	64.7	59.8	58.8	62.3	51.9	39.4	38.1	33.2	**27.7**	-16.3%	-4.6%	0.8%
Norway	85.4	89.1	91.5	86.4	97.9	92.8	92.9	99.9	99.6	105.9	**103.7**	-2.1%	3.2%	3.1%
Poland	3.7	3.7	3.7	3.8	3.9	3.8	3.7	3.7	3.6	3.5	**3.4**	-1.5%	-1.1%	0.1%
Romania	9.0	8.9	8.6	8.7	8.7	8.6	8.8	8.8	7.8	8.5	**8.2**	-3.7%	-0.8%	0.2%
Ukraine	17.5	17.5	16.7	16.8	16.7	17.3	17.4	16.2	16.4	16.7	**17.1**	2.4%	-0.3%	0.5%
United Kingdom	62.6	52.6	49.8	39.6	33.7	31.8	32.2	35.0	35.9	36.0	**34.9**	-3.1%	-5.7%	1.0%
Other Europe	8.6	8.3	8.3	8.5	7.7	6.7	6.2	5.9	7.9	8.2	**7.5**	-7.9%	-1.1%	0.2%
Total Europe	276.0	261.5	267.1	245.4	247.7	241.3	230.0	225.0	224.0	226.3	**215.5**	-4.8%	-1.5%	6.5%
Azerbaijan	13.7	13.7	14.0	13.7	14.5	15.0	15.8	16.2	15.7	15.3	**16.1**	5.6%	5.3%	0.5%
Kazakhstan	15.7	16.3	17.6	17.3	17.1	18.4	18.6	18.9	19.7	20.1	**21.0**	4.1%	4.0%	0.6%
Russian Federation	525.8	461.0	514.5	530.4	517.5	528.4	508.3	502.5	506.7	546.5	**575.6**	5.3%	0.6%	17.3%
Turkmenistan	53.0	28.7	34.5	48.4	50.7	50.7	54.6	56.6	54.4	50.5	**52.9**	4.8%	-0.5%	1.6%
Uzbekistan	52.5	50.2	49.1	48.7	48.6	48.1	48.4	46.1	45.7	45.9	**48.7**	6.1%	-1.0%	1.5%
Other CIS	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	**0.3**	3.3%	♦	♦
Total CIS	660.9	570.2	630.0	658.8	648.6	660.8	646.0	640.6	642.4	678.5	**714.6**	5.3%	0.5%	21.5%
Bahrain	10.3	10.4	10.7	10.9	11.2	12.0	12.6	12.7	12.4	12.4	**12.8**	2.6%	2.6%	0.4%
Iran	106.2	116.7	123.7	129.8	134.9	135.4	150.9	157.8	171.4	189.3	**205.9**	8.8%	6.4%	6.2%
Iraq	5.6	5.9	6.1	5.4	5.5	6.1	6.5	6.3	8.5	8.7	**11.2**	28.4%	8.3%	0.3%
Kuwait	10.4	9.4	9.6	11.1	12.7	13.3	12.3	13.8	14.1	14.0	**15.0**	7.6%	4.3%	0.5%
Oman	20.8	20.6	22.1	23.3	24.4	26.5	25.2	26.4	27.1	27.7	**30.9**	11.4%	2.7%	0.9%
Qatar	68.5	79.5	105.9	129.3	139.8	144.6	145.8	150.5	149.4	148.2	**150.9**	1.8%	10.2%	4.5%
Saudi Arabia	65.7	64.1	71.6	75.4	81.1	81.7	83.6	85.3	90.6	93.9	**96.4**	2.6%	4.4%	2.9%
Syria	4.8	5.3	7.2	6.4	5.2	4.3	4.0	3.5	3.0	2.9	**3.1**	4.0%	-4.9%	0.1%
United Arab Emirates	42.1	40.9	43.0	43.9	45.5	45.8	45.5	50.5	51.9	53.3	**55.6**	4.4%	2.4%	1.7%
Yemen	–	0.7	5.4	8.1	6.5	8.9	8.4	2.5	0.4	0.5	**0.5**	1.9%	n/a	♦
Other Middle East	3.0	2.4	2.8	3.6	2.2	5.4	6.3	6.9	7.8	8.2	**8.7**	6.4%	13.0%	0.3%
Total Middle East	337.4	355.8	408.1	447.1	469.0	484.0	501.1	516.1	536.6	559.2	**590.9**	5.7%	6.0%	17.8%
Algeria	71.0	65.8	66.5	68.4	67.4	68.2	68.9	70.0	78.6	79.9	**79.4**	-0.7%	1.3%	2.4%
Egypt	48.8	51.9	50.7	50.9	50.4	46.4	40.4	36.6	34.6	42.0	**50.4**	20.0%	-0.9%	1.5%
Libya	13.0	13.0	13.7	6.4	10.0	10.5	10.2	9.5	8.1	8.2	**8.4**	2.2%	-4.1%	0.3%
Nigeria	28.2	19.9	26.6	31.3	33.7	28.5	34.4	41.3	39.7	41.4	**42.3**	2.4%	3.6%	1.3%
Other Africa	14.3	14.5	16.3	16.4	16.3	17.0	16.9	17.7	18.6	22.5	**22.9**	1.9%	7.8%	0.7%
Total Africa	175.3	165.2	174.0	173.4	177.8	170.5	170.8	175.0	179.6	194.0	**203.4**	4.8%	1.4%	6.1%
Australia	35.8	40.2	46.4	47.9	51.2	53.1	57.3	65.4	82.9	97.0	**111.9**	15.3%	10.2%	3.4%
Bangladesh	14.1	16.1	16.6	16.8	18.3	18.9	19.8	22.2	22.7	22.9	**23.7**	3.2%	5.7%	0.7%
Brunei	10.2	9.6	10.3	10.7	10.5	10.2	10.9	11.4	11.1	11.1	**10.8**	-2.3%	0.7%	0.3%
China	69.6	73.9	83.0	91.3	95.9	104.7	112.8	116.7	118.6	128.3	**138.9**	8.3%	7.9%	4.2%
India	25.3	31.1	40.8	36.9	32.0	26.7	25.2	24.2	22.9	23.8	**23.6**	-0.7%	-0.4%	0.7%
Indonesia	64.3	67.1	74.8	71.1	67.3	66.7	65.7	65.5	64.6	62.7	**62.9**	0.4%	♦	1.9%
Malaysia	59.5	57.5	56.6	57.6	59.5	62.7	61.9	63.5	62.2	64.0	**62.3**	-2.6%	1.0%	1.9%
Myanmar	10.5	9.8	10.5	10.8	10.8	11.1	14.2	16.5	15.7	15.3	**15.3**	–	3.0%	0.5%
Pakistan	29.8	29.8	30.4	30.4	31.5	30.6	30.1	30.1	29.8	29.8	**29.4**	-1.3%	0.2%	0.9%
Thailand	25.6	27.5	32.2	32.9	36.9	37.2	37.5	35.4	34.7	33.3	**32.4**	-2.6%	3.7%	1.0%
Vietnam	6.2	6.6	7.8	7.0	7.8	8.1	8.5	8.8	8.8	8.2	**8.3**	1.3%	3.4%	0.2%
Other Asia Pacific	15.6	15.9	15.6	15.7	15.5	16.1	20.3	25.3	26.0	26.0	**23.6**	-9.2%	5.8%	0.7%
Total Asia Pacific	366.5	385.1	425.0	429.1	437.1	446.2	464.2	485.1	500.1	522.4	**543.2**	4.0%	4.1%	16.3%
Total World	**2605.1**	**2526.7**	**2709.4**	**2800.5**	**2858.0**	**2891.8**	**2950.2**	**3010.9**	**3045.3**	**3162.3**	**3325.8**	**5.2%**	**2.3%**	**100.0%**
of which: OECD	947.6	941.8	964.7	982.4	1012.5	1019.2	1060.1	1093.8	1107.0	1139.7	**1223.2**	7.3%	2.1%	36.8%
Non-OECD	1657.5	1585.0	1744.6	1818.1	1845.4	1872.5	1890.1	1917.1	1938.3	2022.6	**2102.6**	4.0%	2.4%	63.2%
European Union	172.1	154.1	158.0	141.2	132.1	130.3	118.9	108.1	107.2	102.9	**93.9**	-8.8%	-4.8%	2.8%

*Excludes gas flared or recycled. Includes natural gas produced for gas-to-liquids transformation.
♦Less than 0.05%.
n/a not available.
Note: Annual changes and shares of total are calculated using million tonnes oil equivalent figures.

Source: Includes data from Cedigaz, FGE MENAgas service.

Table E4. Global natural gas consumption (billion cubic metres) (BP Statistical Review of World Energy 2019)

Natural gas: Consumption in billion cubic metres*

Billion cubic metres	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Growth rate per annum 2018	Growth rate per annum 2007-17	Share 2018
Canada	89.3	86.6	88.3	97.5	97.2	104.3	109.6	109.8	105.9	109.7	**115.7**	5.5%	1.9%	3.0%
Mexico	60.0	65.2	66.0	70.8	73.7	77.8	78.8	80.8	83.0	86.4	**89.5**	3.6%	4.2%	2.3%
US	628.9	617.6	648.2	658.2	688.1	707.0	722.3	743.6	749.1	739.4	**817.1**	10.5%	1.7%	21.2%
Total North America	778.2	769.4	802.5	826.6	859.0	889.1	910.7	934.1	938.0	935.5	**1022.3**	9.3%	1.9%	26.6%
Argentina	43.2	41.8	42.1	43.8	45.7	46.0	46.2	46.7	48.2	48.3	**48.7**	0.8%	1.2%	1.3%
Brazil	25.7	20.7	27.6	27.5	32.6	38.4	40.7	42.9	37.1	37.6	**35.9**	-4.6%	5.6%	0.9%
Chile	2.8	2.8	5.7	5.8	5.3	5.3	4.4	4.8	5.9	5.6	**6.4**	14.2%	1.2%	0.2%
Colombia	7.3	8.4	8.7	8.5	9.5	10.5	11.4	11.2	11.8	12.2	**13.0**	7.1%	5.4%	0.3%
Ecuador	0.5	0.6	0.6	0.6	0.7	0.9	0.9	0.8	0.9	0.8	**0.7**	-14.1%	4.2%	♦
Peru	3.3	3.3	4.9	5.4	6.0	5.9	6.7	7.1	7.6	6.7	**7.0**	4.4%	10.1%	0.2%
Trinidad & Tobago	15.8	16.1	17.7	18.0	17.1	17.4	17.0	17.0	15.1	15.3	**15.3**	0.3%	-0.8%	0.4%
Venezuela	34.9	34.2	31.3	33.3	34.6	32.3	34.0	37.0	37.5	38.8	**33.4**	-13.9%	0.4%	0.9%
Other S. & Cent. America	4.7	4.9	5.1	5.8	6.3	6.9	7.2	7.1	7.4	7.3	**7.9**	8.4%	5.0%	0.2%
Total S. & Cent. America	138.1	132.9	143.7	148.7	157.7	163.5	168.5	174.7	171.6	172.6	**168.4**	-2.5%	2.3%	4.4%
Austria	9.1	8.8	9.6	9.0	8.6	8.2	7.5	8.0	8.3	9.1	**8.7**	-4.2%	0.7%	0.2%
Belgium	17.4	17.6	19.4	16.5	16.7	16.5	14.5	15.8	16.2	16.4	**16.9**	2.8%	-0.7%	0.4%
Czech Republic	8.3	7.9	9.4	7.9	8.0	8.1	7.2	7.5	8.2	8.4	**8.0**	-4.7%	-0.1%	0.2%
Finland	4.2	3.7	4.1	3.6	3.2	3.0	2.7	2.3	2.0	1.8	**2.0**	11.5%	-7.7%	0.1%
France	46.4	44.7	49.6	43.0	44.4	45.1	37.9	40.8	44.5	44.8	**42.7**	-4.6%	♦	1.1%
Germany	89.5	84.4	88.1	80.9	81.1	85.0	73.9	77.0	84.9	89.7	**88.3**	-1.6%	0.1%	2.3%
Greece	4.1	3.4	3.7	4.6	4.2	3.7	2.8	3.1	4.0	4.8	**4.7**	-1.8%	2.2%	0.1%
Hungary	12.3	10.6	11.4	10.9	9.7	9.1	8.1	8.7	9.3	9.9	**9.6**	-3.3%	-2.2%	0.2%
Italy	80.9	74.3	79.1	74.2	71.4	66.7	59.0	64.3	67.5	71.6	**69.2**	-3.3%	-1.3%	1.8%
Netherlands	40.4	41.4	46.8	40.9	39.3	39.1	34.5	34.1	35.2	36.1	**35.7**	-1.1%	-0.7%	0.9%
Norway	4.3	4.1	4.1	4.0	4.0	4.0	4.3	4.5	4.4	4.6	**4.5**	-2.2%	0.9%	0.1%
Poland	15.6	15.1	16.2	16.5	17.4	17.4	17.0	17.1	18.3	19.2	**19.7**	2.9%	2.9%	0.5%
Portugal	4.8	4.8	5.2	5.3	4.6	4.3	4.1	4.8	5.1	6.3	**5.9**	-7.6%	3.7%	0.2%
Romania	14.1	12.3	12.5	12.9	12.5	11.4	11.0	10.4	10.5	11.2	**10.9**	-2.8%	-2.8%	0.3%
Spain	40.6	36.3	36.2	33.6	33.2	30.3	27.5	28.5	29.1	31.7	**31.5**	-0.8%	-1.5%	0.8%
Sweden	0.9	1.1	1.5	1.3	1.1	1.1	0.9	0.9	1.0	0.8	**0.8**	2.4%	-2.6%	♦
Switzerland	2.9	2.8	3.2	2.8	3.1	3.2	2.8	3.0	3.1	3.1	**3.0**	-5.0%	1.3%	0.1%
Turkey	35.3	33.7	35.8	41.8	43.3	44.0	46.6	46.0	44.5	51.6	**47.3**	-8.3%	4.3%	1.2%
Ukraine	62.7	48.9	54.6	56.1	51.8	47.7	40.3	32.0	31.4	30.2	**30.6**	1.3%	-7.5%	0.8%
United Kingdom	97.8	91.2	98.5	81.9	76.9	76.3	70.1	72.0	81.2	78.8	**78.9**	0.1%	-1.9%	2.0%
Other Europe	34.0	29.8	33.5	32.3	30.7	30.0	27.2	28.1	28.9	30.3	**30.1**	-0.6%	-1.4%	0.8%
Total Europe	625.6	577.1	622.6	580.1	565.4	554.4	500.0	508.8	537.6	560.4	**549.0**	-2.1%	-1.0%	14.3%
Azerbaijan	10.0	8.6	8.1	8.9	9.4	9.4	9.9	11.1	10.9	10.6	**10.8**	1.9%	1.9%	0.3%
Belarus	19.9	16.9	20.7	19.2	19.4	19.3	19.1	17.9	17.8	18.2	**19.3**	6.1%	-0.7%	0.5%
Kazakhstan	10.6	10.1	11.0	12.2	13.0	13.6	15.0	15.3	15.8	15.9	**19.4**	22.4%	4.1%	0.5%
Russian Federation	422.7	397.8	423.9	435.6	428.6	424.9	422.2	408.7	420.6	431.1	**454.5**	5.4%	0.1%	11.8%
Turkmenistan	7.9	17.1	18.3	20.7	22.9	19.3	20.0	25.4	24.1	25.3	**28.4**	12.0%	8.5%	0.7%
Uzbekistan	44.1	44.1	44.0	47.4	46.2	46.2	48.5	46.3	43.3	43.1	**42.6**	-1.2%	-0.8%	1.1%
Other CIS	5.9	5.3	5.2	5.5	5.7	4.8	5.3	5.2	5.1	5.1	**5.7**	13.2%	-1.5%	0.1%
Total CIS	521.3	499.9	531.3	549.5	545.2	537.3	539.9	530.0	537.7	549.3	**580.8**	5.7%	0.3%	15.1%
Iran	125.8	134.8	144.4	153.2	152.5	153.8	173.4	184.0	196.3	209.9	**225.6**	7.4%	5.9%	5.9%
Iraq	6.5	6.9	7.1	6.3	6.3	7.1	7.5	7.3	9.9	12.7	**17.0**	33.9%	10.9%	0.4%
Israel	3.6	4.0	5.1	4.7	2.4	6.6	7.2	8.1	9.2	9.9	**10.5**	6.4%	14.2%	0.3%
Kuwait	12.1	11.8	14.0	15.9	17.5	17.8	17.9	20.3	21.1	21.0	**21.8**	3.6%	7.0%	0.6%
Oman	13.4	13.7	16.3	18.1	19.7	21.7	21.3	23.0	22.8	23.3	**24.9**	6.9%	6.7%	0.6%
Qatar	20.7	21.3	25.4	28.7	33.6	35.6	38.6	42.5	40.4	43.1	**41.9**	-2.8%	8.4%	1.1%
Saudi Arabia	76.4	74.5	83.3	87.6	94.4	95.0	97.3	99.2	105.3	109.3	**112.1**	2.6%	4.4%	2.9%
United Arab Emirates	58.0	57.6	59.3	61.6	63.9	64.7	63.4	71.5	72.7	74.4	**76.6**	2.9%	4.5%	2.0%
Other Middle East	20.7	22.7	25.2	21.9	20.4	21.0	20.9	22.4	23.0	23.4	**22.7**	-2.9%	1.8%	0.6%
Total Middle East	337.1	347.3	380.1	398.1	410.8	423.3	447.5	478.3	500.9	527.0	**553.1**	4.9%	5.6%	14.4%
Algeria	24.4	26.2	25.3	26.8	29.9	32.1	36.1	37.9	38.6	38.9	**42.7**	9.9%	5.2%	1.1%
Egypt	39.3	40.9	43.4	47.8	50.6	49.5	46.2	46.0	49.4	55.9	**59.6**	6.5%	4.2%	1.5%
Morocco	0.6	0.6	0.7	0.9	1.2	1.1	1.1	1.1	1.1	1.1	**1.0**	-9.6%	6.7%	♦
South Africa	3.9	3.3	4.1	4.3	4.4	4.1	4.3	4.3	4.5	4.4	**4.3**	-2.2%	1.6%	0.1%
Other Africa	26.6	24.5	25.4	27.5	29.1	29.8	32.1	38.7	41.4	40.4	**42.3**	4.9%	4.5%	1.1%
Total Africa	94.8	95.6	98.9	107.2	115.1	116.6	119.9	128.1	135.0	140.8	**150.0**	6.6%	4.5%	3.9%
Australia	28.5	29.1	33.8	35.3	35.4	37.2	40.1	42.1	41.7	41.2	**41.4**	0.4%	3.6%	1.1%
Bangladesh	16.4	18.7	19.3	19.6	21.3	22.0	23.0	25.9	26.5	26.7	**28.4**	6.4%	5.7%	0.7%
China	81.9	90.2	108.9	135.2	150.9	171.9	188.4	194.7	209.4	240.4	**283.0**	17.7%	13.0%	7.4%
China Hong Kong SAR	3.0	2.9	3.6	2.9	2.6	2.5	2.4	3.0	3.1	3.1	**3.0**	-3.2%	1.9%	0.1%
India	40.0	49.1	59.0	60.3	55.7	49.0	48.5	47.8	50.8	53.7	**58.1**	8.1%	3.3%	1.5%
Indonesia	39.7	42.1	44.0	42.7	42.9	41.4	41.5	41.0	39.1	38.5	**39.0**	1.1%	1.1%	1.0%
Japan	99.1	92.5	99.9	112.0	123.2	123.5	124.8	118.7	116.4	117.0	**115.7**	-1.1%	2.1%	3.0%
Malaysia	43.5	40.0	38.0	38.3	42.0	44.6	44.7	43.9	42.4	41.8	**41.3**	-1.2%	0.3%	1.1%
New Zealand	3.9	4.0	4.4	4.0	4.4	4.7	5.2	4.8	4.8	5.0	**4.3**	-12.9%	1.7%	0.1%
Pakistan	34.6	34.7	35.3	35.3	36.6	35.6	35.0	36.5	38.7	40.7	**43.6**	7.0%	1.9%	1.1%
Philippines	3.7	3.7	3.5	3.8	3.6	3.4	3.5	3.3	3.8	3.8	**4.1**	8.3%	0.7%	0.1%
Singapore	8.7	9.2	8.3	8.3	8.9	10.0	10.4	11.6	11.9	12.3	**12.3**	♦	4.2%	0.3%
South Korea	37.3	35.5	45.0	48.4	52.5	55.0	50.0	45.6	47.6	49.8	**55.9**	12.4%	3.2%	1.5%
Sri Lanka	–	–	–	–	–	–	–	–	–	–	**–**	n/a	n/a	n/a
Taiwan	12.8	12.5	15.5	17.0	17.9	17.9	18.9	20.2	21.0	23.2	**23.7**	1.8%	7.1%	0.6%
Thailand	36.9	38.1	43.2	44.3	48.6	48.9	49.9	51.0	50.6	50.1	**49.9**	-0.3%	3.6%	1.3%
Vietnam	7.2	7.7	9.1	8.2	9.0	9.4	9.9	10.3	10.2	9.5	**9.6**	1.3%	3.4%	0.3%
Other Asia Pacific	6.3	5.5	6.8	7.5	8.5	8.6	10.1	12.0	11.4	11.4	**12.0**	5.3%	5.9%	0.3%
Total Asia Pacific	503.7	515.6	577.6	623.1	664.3	685.5	706.2	712.5	729.3	768.3	**825.3**	7.4%	5.0%	21.4%
Total World	**2998.8**	**2937.8**	**3156.7**	**3233.3**	**3317.5**	**3369.8**	**3392.6**	**3466.5**	**3550.2**	**3654.0**	**3848.9**	**5.3%**	**2.2%**	**100.0%**
of which: OECD	1489.0	1442.4	1539.7	1534.4	1570.5	1604.4	1579.3	1612.2	1646.8	1669.2	**1750.6**	4.9%	1.3%	45.5%
Non-OECD	1509.8	1495.4	1617.0	1698.9	1747.0	1765.4	1813.3	1854.2	1903.4	1984.8	**2098.3**	5.7%	3.1%	54.5%
European Union	516.6	484.5	521.3	471.0	459.1	451.2	401.7	418.7	449.3	465.7	**458.5**	-1.6%	-0.8%	11.9%

Source: Includes data from Cedigaz, FGE MENAgas service.

*Excludes natural gas converted to liquid fuels but includes derivatives of coal as well as natural gas consumed in gas-to-liquids transformation.
♦Less than 0.05%.
n/a not available.
Notes: As far as possible, the data above represents standard cubic metres (measured at 15°C and 1013 mbar); as they are derived directly from tonnes of oil equivalent using an average conversion factor and have been standardized using a gross calorific value (GCV) of 40 MJ/m³.
The difference between these world consumption figures and the world production statistics is due to variations in stocks at storage facilities and liquefaction plants, together with unavoidable disparities in the definition, measurement or conversion of gas supply and demand data.
Annual changes and shares of total are calculated using billion cubic metres figures.
Natural gas consumption data expressed in billion cubic feet per day is available at *bp.com/statisticalreview*.

Table E5. Global natural gas consumption (Mtoe) (BP Statistical Review of World Energy 2019)

Natural gas: Consumption in million tonnes oil equivalent*

Million tonnes oil equivalent	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Growth rate per annum 2018	Growth rate per annum 2007-17	Share 2018
Canada	76.8	74.4	75.9	83.9	83.6	89.7	94.2	94.4	91.0	94.3	**99.5**	5.5%	1.9%	3.0%
Mexico	51.6	56.0	56.8	60.9	63.3	66.9	67.8	69.5	71.4	74.3	**77.0**	3.6%	4.2%	2.3%
US	540.7	531.1	557.3	566.0	591.7	607.9	621.0	639.4	644.1	635.8	**702.6**	10.5%	1.7%	21.2%
Total North America	669.2	661.5	690.0	710.7	738.6	764.5	783.1	803.2	806.5	804.4	**879.1**	9.3%	1.9%	26.6%
Argentina	37.1	36.0	36.2	37.7	39.3	39.6	39.7	40.1	41.5	41.5	**41.9**	0.8%	1.2%	1.3%
Brazil	22.1	17.8	23.7	23.6	28.0	33.0	35.0	36.9	31.9	32.4	**30.9**	-4.6%	5.6%	0.9%
Chile	2.4	2.4	4.9	5.0	4.6	4.6	3.8	4.1	5.1	4.8	**5.5**	14.2%	1.2%	0.2%
Colombia	6.3	7.2	7.5	7.3	8.1	9.0	9.8	9.6	10.1	10.5	**11.2**	7.1%	5.4%	0.3%
Ecuador	0.4	0.5	0.5	0.5	0.6	0.7	0.8	0.7	0.8	0.7	**0.6**	-14.1%	4.2%	◆
Peru	2.8	2.9	4.2	4.6	5.2	5.1	5.8	6.1	6.5	5.8	**6.1**	4.4%	10.1%	0.2%
Trinidad & Tobago	13.6	13.8	15.2	15.4	14.7	14.9	14.7	14.6	13.0	13.1	**13.2**	0.3%	-0.8%	0.4%
Venezuela	30.0	29.4	26.9	28.7	29.8	27.8	29.3	31.8	32.3	33.4	**28.7**	-13.9%	0.4%	0.9%
Other S. & Cent. America	4.1	4.2	4.4	5.0	5.4	5.9	6.2	6.1	6.4	6.2	**6.8**	8.4%	5.0%	0.2%
Total S. & Cent. America	118.7	114.2	123.5	127.8	135.6	140.6	144.8	150.2	147.5	148.4	**144.8**	-2.5%	2.3%	4.4%
Austria	7.8	7.6	8.3	7.8	7.4	7.1	6.5	6.9	7.2	7.8	**7.5**	-4.2%	0.7%	0.2%
Belgium	15.0	15.1	16.7	14.2	14.4	14.2	12.4	13.6	13.9	14.1	**14.5**	2.8%	-0.7%	0.4%
Czech Republic	7.2	6.8	8.1	6.8	6.9	6.9	6.2	6.5	7.0	7.2	**6.9**	-4.7%	-0.1%	0.2%
Finland	3.6	3.2	3.6	3.1	2.7	2.6	2.3	2.0	1.7	1.6	**1.8**	11.5%	-7.7%	0.1%
France	39.9	38.5	42.6	37.0	38.2	38.8	32.6	35.0	38.3	38.5	**36.7**	-4.6%	◆	1.1%
Germany	77.0	72.6	75.7	69.5	69.7	73.1	63.5	66.2	73.0	77.2	**75.9**	-1.6%	0.1%	2.3%
Greece	3.5	2.9	3.2	4.0	3.6	3.2	2.4	2.6	3.4	4.1	**4.1**	-1.8%	2.2%	0.1%
Hungary	10.6	9.2	9.8	9.4	8.4	7.8	7.0	7.5	8.0	8.5	**8.3**	-3.3%	-2.2%	0.2%
Italy	69.5	63.9	68.1	63.8	61.4	57.4	50.7	55.3	58.1	61.5	**59.5**	-3.3%	-1.3%	1.8%
Netherlands	34.7	35.6	40.2	35.2	33.8	33.6	29.6	29.3	30.2	31.0	**30.7**	-1.1%	-0.7%	0.9%
Norway	3.7	3.5	3.5	3.5	3.4	3.4	3.7	3.9	3.8	3.9	**3.9**	-2.2%	0.9%	0.1%
Poland	13.5	13.0	14.0	14.1	15.0	15.0	14.6	14.7	15.7	16.5	**17.0**	2.9%	2.9%	0.5%
Portugal	4.1	4.1	4.5	4.5	3.9	3.7	3.5	4.1	4.4	5.5	**5.0**	-7.6%	3.7%	0.2%
Romania	12.2	10.6	10.8	11.1	10.8	9.8	9.5	8.9	9.0	9.6	**9.3**	-2.8%	-2.8%	0.3%
Spain	34.9	31.2	31.1	28.9	28.6	26.1	23.7	24.5	25.0	27.3	**27.1**	-0.8%	-1.5%	0.8%
Sweden	0.8	1.0	1.3	1.1	0.9	0.9	0.8	0.8	0.8	0.7	**0.7**	2.4%	-2.6%	◆
Switzerland	2.5	2.4	2.7	2.4	2.6	2.8	2.4	2.6	2.7	2.7	**2.6**	-5.0%	1.3%	0.1%
Turkey	30.4	29.0	30.8	36.0	37.2	37.8	40.1	39.5	38.3	44.3	**40.7**	-8.3%	4.3%	1.2%
Ukraine	54.0	42.1	46.9	48.3	44.6	41.0	34.7	27.5	27.0	26.0	**26.3**	1.3%	-7.5%	0.8%
United Kingdom	84.1	78.4	84.7	70.4	66.1	65.6	60.2	61.9	69.8	67.8	**67.8**	0.1%	-1.9%	2.0%
Other Europe	29.2	25.6	28.8	27.8	26.4	25.8	23.4	24.1	24.8	26.1	**25.9**	-0.6%	-1.4%	0.8%
Total Europe	538.0	496.2	535.3	498.8	486.1	476.7	429.9	437.5	462.2	481.9	**472.0**	-2.1%	-1.0%	14.3%
Azerbaijan	8.6	7.4	7.0	7.7	8.0	8.1	8.5	9.6	9.4	9.1	**9.3**	1.9%	1.9%	0.3%
Belarus	17.1	14.6	17.8	16.5	16.7	16.6	16.4	15.4	15.3	15.7	**16.6**	6.1%	-0.7%	0.5%
Kazakhstan	9.1	8.7	9.5	10.5	11.1	11.7	12.9	13.2	13.6	13.7	**16.7**	22.4%	4.1%	0.5%
Russian Federation	363.5	342.0	364.5	374.6	368.6	365.3	363.0	351.4	361.7	370.7	**390.8**	5.4%	0.1%	11.8%
Turkmenistan	6.8	14.7	15.7	17.8	19.7	16.6	17.2	21.8	20.7	21.8	**24.4**	12.0%	8.5%	0.7%
Uzbekistan	37.9	37.9	37.9	40.7	39.8	39.7	41.7	39.8	37.3	37.1	**36.6**	-1.2%	-0.8%	1.1%
Other CIS	5.1	4.6	4.4	4.7	4.9	4.1	4.5	4.5	4.4	4.3	**4.9**	13.2%	-1.5%	0.1%
Total CIS	448.2	429.9	456.8	472.5	468.8	462.0	464.3	455.7	462.4	472.3	**499.4**	5.7%	0.3%	15.1%
Iran	108.2	115.9	124.2	131.7	131.2	132.3	149.1	158.2	168.8	180.5	**193.9**	7.4%	5.9%	5.9%
Iraq	5.6	5.9	6.1	5.4	5.5	6.1	6.5	6.3	8.5	11.0	**14.7**	33.9%	10.9%	0.4%
Israel	3.1	3.4	4.4	4.1	2.1	5.7	6.2	6.9	8.0	8.5	**9.0**	6.4%	14.2%	0.3%
Kuwait	10.4	10.2	12.0	13.6	15.1	15.3	15.4	17.5	18.2	18.1	**18.7**	3.6%	7.0%	0.6%
Oman	11.5	11.8	14.0	15.6	16.9	18.6	18.3	19.8	19.6	20.0	**21.4**	6.9%	6.7%	0.6%
Qatar	17.8	18.3	21.9	24.7	28.9	30.6	33.2	36.5	34.7	37.0	**36.0**	-2.8%	8.4%	1.1%
Saudi Arabia	65.7	64.1	71.6	75.4	81.1	81.7	83.6	85.3	90.6	93.9	**96.4**	2.6%	4.4%	2.9%
United Arab Emirates	49.8	49.5	51.0	53.0	55.0	55.7	54.5	61.5	62.5	64.0	**65.8**	2.9%	4.5%	2.0%
Other Middle East	17.8	19.5	21.7	18.8	17.5	18.0	18.0	19.3	19.8	20.1	**19.5**	-2.9%	1.8%	0.6%
Total Middle East	289.8	298.6	326.8	342.3	353.2	364.0	384.8	411.3	430.7	453.2	**475.6**	4.9%	5.6%	14.4%
Algeria	21.0	22.5	21.8	23.0	25.7	27.6	31.0	32.6	33.2	33.4	**36.7**	9.9%	5.2%	1.1%
Egypt	33.8	35.2	37.3	41.1	43.5	42.6	39.7	39.6	42.4	48.1	**51.2**	6.5%	4.2%	1.5%
Morocco	0.5	0.6	0.6	0.8	1.0	1.0	1.0	1.0	1.0	1.0	**0.9**	-9.6%	6.7%	◆
South Africa	3.4	2.9	3.5	3.7	3.7	3.5	3.7	3.7	3.9	3.8	**3.7**	-2.2%	1.6%	0.1%
Other Africa	22.8	21.0	21.8	23.6	25.0	25.6	27.6	33.2	35.6	34.7	**36.4**	4.9%	4.5%	1.1%
Total Africa	81.5	82.2	85.1	92.2	99.0	100.3	103.1	110.1	116.1	121.0	**129.0**	6.6%	4.5%	3.9%
Australia	24.5	25.1	29.0	30.3	30.4	32.0	34.5	36.2	35.9	35.5	**35.6**	0.4%	3.6%	1.1%
Bangladesh	14.1	16.1	16.6	16.8	18.3	18.9	19.8	22.2	22.7	22.9	**24.4**	6.4%	5.7%	0.7%
China	70.4	77.6	93.6	116.2	129.7	147.8	162.0	167.4	180.1	206.7	**243.3**	17.7%	13.0%	7.4%
China Hong Kong SAR	2.6	2.5	3.1	2.5	2.3	2.1	2.1	2.6	2.7	2.7	**2.6**	-3.2%	1.9%	0.1%
India	34.4	42.2	50.7	51.8	47.9	42.1	41.7	41.1	43.7	46.2	**49.9**	8.1%	3.3%	1.5%
Indonesia	34.1	36.2	37.9	36.7	36.9	35.6	35.7	35.3	33.6	33.1	**33.5**	1.1%	1.1%	1.0%
Japan	85.2	79.5	85.9	96.3	105.9	106.2	107.3	102.1	100.1	100.6	**99.5**	-1.1%	2.1%	3.0%
Malaysia	37.4	34.4	32.7	32.9	36.1	38.3	38.4	37.8	36.4	35.9	**35.5**	-1.2%	0.3%	1.1%
New Zealand	3.3	3.4	3.8	3.4	3.8	4.0	4.5	4.1	4.1	4.3	**3.7**	-12.9%	1.7%	0.1%
Pakistan	29.8	29.8	30.4	30.4	31.5	30.6	30.1	31.4	33.2	35.0	**37.5**	7.0%	1.9%	1.1%
Philippines	3.2	3.2	3.0	3.3	3.1	2.9	3.0	2.9	3.3	3.2	**3.5**	8.3%	0.7%	0.1%
Singapore	7.5	7.9	7.2	7.1	7.7	8.6	8.9	10.0	10.2	10.6	**10.6**	◆	4.2%	0.3%
South Korea	32.1	30.5	38.7	41.7	45.2	47.3	43.0	39.3	41.0	42.8	**48.1**	12.4%	3.2%	1.5%
Sri Lanka	–	–	–	–	–	–	–	–	–	–	–	n/a	n/a	n/a
Taiwan	11.0	10.7	13.3	14.7	15.4	15.4	16.2	17.4	18.0	20.0	**20.3**	1.8%	7.1%	0.6%
Thailand	31.8	32.8	37.2	38.1	41.8	42.0	42.9	43.8	43.5	43.1	**42.9**	-0.3%	3.6%	1.3%
Vietnam	6.2	6.6	7.8	7.0	7.8	8.1	8.5	8.8	8.8	8.2	**8.3**	1.3%	3.4%	0.3%
Other Asia Pacific	5.5	4.7	5.8	6.5	7.3	7.4	8.7	10.3	9.8	9.8	**10.3**	5.3%	5.9%	0.3%
Total Asia Pacific	433.1	443.4	496.7	535.8	571.2	589.5	607.2	612.7	627.1	660.6	**709.6**	7.4%	5.0%	21.4%
Total World	**2578.5**	**2526.0**	**2714.3**	**2780.1**	**2852.6**	**2897.5**	**2917.1**	**2980.6**	**3052.6**	**3141.9**	**3309.4**	**5.3%**	**2.2%**	**100.0%**
of which: OECD	1280.3	1240.2	1323.9	1319.3	1350.4	1379.5	1358.0	1386.3	1416.0	1435.2	**1505.2**	4.9%	1.3%	45.5%
Non-OECD	1298.2	1285.8	1390.4	1460.8	1502.2	1517.9	1559.2	1594.4	1636.6	1706.7	**1804.2**	5.7%	3.1%	54.5%
European Union	444.2	416.6	448.2	405.0	394.7	387.9	345.4	360.0	386.3	400.4	**394.2**	-1.6%	-0.8%	11.9%

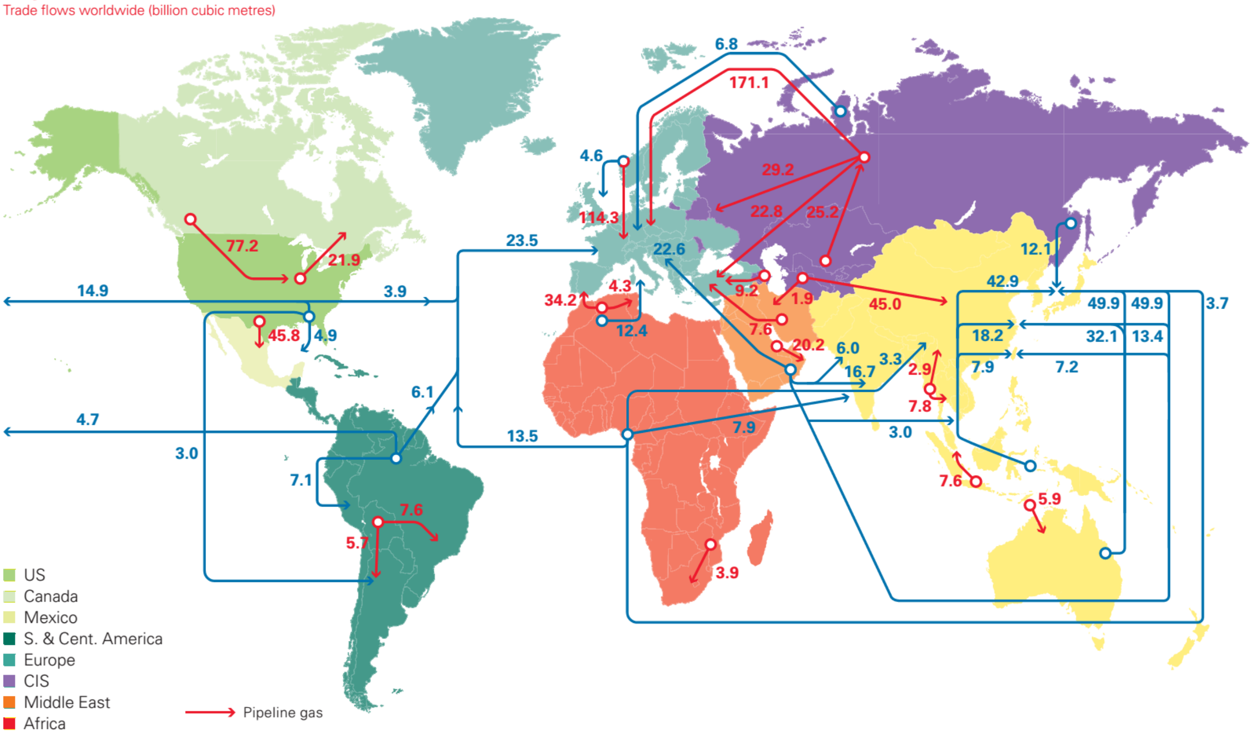
Source: Includes data from Cedigaz, FGE MENAgas service.

*Excludes natural gas converted to liquid fuels but includes derivatives of coal as well as natural gas consumed in gas-to-liquids transformation.
◆Less than 0.05%.
n/a not available.
Notes: The difference between these world consumption figures and the world production statistics is due to variations in stocks at storage facilities and liquefaction plants, together with unavoidable disparities in the definition, measurement or conversion of gas supply and demand data.
Annual changes and shares of total are calculated using million tonnes oil equivalent figures.

Table E6. Global major trade movements 2018 (BP Statistical Review of World Energy 2019)

Major trade movements 2018

Trade flows worldwide (billion cubic metres)



Source: Includes data from FGE MENAgas service, IHS.

Natural gas: Trade movements 2018 by pipeline

Billion cubic metres To	From Canada	Mexico	US	Bolivia	Other S. & Cent. America	Netherlands	Norway	Other Europe	Azerbaijan	Kazakhstan	Russian Federation	Turkmenistan	Uzbekistan	Iran	Qatar	Other Middle East	Algeria	Libya	Other Africa	Indonesia	Myanmar	Other Asia Pacific	Total imports
Canada	–	–	21.9	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	**21.9**
Mexico	–	–	45.8	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	**45.8**
US	77.2	0.1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	**77.3**
North America	77.2	0.1	67.6	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	**145.0**
Argentina	–	–	–	5.7	0.2	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	**5.9**
Brazil	–	–	–	7.6	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	**7.6**
Other S. & Cent. America	–	–	–	–	0.4	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	**0.4**
S. & Cent. America	–	–	–	13.4	0.6	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	**14.0**
Belgium	–	–	–	–	–	7.0	5.0	7.9	–	–	–	–	–	–	–	–	–	–	–	–	–	–	**19.9**
France	–	–	–	–	–	5.3	19.6	3.0	–	–	8.9	–	–	–	–	–	–	–	–	–	–	–	**36.8**
Germany	–	–	–	–	–	15.8	24.7	4.9	–	–	55.3	–	–	–	–	–	–	–	–	–	–	–	**100.8**
Italy	–	–	–	–	–	1.1	2.3	6.8	–	–	25.4	–	–	–	–	–	16.3	4.3	–	–	–	–	**56.2**
Netherlands	–	–	–	–	–	–	20.7	7.5	–	–	7.4	–	–	–	–	–	–	–	–	–	–	–	**35.6**
Spain	–	–	–	–	–	–	2.6	1.0	–	–	–	–	–	–	–	–	16.6	–	–	–	–	–	**20.2**
Turkey	–	–	–	–	–	–	–	–	7.2	–	22.8	–	–	7.6	–	–	–	–	–	–	–	–	**37.6**
Ukraine	–	–	–	–	–	0.2	–	9.6	–	–	–	–	–	–	–	–	–	–	–	–	–	–	**9.8**
United Kingdom	–	–	–	–	–	2.7	32.6	3.2	–	–	4.4	–	–	–	–	–	–	–	–	–	–	–	**42.8**
Other EU	–	–	–	–	–	–	6.8	32.6	–	–	67.1	–	–	–	–	–	1.4	–	–	–	–	–	**107.9**
Rest of Europe	–	–	–	–	–	0.3	†	6.6	2.0	–	2.6	–	–	–	–	–	–	–	–	–	–	–	**11.5**
Europe	–	–	–	–	–	32.5	114.3	83.1	9.2	–	193.8	–	–	7.6	–	–	34.2	4.3	–	–	–	–	**478.9**
Belarus	–	–	–	–	–	–	–	–	–	–	19.0	–	–	–	–	–	–	–	–	–	–	–	**19.0**
Kazakhstan	–	–	–	–	–	–	–	–	–	–	4.2	–	2.4	–	–	–	–	–	–	–	–	–	**6.6**
Russian Federation	–	–	–	–	–	–	–	–	–	19.9	–	–	5.3	–	–	–	–	–	–	–	–	–	**25.2**
Other CIS	–	–	–	–	–	–	–	–	–	0.3	5.9	–	0.1	0.5	–	–	–	–	–	–	–	–	**6.7**
CIS	–	–	–	–	–	–	–	–	–	20.1	29.2	–	7.7	0.5	–	–	–	–	–	–	–	–	**57.5**
United Arab Emirates	–	–	–	–	–	–	–	–	–	–	–	–	–	–	18.2	–	–	–	–	–	–	–	**18.2**
Other Middle East	–	–	–	–	–	–	–	–	†	–	–	1.9	–	4.1	2.0	0.1	–	–	0.1	–	–	–	**8.3**
Middle East	–	–	–	–	–	–	–	–	†	–	–	1.9	–	4.1	20.2	0.1	–	–	0.1	–	–	–	**26.6**
South Africa	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	3.9	–	–	–	**3.9**
Other Africa	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	4.7	–	0.8	–	–	–	**5.5**
Africa	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	4.7	–	4.7	–	–	–	**9.4**
Australia	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	5.9	**5.9**
China	–	–	–	–	–	–	–	–	–	5.4	–	33.3	6.3	–	–	–	–	–	–	–	2.9	–	**47.9**
Malaysia	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.6	–	–	**0.6**
Singapore	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	7.0	–	1.8	**8.8**
Thailand	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	7.8	–	**7.8**
Asia Pacific	–	–	–	–	–	–	–	–	–	5.4	–	33.3	6.3	–	–	–	–	–	–	7.6	10.6	10.7	**74.0**
Total exports	**77.2**	**0.1**	**67.6**	**13.4**	**0.6**	**32.5**	**114.3**	**83.1**	**9.2**	**25.6**	**223.0**	**35.2**	**14.0**	**12.1**	**20.2**	**0.1**	**38.9**	**4.3**	**4.8**	**7.6**	**10.6**	**10.7**	**805.4**

Source: Includes data from FGE MENAgas service, IHS.

†Less than 0.05.

Note: As far as possible, the data above represents standard cubic metres (measured at 15°C and 1013 mbar) and has been standardized using a gross calorific value (GCV) of 40 MJ/m³.

Table E7. Global gas prices (BP Statistical Review of World Energy 2019)

Prices

US dollars per million Btu	LNG		Natural gas					Crude oil
	Japan CIF[1]	Japan Korea Marker (JKM)[2]	Average German Import Price[3]	UK (Heren NBP Index)[4]	Netherlands TTF (DA Heren Index)[4]	US Henry Hub[5]	Canada (Alberta)[5]	OECD countries CIF[6]
1988	3.34	–	2.22	–	–	–	–	2.56
1989	3.28	–	2.00	–	–	1.70	–	3.01
1990	3.64	–	2.78	–	–	1.64	1.05	3.82
1991	3.99	–	3.23	–	–	1.49	0.89	3.33
1992	3.62	–	2.70	–	–	1.77	0.98	3.19
1993	3.52	–	2.51	–	–	2.12	1.69	2.82
1994	3.18	–	2.35	–	–	1.92	1.45	2.70
1995	3.46	–	2.43	–	–	1.69	0.89	2.96
1996	3.66	–	2.50	1.87	–	2.76	1.12	3.54
1997	3.91	–	2.66	1.96	–	2.53	1.36	3.29
1998	3.05	–	2.33	1.86	–	2.08	1.42	2.16
1999	3.14	–	1.86	1.58	–	2.27	2.00	2.98
2000	4.72	–	2.91	2.71	–	4.23	3.75	4.83
2001	4.64	–	3.67	3.17	–	4.07	3.61	4.08
2002	4.27	–	3.21	2.37	–	3.33	2.57	4.17
2003	4.77	–	4.06	3.33	–	5.63	4.83	4.89
2004	5.18	–	4.30	4.46	–	5.85	5.03	6.27
2005	6.05	–	5.83	7.38	6.07	8.79	7.25	8.74
2006	7.14	–	7.87	7.87	7.46	6.76	5.83	10.66
2007	7.73	–	7.99	6.01	5.93	6.95	6.17	11.95
2008	12.55	–	11.60	10.79	10.66	8.85	7.99	16.76
2009	9.06	5.28	8.53	4.85	4.96	3.89	3.38	10.41
2010	10.91	7.72	8.03	6.56	6.77	4.39	3.69	13.47
2011	14.73	14.02	10.49	9.04	9.26	4.01	3.47	18.56
2012	16.75	15.12	10.93	9.46	9.45	2.76	2.27	18.82
2013	16.17	16.56	10.73	10.64	9.75	3.71	2.93	18.25
2014	16.33	13.86	9.11	8.25	8.14	4.35	3.87	16.80
2015	10.31	7.45	6.72	6.53	6.44	2.60	2.01	8.77
2016	6.94	5.72	4.93	4.69	4.54	2.46	1.55	7.04
2017	8.10	7.13	5.62	5.80	5.72	2.96	1.60	8.97
2018	10.05	9.76	6.62	8.06	7.90	3.13	1.12	11.69

[1]Source: EDMC Energy Trend.
[2]Source: S&P Global Platts ©2019, S&P Global Inc.
[3]Source: 1988-1990 German Federal Statistical Office, 1991-2018 German Federal Office of Economics and Export Control (BAFA).
[4]Source: ICIS Heren Energy Ltd.
[5]Source: Energy Intelligence Group, Natural Gas Week.
[6]Source: ©OECD/IEA 2019, Oil, Gas, Coal and Electricity, Quarterly Statistics *www.iea.org/statistics*.

Note: CIF = cost+insurance+freight (average prices).

Prices
$/mmBtu

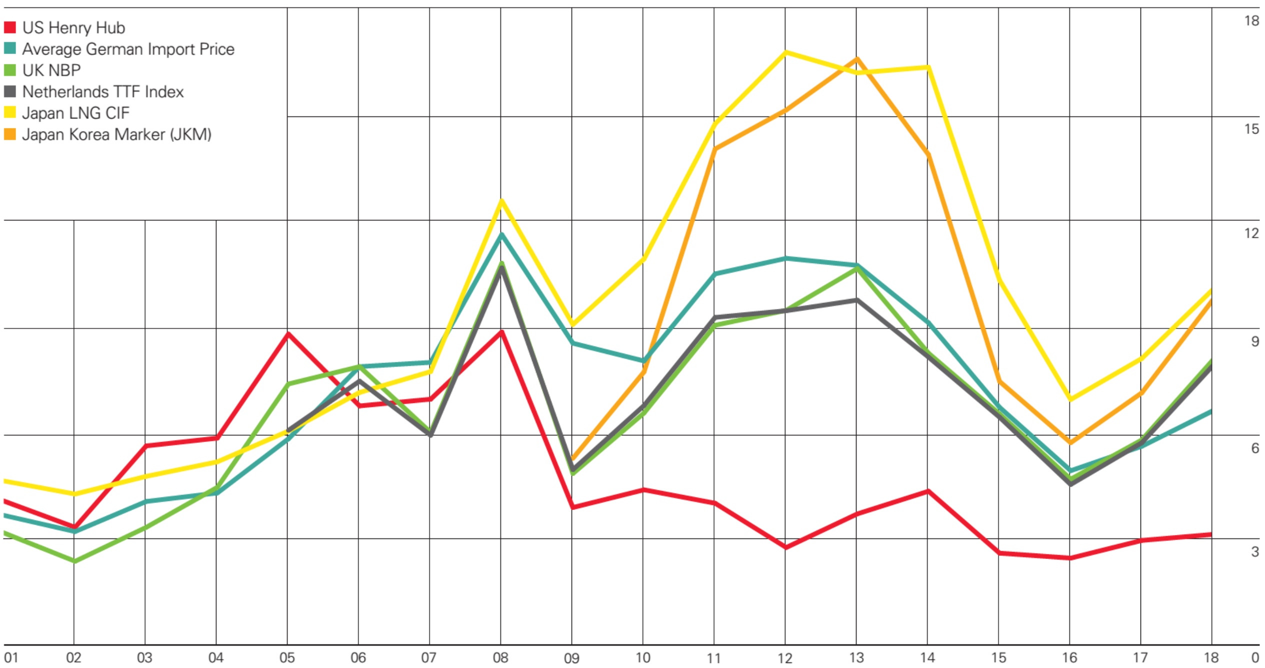


Table E8.1. Gas production in EU, US and China
(Source: BP Statistical Review of World Energy 2019 and BP Statistical Review of World Energy 2011)

Year	European Union (bcm)	United States (bcm)	China (bcm)	India (bcm)
1970	101,7	595,1	2,87	0,66
1971	124,1	611,9	3,74	0,70
1972	148,8	612,3	4,84	0,76
1973	167,0	615,4	5,98	0,76
1974	185,4	586,5	7,53	0,86
1975	192,9	544,7	8,85	1,10
1976	205,2	540,8	10,1	1,34
1977	209,1	542,6	12,12	1,43
1978	203,7	541,5	13,73	1,60
1979	204,4	556,8	14,51	1,99
1980	197,2	549,4	14,27	1,18
1981	194,0	543,2	12,74	2,06
1982	183,2	504,6	11,93	2,69
1983	187,0	455,7	12,21	3,21
1984	189,6	494,6	12,43	3,67
1985	194,8	465,9	12,93	4,49
1986	190,7	454,7	13,76	6,28
1987	193,7	470,6	13,89	7,23
1988	181,9	484,3	14,26	8,47
1989	183,1	490,2	15,05	10,07
1990	185,1	504,3	15,30	12,04
1991	194,4	501,1	15,49	13,41
1992	193,6	505,2	15,79	15,00
1993	205,1	512,4	16,77	15,24
1994	205,0	533,0	17,56	16,47
1995	212,1	526,7	17,95	18,78
1996	235,3	533,9	20,11	20,50
1997	225,2	535,3	22,70	22,29
1998	223,4	538,7	23,28	24,46
1999	226,6	533,3	25,20	25,06
2000	231,9	543,2	27,20	26,35
2001	232,8	555,5	30,33	26,42
2002	227,6	536,0	32,66	27,59
2003	223,6	540,8	35,02	29,53
2004	227,3	526,4	41,46	29,23
2005	212,0	511,1	49,32	29,62
2006	201,3	524,0	58,55	29,29
2007	187,5	545,6	69,24	30,09
2008	200,2	546,1	80,90	29,40
2009	179,2	557,6	85,90	36,10
2010	183,8	575,2	96,50	47,40
2011	164,2	617,4	106,20	42,90
2012	153,7	649,1	111,50	37,30
2013	151,5	655,7	121,80	31,10
2014	138,2	704,7	131,20	29,40
2015	125,7	740,3	135,70	28,10
2016	124,7	727,4	137,90	26,60
2017	119,7	745,8	149,20	27,70
2018	109,2	831,8	161,50	27,50

Table E8.2. Gas consumption in EU, US and China
(Source: BP Statistical Review of World Energy 2019 and BP Statistical Review of World Energy 2011)

Year	European Union (bcm)	United States (bcm)	China (bcm)	India (bcm)
1970	108,8	598,6	2,9	0,66
1971	133,2	617,1	3,7	0,70
1972	158,3	625,8	4,8	0,76
1973	180,7	624,4	6,0	0,76
1974	204,5	601,0	7,5	0,86
1975	216,6	553,2	8,9	1,1
1976	237,0	564,8	10,1	1,3
1977	247,4	552,8	12,1	1,4
1978	257,2	555,8	13,7	1,6
1979	270,7	573,2	14,5	2,0
1980	272,0	562,9	14,3	1,2
1981	270,1	549,5	12,7	2,1
1982	263,6	509,7	11,9	2,7
1983	269,5	476,7	12,2	3,2
1984	282,9	508,3	12,4	3,7
1985	296,9	489,3	12,9	4,5
1986	302,1	459,3	13,8	6,3
1987	317,0	487,4	13,9	7,2
1988	312,3	510,5	14,4	8,5
1989	322,4	541,4	15,0	10,1
1990	326,8	542,9	15,3	12,0
1991	335,6	553,9	15,9	13,4
1992	329,3	572,8	15,9	15,0
1993	343,9	588,7	16,8	15,2
1994	344,9	601,6	17,3	16,5
1995	372,1	628,8	17,7	18,8
1996	409,5	640,2	18,5	20,5
1997	402,0	643,8	19,5	22,3
1998	415,2	629,9	20,3	24,5
1999	429,6	634,4	21,5	25,1
2000	440,4	660,7	24,5	26,4
2001	451,8	629,7	27,4	26,4
2002	451,2	651,5	29,2	27,6
2003	473,2	630,8	33,9	29,5
2004	486,0	634,0	39,7	31,9
2005	494,2	623,3	46,8	35,7
2006	486,9	614,1	56,1	37,3
2007	481,2	654,0	70,5	40,1
2008	516,6	628,9	81,9	40,0
2009	484,5	617,6	90,2	49,1
2010	521,3	648,2	108,9	59,0
2011	471,0	658,2	135,2	60,3
2012	459,1	688,1	150,9	55,7
2013	451,2	707,0	171,9	49,0
2014	401,7	722,3	188,4	48,5
2015	418,7	743,6	194,7	47,8
2016	449,3	749,1	209,4	50,8
2017	465,7	739,4	240,4	53,7
2018	458,5	817,1	283,0	58,1

Table E8.3. Gas deficit consumption subtracted from production in EU, US and China
(Source: BP Statistical Review of World Energy 2019 and BP Statistical Review of World Energy 2011)

Year	European Union (bcm)	United States (bcm)	China (bcm)	India (bcm)
1970	-7,1	-3,5	0,0	0,0
1971	-9,1	-5,2	0,0	0,0
1972	-9,5	-13,5	0,0	0,0
1973	-13,6	-9,0	0,0	0,0
1974	-19,1	-14,4	0,0	0,0
1975	-23,7	-8,5	0,0	0,0
1976	-31,8	-24,0	0,0	0,0
1977	-38,3	-10,1	0,0	0,0
1978	-53,5	-14,3	0,0	0,0
1979	-66,3	-16,3	0,0	0,0
1980	-74,8	-13,4	0,0	0,0
1981	-76,1	-6,3	0,0	0,0
1982	-80,4	-5,1	0,0	0,0
1983	-82,5	-21,0	0,0	0,0
1984	-93,3	-13,7	0,0	0,0
1985	-102,1	-23,4	0,0	0,0
1986	-111,4	-4,6	0,0	0,0
1987	-123,4	-16,7	0,0	0,0
1988	-130,4	-26,2	-0,1	0,0
1989	-139,3	-51,2	0,0	0,0
1990	-141,7	-38,6	0,0	0,0
1991	-141,2	-52,8	-0,4	0,0
1992	-135,7	-67,6	-0,1	0,0
1993	-138,8	-76,3	0,0	0,0
1994	-139,9	-68,7	0,2	0,0
1995	-159,9	-102,2	0,2	0,0
1996	-174,2	-106,4	1,6	0,0
1997	-176,8	-108,6	3,2	0,0
1998	-191,9	-91,2	3,0	0,0
1999	-203,0	-101,2	3,7	0,0
2000	-208,5	-117,5	2,7	0,0
2001	-218,9	-74,3	2,9	0,0
2002	-223,5	-115,5	3,5	0,0
2003	-249,6	-90,0	1,1	0,0
2004	-258,7	-107,5	1,8	-2,6
2005	-282,2	-112,1	2,6	-6,0
2006	-285,6	-90,1	2,4	-8,0
2007	-293,7	-108,5	-1,3	-10,0
2008	-316,4	-82,8	-1,0	-10,6
2009	-305,3	-60,0	-4,3	-13,0
2010	-337,5	-73,0	-12,4	-11,6
2011	-306,8	-40,8	-29,0	-17,4
2012	-305,4	-39,0	-39,4	-18,4
2013	-299,7	-51,3	-50,1	-17,9
2014	-263,5	-17,6	-57,2	-19,1
2015	-293,0	-3,3	-59,0	-19,7
2016	-324,6	-21,7	-71,5	-24,2
2017	-346,0	6,4	-91,2	-26,0
2018	-349,3	14,7	-121,5	-30,6

35 APPENDIX F – COAL RESERVES, PRODUCTION AND CONSUMPTION

Table F1. Global total proved coal reserves (Million tonnes) (Source: BP Statistical Review of World Energy 2019)

Total proved reserves at end 2018

Million tonnes	Anthracite and bituminous	Sub-bituminous and lignite	**Total**	Share of total	R/P ratio
Canada	4346	2236	**6582**	0.6%	121
Mexico	1160	51	**1211**	0.1%	89
US	220167	30052	**250219**	23.7%	365
Total North America	225673	32339	**258012**	24.5%	342
Brazil	1547	5049	**6596**	0.6%	*
Colombia	4881	–	**4881**	0.5%	58
Venezuela	731	–	**731**	0.1%	*
Other S. & Cent. America	1784	24	**1808**	0.2%	*
Total S. & Cent. America	8943	5073	**14016**	1.3%	158
Bulgaria	192	2174	**2366**	0.2%	78
Czech Republic	110	2547	**2657**	0.3%	61
Germany	3	36100	**36103**	3.4%	214
Greece	–	2876	**2876**	0.3%	79
Hungary	276	2633	**2909**	0.3%	368
Poland	20542	5937	**26479**	2.5%	216
Romania	11	280	**291**	◆	12
Serbia	402	7112	**7514**	0.7%	199
Spain	868	319	**1187**	0.1%	433
Turkey	551	10975	**11526**	1.1%	139
Ukraine	32039	2336	**34375**	3.3%	*
United Kingdom	29	–	**29**	◆	11
Other Europe	1109	5172	**6281**	0.6%	189
Total Europe	56132	78461	**134593**	12.8%	215
Kazakhstan	25605	–	**25605**	2.4%	217
Russian Federation	69634	90730	**160364**	15.2%	364
Uzbekistan	1375	–	**1375**	0.1%	125
Other CIS	1509	–	**1509**	0.1%	358
Total CIS	98123	90730	**188853**	17.9%	329
South Africa	9893	–	**9893**	0.9%	39
Zimbabwe	502	–	**502**	◆	165
Other Africa	2756	66	**2822**	0.3%	164
Middle East	1203	–	**1203**	0.1%	*
Total Middle East & Africa	14354	66	**14420**	1.4%	53
Australia	70927	76508	**147435**	14.0%	304
China	130851	7968	**138819**	13.2%	38
India	96468	4895	**101363**	9.6%	132
Indonesia	26122	10878	**37000**	3.5%	67
Japan	340	10	**350**	◆	336
Mongolia	1170	1350	**2520**	0.2%	46
New Zealand	825	6750	**7575**	0.7%	*
Pakistan	207	2857	**3064**	0.3%	*
South Korea	326	–	**326**	◆	271
Thailand	–	1063	**1063**	0.1%	72
Vietnam	3116	244	**3360**	0.3%	81
Other Asia Pacific	1326	687	**2013**	0.2%	38
Total Asia Pacific	331678	113210	**444888**	42.2%	79
Total World	**734903**	**319879**	**1054782**	**100.0%**	**132**
of which: OECD	322234	177484	**499718**	47.4%	291
Non-OECD	412669	142395	**555064**	52.6%	89
European Union	22612	53356	**75968**	7.2%	171

*More than 500 years.
◆Less than 0.05%.

Source: Federal Institute for Geosciences and Natural Resources (BGR) Energy Study 2019.

Notes: Total proved reserves of coal – Generally taken to be those quantities that geological and engineering information indicates with reasonable certainty can be recovered in the future from known reservoirs under existing economic and operating conditions. The data series for total proved coal reserves does not necessarily meet the definitions, guidelines and practices used for determining proved reserves at company level, for instance as published by the US Securities and Exchange Commission, nor does it necessarily represent BP's view of proved reserves by country.
Reserves-to-production (R/P) ratio – If the reserves remaining at the end of any year are divided by the production in that year, the result is the length of time that those remaining reserves would last if production were to continue at that rate.
Reserves-to-production (R/P) ratios are calculated excluding other solid fuels in reserves and production.
Shares of total and R/P ratios are calculated using million tonnes figures.

Table F2. Global coal production (Mtoe) (Source: BP Statistical Review of World Energy 2019)

Coal: Production*

Million tonnes oil equivalent	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Growth rate per annum 2018	Growth rate per annum 2007-17	Share 2018
Canada	35.6	33.1	35.4	35.5	35.5	36.1	35.9	32.4	32.7	31.8	**28.6**	-10.3%	-1.1%	0.7%
Mexico	6.9	6.1	7.3	9.4	7.4	7.2	7.3	6.9	6.1	7.4	**7.7**	4.7%	0.1%	0.2%
US	566.9	513.7	523.7	528.3	491.9	475.8	482.3	426.9	348.3	371.3	**364.5**	-1.9%	-4.0%	9.3%
Total North America	609.4	552.9	566.4	573.1	534.9	519.1	525.5	466.1	387.1	410.6	**400.7**	-2.4%	-3.7%	10.2%
Brazil	2.9	2.6	2.3	2.4	2.6	3.3	3.3	2.6	2.4	1.9	**1.2**	-37.4%	-2.7%	◆
Colombia	50.5	50.0	51.1	58.9	61.2	58.7	60.8	58.8	62.2	62.2	**57.9**	-6.9%	2.6%	1.5%
Venezuela	3.7	2.4	1.9	1.9	1.4	0.9	0.6	0.6	0.3	0.3	**0.2**	-49.8%	-23.8%	◆
Other S. & Cent. America	0.4	0.4	0.4	0.4	0.5	1.7	3.0	2.3	2.0	1.2	**1.1**	-10.9%	16.8%	◆
Total S. & Cent. America	57.4	55.4	55.7	63.7	65.6	64.7	67.6	64.2	66.8	65.6	**60.4**	-8.1%	1.6%	1.5%
Bulgaria	4.9	4.6	4.9	6.2	5.6	4.8	5.1	5.9	5.1	5.7	**5.2**	-8.4%	1.7%	0.1%
Czech Republic	22.8	20.9	20.8	21.0	20.3	17.8	17.0	16.9	16.1	15.3	**14.6**	-4.2%	-4.3%	0.4%
Germany	50.1	46.4	45.9	46.7	47.8	45.1	44.1	42.8	39.6	39.4	**37.6**	-4.6%	-3.2%	1.0%
Greece	8.1	8.2	7.3	7.5	8.0	6.7	6.4	5.7	4.0	4.6	**4.4**	-3.3%	-5.9%	0.1%
Hungary	1.7	1.6	1.6	1.6	1.6	1.6	1.6	1.5	1.5	1.3	**1.3**	-0.8%	-3.2%	◆
Poland	60.9	56.4	55.4	55.7	57.8	57.2	54.0	53.0	52.1	49.8	**47.5**	-4.5%	-2.2%	1.2%
Romania	7.0	6.6	5.9	6.7	6.3	4.7	4.4	4.7	4.2	4.5	**4.1**	-7.9%	-4.2%	0.1%
Serbia	7.5	7.4	7.2	7.8	7.3	7.7	5.7	7.2	7.3	7.3	**6.9**	-5.5%	0.1%	0.2%
Spain	4.4	3.8	3.3	2.6	2.5	1.8	1.6	1.2	0.7	1.1	**1.1**	-6.8%	-15.2%	◆
Turkey	16.7	17.4	17.5	17.9	17.0	15.5	16.4	12.8	15.5	15.1	**17.0**	13.0%	0.2%	0.4%
Ukraine	34.4	31.8	31.8	36.3	38.0	36.6	25.9	16.4	17.1	14.4	**14.5**	0.8%	-8.2%	0.4%
United Kingdom	11.3	11.0	11.4	11.5	10.6	8.0	7.3	5.4	2.6	1.9	**1.6**	-15.1%	-15.7%	◆
Other Europe	15.3	15.5	15.8	15.7	14.0	16.4	15.1	13.7	12.8	12.9	**14.1**	9.0%	-1.6%	0.4%
Total Europe	244.9	231.5	228.9	237.4	236.9	223.7	204.7	187.2	178.6	173.3	**170.0**	-1.9%	-3.6%	4.3%
Kazakhstan	47.9	43.4	47.5	49.8	51.6	51.4	48.9	46.2	44.3	48.3	**50.6**	4.9%	1.4%	1.3%
Russian Federation	149.0	141.7	151.0	157.6	168.3	173.1	176.6	186.4	194.0	205.8	**220.2**	7.0%	3.7%	5.6%
Uzbekistan	0.9	1.0	1.0	1.1	1.2	1.1	1.2	1.1	2.8	3.4	**3.0**	-11.2%	13.3%	0.1%
Other CIS	0.8	0.8	0.9	1.0	1.2	1.3	1.4	1.4	1.7	2.0	**2.2**	10.6%	9.2%	0.1%
Total CIS	198.7	187.0	200.3	209.4	222.3	226.9	228.1	235.1	242.7	259.5	**276.0**	6.4%	3.3%	7.0%
Total Middle East	1.0	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	**0.7**	–	-3.6%	◆
South Africa	141.0	139.7	144.1	143.2	146.6	145.3	148.2	142.9	142.4	143.0	**143.2**	0.2%	0.3%	3.7%
Zimbabwe	1.0	1.1	1.7	1.7	1.0	2.0	3.7	2.8	1.7	1.9	**2.0**	3.9%	3.5%	0.1%
Other Africa	0.8	0.7	0.9	1.1	4.3	5.1	5.8	6.0	5.4	10.4	**10.6**	2.5%	30.0%	0.3%
Total Africa	142.7	141.5	146.8	146.0	151.9	152.4	157.7	151.6	149.6	155.2	**155.8**	0.4%	1.0%	4.0%
Australia	233.9	242.7	250.6	245.1	265.9	285.8	305.9	305.6	306.7	299.0	**301.1**	0.7%	2.8%	7.7%
China	1491.8	1537.9	1665.3	1851.7	1873.5	1894.6	1864.2	1825.6	1691.4	1746.6	**1828.8**	4.7%	2.0%	46.7%
India	227.5	246.0	252.4	250.8	255.0	255.7	269.5	281.0	283.9	286.6	**308.0**	7.5%	3.1%	7.9%
Indonesia	141.6	151.0	162.1	208.2	227.4	279.7	269.9	272.0	268.8	271.8	**323.3**	18.9%	7.8%	8.3%
Japan	0.7	0.7	0.5	0.7	0.7	0.7	0.7	0.6	0.7	0.8	**0.6**	-25.0%	-0.2%	◆
Mongolia	5.2	8.2	15.2	19.9	17.9	18.0	15.2	14.3	21.6	30.3	**34.4**	13.3%	20.3%	0.9%
New Zealand	3.0	2.8	3.3	3.1	3.0	2.9	2.5	2.0	1.7	1.7	**1.9**	10.5%	-5.2%	◆
Pakistan	1.8	1.6	1.5	1.4	1.4	1.3	1.5	1.5	1.8	1.8	**1.7**	-5.2%	1.0%	◆
South Korea	1.3	1.2	1.0	1.0	0.9	0.8	0.8	0.8	0.8	0.7	**0.6**	-19.2%	-6.3%	◆
Thailand	4.8	4.7	4.9	6.0	4.8	4.7	4.6	3.9	4.3	4.1	**3.8**	-8.5%	-1.8%	0.1%
Vietnam	22.3	24.7	25.1	26.1	23.6	23.0	23.0	23.3	21.7	21.4	**23.3**	8.8%	-1.0%	0.6%
Other Asia Pacific	22.1	19.3	20.7	22.2	22.8	23.4	23.8	25.2	31.8	25.2	**25.6**	1.5%	2.0%	0.7%
Total Asia Pacific	2155.9	2240.7	2402.7	2636.2	2696.9	2790.5	2781.6	2755.9	2635.2	2690.1	**2853.1**	6.1%	2.7%	72.8%
Total World	**3410.0**	**3409.8**	**3601.4**	**3866.5**	**3909.1**	**3978.0**	**3966.0**	**3860.9**	**3660.8**	**3755.0**	**3916.8**	**4.3%**	**1.3%**	**100.0%**
of which: OECD	1034.1	976.2	995.7	997.5	979.5	975.1	996.3	924.8	838.0	849.5	**839.5**	-1.2%	-1.9%	21.4%
Non-OECD	2375.9	2433.6	2605.7	2868.9	2929.7	3002.9	2969.7	2936.0	2822.8	2905.5	**3077.2**	5.9%	2.5%	78.6%
European Union	178.6	167.6	165.6	168.3	167.9	157.1	150.3	144.5	132.5	130.7	**125.8**	-3.7%	-3.5%	3.2%

*Commercial solid fuels only, i.e. bituminous coal and anthracite (hard coal), lignite and brown (sub-bituminous) coal, and other commercial solid fuels. Includes coal produced for coal-to-liquids and coal-to-gas transformations.
◆Less than 0.05%.
Coal production data expressed in million tonnes is available at *bp.com/statisticalreview.*

Table F3. Global coal consumption (Mtoe) (Source: BP Statistical Review of World Energy 2019)

Coal: Consumption*

Million tonnes oil equivalent	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Growth rate per annum 2018	Growth rate per annum 2007-17	Share 2018
Canada	29.4	23.5	24.8	22.2	21.1	20.8	19.6	19.9	18.7	18.6	**14.4**	-22.5%	-4.8%	0.4%
Mexico	10.1	10.3	12.7	14.7	12.8	12.7	12.7	12.7	12.4	15.2	**11.9**	-21.7%	3.0%	0.3%
US	535.9	471.4	498.8	470.6	416.0	431.8	430.9	372.2	340.6	331.3	**317.0**	-4.3%	-4.9%	8.4%
Total North America	575.5	505.2	536.3	507.5	449.9	465.4	463.2	404.8	371.7	365.1	**343.3**	-6.0%	-4.6%	9.1%
Argentina	1.5	0.8	1.2	1.3	1.2	1.3	1.4	1.4	1.0	1.1	**1.2**	13.0%	-1.4%	◆
Brazil	13.8	11.1	14.5	15.4	15.3	16.5	17.5	17.6	15.9	16.6	**15.9**	-4.0%	2.0%	0.4%
Chile	4.4	4.0	4.5	5.8	6.7	7.5	7.6	7.3	7.4	7.7	**7.7**	-0.4%	6.6%	0.2%
Colombia	4.4	4.1	4.8	3.9	4.7	5.0	5.3	5.0	6.3	5.2	**5.9**	13.4%	4.4%	0.2%
Ecuador	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Peru	0.9	0.8	0.8	0.8	0.9	0.9	0.9	0.8	1.0	0.6	**0.9**	61.8%	-5.6%	◆
Trinidad & Tobago	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Venezuela	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	**0.1**	-9.9%	-2.1%	◆
Other S. & Cent. America	2.5	2.2	2.4	2.8	2.8	3.2	3.5	3.6	3.8	3.5	**4.3**	22.0%	3.1%	0.1%
Total S. & Cent. America	27.7	23.3	28.3	30.2	31.7	34.6	36.4	35.8	35.5	34.8	**36.0**	3.7%	2.9%	1.0%
Austria	3.8	2.9	3.4	3.5	3.2	3.3	3.0	3.2	3.0	3.1	**2.9**	-8.4%	-2.1%	0.1%
Belgium	4.6	3.0	3.7	3.5	3.3	3.4	3.3	3.4	3.2	3.1	**3.3**	4.9%	-3.9%	0.1%
Czech Republic	19.7	18.2	18.8	18.5	17.7	16.9	16.4	16.3	16.4	15.6	**15.7**	1.0%	-2.8%	0.4%
Finland	5.3	5.4	6.8	5.5	4.5	5.0	4.5	3.8	4.4	4.0	**4.3**	6.7%	-5.4%	0.1%
France	12.1	10.8	11.5	9.8	11.1	11.6	8.6	8.4	8.2	9.3	**8.4**	-9.6%	-3.2%	0.2%
Germany	80.1	71.7	77.1	78.3	80.5	82.8	79.6	78.7	76.5	71.5	**66.4**	-7.2%	-1.9%	1.8%
Greece	8.3	8.4	7.9	7.9	8.1	7.0	6.7	5.6	4.4	4.8	**4.7**	-2.8%	-6.0%	0.1%
Hungary	3.0	2.6	2.7	2.7	2.6	2.3	2.3	2.3	2.2	2.2	**2.2**	-2.4%	-3.3%	0.1%
Italy	15.8	12.4	13.7	15.3	15.7	13.5	13.2	12.3	11.0	9.6	**8.9**	-7.7%	-5.1%	0.2%
Netherlands	8.0	7.5	7.5	7.4	8.2	8.2	9.1	11.0	10.2	9.1	**8.2**	-10.5%	0.8%	0.2%
Norway	0.7	0.6	0.8	0.8	0.8	0.8	0.9	0.8	0.8	0.8	**0.8**	3.3%	1.8%	◆
Poland	55.2	51.8	55.1	55.0	51.2	53.4	49.4	48.7	49.5	49.8	**50.5**	1.5%	-1.2%	1.3%
Portugal	2.5	2.9	1.6	2.2	2.9	2.6	2.7	3.3	2.8	3.2	**2.7**	-16.1%	1.2%	0.1%
Romania	9.4	7.5	7.0	8.2	7.6	5.9	5.8	6.0	5.4	5.4	**5.3**	-1.2%	-5.8%	0.1%
Spain	13.5	9.4	6.9	12.8	15.5	11.4	11.6	13.7	10.5	13.4	**11.1**	-17.3%	-3.9%	0.3%
Sweden	2.8	2.0	2.8	2.5	2.1	2.2	2.0	2.0	2.0	2.0	**2.0**	-0.3%	-3.5%	0.1%
Switzerland	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	**0.1**	–	-4.5%	◆
Turkey	29.6	30.9	31.4	33.9	36.5	31.6	36.1	34.7	38.5	39.5	**42.3**	7.2%	3.0%	1.1%
Ukraine	41.8	35.9	38.3	41.5	42.5	41.6	35.6	27.3	32.5	25.7	**26.2**	2.0%	-4.3%	0.7%
United Kingdom	35.6	29.8	30.9	31.4	39.0	37.0	29.8	23.1	11.1	9.1	**7.6**	-16.6%	-13.4%	0.2%
Other Europe	39.1	36.8	38.3	40.9	37.0	37.1	33.8	34.3	34.3	34.1	**33.6**	-1.5%	-1.4%	0.9%
Total Europe	391.2	350.4	366.3	381.8	390.2	377.6	354.5	339.2	326.8	315.5	**307.1**	-2.7%	-2.6%	8.1%
Azerbaijan	†	†	†	†	†	†	†	†	†	†	**†**	–	-13.0%	◆
Belarus	0.6	0.6	0.6	0.8	0.8	0.8	0.8	0.7	0.8	0.8	**1.0**	13.7%	1.9%	◆
Kazakhstan	33.8	30.9	33.4	36.3	37.9	37.5	37.0	34.2	33.9	36.4	**40.8**	12.2%	1.6%	1.1%
Russian Federation	100.7	92.2	90.5	94.0	98.4	90.5	87.6	92.1	89.3	83.9	**88.0**	4.9%	-1.1%	2.3%
Turkmenistan	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Uzbekistan	1.0	1.0	0.9	1.1	1.2	1.1	1.2	1.1	2.7	3.5	**3.1**	-11.1%	13.5%	0.1%
Other CIS	1.1	0.9	0.9	1.0	1.4	1.4	1.7	1.8	1.6	1.8	**2.0**	10.6%	8.4%	0.1%
Total CIS	137.2	125.6	126.4	133.2	139.6	131.4	128.3	130.0	128.3	126.4	**134.9**	6.7%	-0.1%	3.6%
Iran	1.2	1.4	1.3	1.4	1.1	1.4	1.6	1.6	1.5	1.4	**1.5**	4.3%	-0.9%	◆
Iraq	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Israel	7.9	7.7	7.7	7.9	8.8	7.1	6.6	6.5	5.5	5.0	**4.7**	-6.5%	-4.6%	0.1%
Kuwait	†	–	†	†	–	0.3	0.2	0.2	0.2	0.2	**0.2**	–	81.9%	◆
Oman	†	†	†	†	†	0.1	0.1	0.1	0.1	0.1	**0.1**	–	35.8%	◆
Qatar	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Saudi Arabia	0.1	†	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.1	**0.1**	–	6.5%	◆
United Arab Emirates	0.3	0.3	0.7	0.4	1.4	1.8	2.0	1.7	1.8	1.0	**1.1**	4.8%	22.2%	◆
Other Middle East	0.2	0.2	0.3	0.4	0.5	0.5	0.6	0.4	0.4	0.4	**0.4**	◆	11.2%	◆
Total Middle East	9.7	9.6	10.1	10.3	11.9	11.2	11.2	10.5	9.7	8.2	**7.9**	-2.7%	-1.9%	0.2%
Algeria	0.8	0.5	0.3	0.3	0.3	0.2	0.2	0.1	†	0.2	**0.2**	–	-13.3%	◆
Egypt	0.7	0.6	0.5	0.4	0.4	0.4	0.4	1.1	1.7	1.6	**2.8**	68.7%	7.9%	0.1%
Morocco	3.7	2.7	2.8	3.0	3.0	3.0	4.0	4.4	4.3	4.5	**5.4**	22.4%	3.3%	0.1%
South Africa	93.3	93.8	92.8	90.5	88.3	88.4	89.5	85.2	86.9	84.3	**86.0**	2.0%	0.1%	2.3%
Other Africa	3.0	3.3	3.7	4.2	3.9	5.3	7.8	6.8	6.2	7.0	**7.0**	0.2%	6.9%	0.2%
Total Africa	101.4	101.0	100.1	98.4	96.0	97.2	101.9	97.7	99.1	97.6	**101.4**	3.9%	0.6%	2.7%
Australia	58.2	56.3	52.2	50.9	47.8	45.4	45.0	46.5	46.5	45.1	**44.3**	-1.8%	-2.1%	1.2%
Bangladesh	0.6	0.8	0.8	0.7	0.9	1.0	0.9	2.3	1.7	1.9	**2.1**	12.1%	11.9%	0.1%
China	1609.3	1685.8	1748.9	1903.9	1927.8	1969.1	1954.5	1914.0	1889.1	1890.4	**1906.7**	0.9%	1.8%	50.5%
China Hong Kong SAR	6.9	7.2	6.2	7.4	7.3	7.8	8.1	6.7	6.7	6.3	**6.3**	–	-1.7%	0.2%
India	259.3	280.8	290.4	304.6	330.0	352.8	387.5	395.3	400.4	415.9	**452.2**	8.7%	5.7%	12.0%
Indonesia	31.5	33.2	39.5	46.9	53.0	57.0	45.1	51.2	53.4	57.2	**61.6**	7.7%	4.7%	1.6%
Japan	120.3	101.6	115.7	109.6	115.8	121.2	119.1	119.3	118.8	119.9	**117.5**	-2.1%	0.2%	3.1%
Malaysia	9.8	10.6	14.8	14.8	15.9	15.1	15.4	17.4	18.9	19.3	**21.1**	9.4%	8.1%	0.6%
New Zealand	2.1	1.6	1.4	1.4	1.7	1.6	1.4	1.4	1.2	1.2	**1.3**	1.3%	-3.0%	◆
Pakistan	6.0	4.9	4.6	4.0	4.0	3.2	4.7	4.7	5.3	7.1	**11.6**	63.3%	2.7%	0.3%
Philippines	6.4	6.1	7.0	7.7	8.1	10.0	10.6	11.6	13.1	15.5	**16.3**	5.2%	11.1%	0.4%
Singapore	†	†	†	†	†	0.3	0.4	0.4	0.4	0.9	**0.9**	1.6%	60.1%	◆
South Korea	66.1	68.6	77.1	83.7	80.6	81.5	84.4	85.4	81.5	86.2	**88.2**	2.4%	3.7%	2.3%
Sri Lanka	0.1	0.1	0.1	0.3	0.5	0.5	0.9	1.2	1.3	1.4	**1.2**	-14.3%	41.5%	◆
Taiwan	37.0	35.2	37.6	38.9	38.0	38.6	39.0	37.8	38.6	39.4	**39.3**	-0.3%	0.2%	1.0%
Thailand	15.0	15.0	15.4	15.7	16.5	16.2	17.9	17.5	17.7	18.3	**18.5**	1.0%	2.8%	0.5%
Vietnam	11.7	11.2	14.6	17.3	16.1	17.2	20.7	26.1	28.1	27.9	**34.3**	22.9%	16.3%	0.9%
Other Asia Pacific	20.5	16.6	16.2	13.2	13.9	11.4	12.9	12.2	16.1	16.9	**18.0**	7.0%	-1.0%	0.5%
Total Asia Pacific	2260.8	2335.5	2442.6	2621.1	2677.8	2749.7	2768.6	2751.0	2738.9	2770.8	**2841.3**	2.5%	2.3%	75.3%
Total World	**3503.4**	**3450.6**	**3610.1**	**3782.5**	**3797.2**	**3867.0**	**3864.2**	**3769.0**	**3710.0**	**3718.4**	**3772.1**	**1.4%**	**0.7%**	**100.0%**
of which: OECD	1150.8	1029.9	1092.9	1072.8	1028.2	1037.1	1020.1	954.9	900.0	892.9	**861.3**	-3.5%	-2.7%	22.8%
Non-OECD	2352.6	2420.8	2517.1	2709.8	2769.0	2829.9	2844.1	2814.0	2810.1	2825.6	**2910.8**	3.0%	2.2%	77.2%
European Union	303.7	267.7	280.4	288.2	294.6	287.6	268.6	261.4	239.7	234.2	**222.4**	-5.1%	-3.3%	5.9%

*Commercial solid fuels only, i.e. bituminous coal and anthracite (hard coal), lignite and brown (sub-bituminous) coal, and other commercial solid fuels. Excludes coal converted to liquid or gaseous fuels, but includes coal consumed in transformation processes.
†Less than 0.05.
◆Less than 0.05%.
Note: Differences between these world consumption figures and the world production statistics are accounted for by stock changes, and unavoidable disparities in the definition, measurement or conversion of coal supply and demand data.

Table F4. Global coal trade movements (Source: BP Statistical Review of World Energy 2019)

Coal: Trade movements

Million tonnes oil equivalent	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Growth rate per annum 2018	Growth rate per annum 2007-17	Share 2018
Imports														
Canada	16.1	8.5	8.7	5.6	5.5	5.2	6.1	5.2	4.4	5.2	**5.5**	5.6%	-9.0%	0.6%
Mexico	3.1	4.2	5.2	4.9	5.2	4.8	5.3	5.4	5.1	8.2	**5.8**	-29.2%	7.8%	0.7%
US	22.3	13.6	12.1	8.5	6.3	5.6	6.7	6.7	6.0	4.6	**2.6**	-42.7%	-15.0%	0.3%
S. & Cent. America	23.6	16.0	20.3	23.6	21.0	25.2	25.3	24.0	25.3	28.9	**26.6**	-7.9%	5.4%	3.1%
Europe	147.3	119.5	115.1	134.6	145.5	139.7	145.3	143.8	128.8	139.9	**149.6**	6.9%	-1.5%	17.4%
CIS	16.3	12.4	8.9	14.1	12.6	13.3	13.3	12.7	11.6	13.4	**14.5**	8.1%	0.8%	1.7%
Middle East	11.9	9.6	8.4	10.3	11.6	10.5	11.7	8.9	8.2	8.2	**7.9**	-3.3%	-0.4%	0.9%
Africa	6.6	5.3	7.6	8.3	7.4	19.7	9.2	10.9	11.8	13.5	**14.4**	6.9%	0.4%	1.7%
China	25.0	78.3	106.2	124.2	160.2	182.1	158.2	111.9	135.0	140.1	**146.5**	4.6%	16.5%	17.1%
India	30.9	36.0	47.8	56.6	73.7	87.3	110.5	115.1	110.8	113.0	**141.7**	25.5%	15.1%	16.5%
Japan	120.1	100.8	115.6	110.2	116.3	120.9	119.5	120.6	119.8	120.9	**119.7**	-1.0%	0.2%	13.9%
South Korea	63.8	65.0	74.7	80.1	76.3	77.6	81.1	84.4	85.7	92.2	**92.7**	0.5%	5.1%	10.8%
Other Asia Pacific	70.1	66.0	76.0	78.6	87.2	86.3	65.2	94.7	109.5	118.5	**131.1**	10.7%	5.3%	15.3%
Total World	**557.0**	**535.3**	**606.6**	**659.7**	**728.8**	**778.3**	**757.4**	**744.2**	**762.0**	**806.6**	**858.8**	**6.5%**	**3.8%**	**100.0%**
Exports														
Canada	18.6	17.0	19.9	20.9	20.1	23.6	20.1	18.1	18.1	19.6	**21.0**	7.2%	0.5%	2.4%
US	49.9	35.1	49.9	62.1	73.2	70.0	59.0	46.5	36.8	59.7	**66.3**	10.9%	6.1%	7.7%
Colombia	47.2	39.0	42.5	48.2	53.8	48.7	54.2	52.2	56.2	59.1	**46.7**	-21.0%	3.6%	5.4%
Europe	6.0	5.5	3.0	3.8	4.7	16.2	3.1	2.3	3.2	4.6	**6.2**	35.2%	3.1%	0.7%
Russia	56.5	58.6	59.8	68.2	77.2	84.9	90.3	98.0	106.8	120.5	**136.2**	13.0%	5.9%	15.9%
Other CIS	15.4	11.9	8.4	13.8	12.0	12.1	12.2	11.5	10.7	11.3	**11.9**	4.9%	-0.5%	1.4%
South Africa	34.6	37.2	47.0	48.9	52.3	50.1	52.1	55.1	51.6	56.4	**49.2**	-12.8%	2.1%	5.7%
Other Africa	0.7	0.6	2.6	1.1	3.1	2.7	4.1	4.3	4.7	7.7	**5.3**	-31.7%	18.3%	0.6%
Australia	156.7	167.7	178.8	168.8	190.7	220.2	218.6	238.4	236.3	232.2	**249.4**	7.4%	4.3%	29.0%
China	37.4	14.2	14.0	10.6	6.7	6.8	8.5	10.8	12.2	9.9	**9.9**	-0.6%	-13.7%	1.1%
Indonesia	110.4	121.1	148.0	171.6	195.0	204.7	201.2	178.7	184.7	193.1	**220.3**	14.1%	6.0%	25.7%
Mongolia	2.8	4.1	11.4	13.9	14.9	11.7	12.7	9.7	17.5	22.6	**23.9**	5.6%	26.2%	2.8%
Other Asia Pacific	15.7	19.5	18.3	24.0	21.5	22.1	18.3	15.6	18.4	7.1	**9.5**	35.2%	-10.1%	1.1%
Rest of World	5.1	3.6	3.1	3.8	3.5	4.5	3.1	2.8	4.8	2.8	**3.3**	15.3%	-8.9%	0.4%
Total World	**557.0**	**535.3**	**606.6**	**659.7**	**728.8**	**778.3**	**757.4**	**744.2**	**762.0**	**806.6**	**858.8**	**6.5%**	**3.8%**	**100.0%**

Note: Commercial solid fuels only, i.e. bituminous coal and anthracite (hard coal), and lignite and brown (sub-bituminous) coal, and other commercial solid fuels. Intra-area movements (for example between countries in Europe) are excluded.

Table F5. Global coal prices ($USD/tonne) (Source: BP Statistical Review of World Energy 2019)

Coal: Prices

US dollars per tonne	Northwest Europe marker price†	US Central Appalachian coal spot price index‡	Japan steam spot CIF price†	China Qinhuangdao spot price*
1998	32.00	31.00	–	–
1999	28.79	31.29	–	–
2000	35.99	29.90	–	27.52
2001	39.03	50.15	37.69	31.78
2002	31.65	33.20	31.47	33.19
2003	43.60	38.52	39.61	31.74
2004	72.08	64.90	74.22	42.76
2005	60.54	70.12	64.62	51.34
2006	64.11	57.82	65.22	53.53
2007	88.79	49.73	95.59	61.23
2008	147.67	117.42	157.88	104.97
2009	70.66	60.73	83.59	87.86
2010	92.50	67.87	108.47	110.08
2011	121.52	84.75	126.13	127.27
2012	92.50	67.28	100.30	111.89
2013	81.69	69.72	90.07	95.42
2014	75.38	67.08	76.13	84.12
2015	56.64	51.57	60.10	67.53
2016	60.09	51.45	71.66	71.35
2017	84.51	63.83	96.02	94.72
2018	91.83	72.84	112.73	99.45

†Source: IHS Northwest Europe prices for 1998-2000 are the average of the monthly marker, 2001-2018 the average of weekly prices. IHS Japan prices basis = 6,000 kilocalories per kilogram NAR CIF. Chinese prices are the average monthly price for 2000-2005, weekly prices 2006 -2018, 5,500 kilocalories per kilogram NAR, including cost and freight (CFR).
‡Source: S&P Global Platts ©2019, S&P Global Inc. Prices are for Central Appalachian 12,500 BTU, 1.2 SO_2 coal, FOB. Prices for 1998-2000 are by coal price publication date, 2001-2005 by coal price assessment date. 2006-2018 weekly CAPP 12,500 BTU, 1.6 SO_2 coal, FOB.
Note: CIF = cost+insurance+freight (average prices); FOB = free on board.

Coal prices
US dollars per tonne

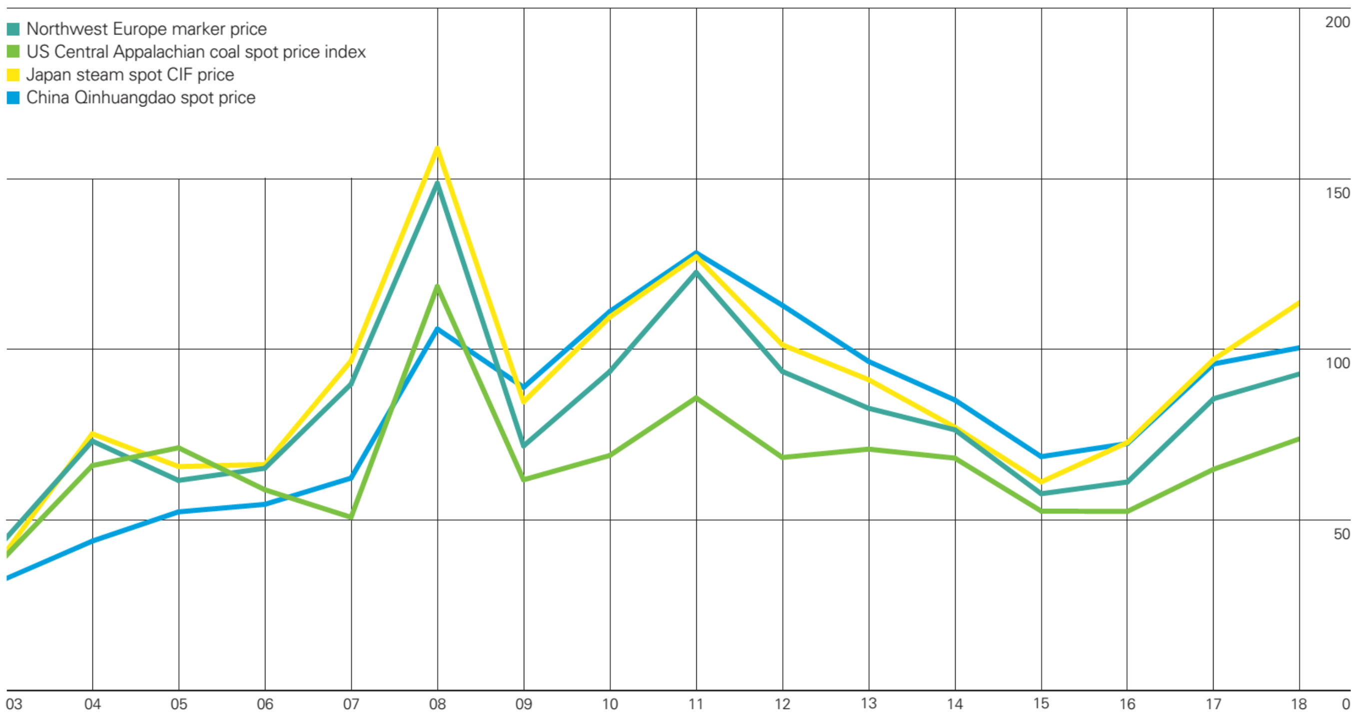


Table F6.1. Coal production in EU, US and China
(Source: BP Statistical Review of World Energy 2019 and BP Statistical Review of World Energy 2011)

Year	European Union (mtoe)	United States (mtoe)	China (mtoe)	India (mtoe)
1981	417,1	463,1	310,9	62,9
1982	432,4	469,7	333,4	62,3
1983	424,4	434,6	357,7	65,9
1984	388,5	496,9	395,3	69,2
1985	418,3	487,0	443,9	71,4
1986	423,4	491,6	455,2	76,8
1987	417,2	507,5	472,8	84,2
1988	412,7	522,6	499,8	89,5
1989	393,4	537,9	537,6	97,4
1990	351,4	565,9	562,3	91,9
1991	327,8	544,2	566,3	98,6
1992	309,8	545,0	582,4	104,4
1993	288,2	510,3	599,3	108,2
1994	266,1	557,2	645,1	109,8
1995	267,0	555,1	711,0	117,7
1996	264,0	571,6	731,6	126,7
1997	256,4	584,9	741,8	126,3
1998	229,2	603,2	718,9	126,5
1999	216,7	584,3	750,6	124,4
2000	206,6	570,1	762,5	132,2
2001	205,1	590,3	809,5	133,6
2002	202,5	570,1	853,8	138,5
2003	200,7	553,6	1013,4	144,4
2004	195,8	572,4	1174,1	155,7
2005	188,1	580,2	1302,2	162,1
2006	181,5	595,1	1406,4	170,2
2007	177,4	587,7	1501,1	181,0
2008	178,6	566,9	1491,8	227,5
2009	167,6	513,7	1537,9	246,0
2010	165,6	523,7	1665,3	252,4
2011	168,3	528,3	1851,7	250,8
2012	167,9	491,9	1873,5	255,0
2013	157,1	475,8	1894,6	255,7
2014	150,3	482,3	1864,2	269,5
2015	144,5	426,9	1825,6	281,0
2016	132,5	348,3	1691,4	283,9
2017	130,7	371,3	1746,6	286,6
2018	125,8	364,5	1828,8	308,0

Table F6.2. Coal consumption in EU, US and China
(Source: BP Statistical Review of World Energy 2019 and BP Statistical Review of World Energy 2011)

Year	European Union (mtoe)	United States (mtoe)	China (mtoe)	India (mtoe)
1981	465,5	400,9	302,3	63,2
1982	471,4	386,1	320,1	63,1
1983	472,7	400,5	343,4	66,2
1984	471,2	430,2	374,9	69,5
1985	491,6	440,4	399,8	72,5
1986	489,9	435,0	422,1	78,0
1987	494,4	453,8	455,7	85,9
1988	486,2	474,9	486,7	91,7
1989	482,5	480,5	508,8	100,0
1990	442,6	483,1	525,3	95,5
1991	420,9	478,6	549,2	101,8
1992	390,1	481,9	565,6	108,2
1993	366,0	499,8	602,6	112,5
1994	358,1	501,7	642,8	115,8
1995	355,3	506,2	690,2	125,0
1996	350,6	529,2	692,7	134,4
1997	334,5	540,4	693,6	135,9
1998	323,2	545,7	698,5	136,1
1999	305,7	544,9	731,0	135,8
2000	314,9	569,0	737,1	144,2
2001	315,7	552,2	751,9	145,2
2002	314,0	552,0	794,9	151,8
2003	324,3	562,5	936,3	156,8
2004	319,1	566,1	1084,3	172,3
2005	310,4	574,2	1218,7	184,4
2006	317,7	565,7	1343,9	195,4
2007	316,7	573,3	1438,4	210,3
2008	303,7	535,9	1609,3	259,3
2009	267,7	471,4	1685,8	280,8
2010	280,4	498,8	1748,9	290,4
2011	288,2	470,6	1903,9	304,6
2012	294,6	416,0	1927,8	330,0
2013	287,6	431,8	1969,1	352,8
2014	268,6	430,9	1954,5	387,5
2015	261,4	372,2	1914,0	395,3
2016	239,7	340,6	1889,1	400,4
2017	234,2	331,3	1890,4	415,9
2018	222,4	317,0	1906,7	452,2

Table F6.3. Coal deficit consumption subtracted from production in EU, US and China
(Source: BP Statistical Review of World Energy 2019 and BP Statistical Review of World Energy 2011)

Year	European Union (mtoe)	United States (mtoe)	China (mtoe)	India (mtoe)
1981	-48	62	9	0
1982	-39	84	13	-1
1983	-48	34	14	0
1984	-83	67	20	0
1985	-73	47	44	-1
1986	-67	57	33	-1
1987	-77	54	17	-2
1988	-74	48	13	-2
1989	-89	57	29	-3
1990	-91	83	37	-4
1991	-93	66	17	-3
1992	-80	63	17	-4
1993	-78	10	-3	-4
1994	-92	55	2	-6
1995	-88	49	21	-7
1996	-87	42	39	-8
1997	-78	44	48	-10
1998	-94	57	20	-10
1999	-89	39	20	-11
2000	-108	1	25	-12
2001	-111	38	58	-12
2002	-112	18	59	-13
2003	-124	-9	77	-12
2004	-123	6	90	-17
2005	-122	6	83	-22
2006	-136	29	62	-25
2007	-139	14	63	-29
2008	-125	31	-118	-32
2009	-100	42	-148	-35
2010	-115	25	-84	-38
2011	-120	58	-52	-54
2012	-127	76	-54	-75
2013	-131	44	-75	-97
2014	-118	51	-90	-118
2015	-117	55	-88	-114
2016	-107	8	-198	-117
2017	-104	40	-144	-129
2018	-97	48	-78	-144

36 APPENDIX G - NUCLEAR ENERGY

Table G1. Global nuclear energy consumption (Mtoe) (BP Statistical Review of World Energy 2019)

Consumption*

Million tonnes oil equivalent	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Growth rate per annum 2018	Growth rate per annum 2007-17	Share 2018
Canada	21.6	20.2	20.4	21.0	21.3	23.2	24.1	22.9	22.7	22.7	**22.6**	-0.4%	0.8%	3.7%
Mexico	2.2	2.4	1.3	2.3	2.0	2.7	2.2	2.6	2.4	2.5	**3.1**	24.9%	0.4%	0.5%
US	192.0	190.3	192.2	188.2	183.2	187.9	189.9	189.9	191.9	191.7	**192.2**	0.3%	◆	31.4%
Total North America	215.8	212.9	213.9	211.5	206.5	213.8	216.2	215.4	217.0	216.9	**217.9**	0.5%	0.1%	35.7%
Argentina	1.7	1.9	1.6	1.4	1.4	1.4	1.2	1.6	1.9	1.4	**1.6**	12.9%	-1.7%	0.3%
Brazil	3.2	2.9	3.3	3.5	3.6	3.5	3.5	3.3	3.6	3.6	**3.5**	-0.7%	2.5%	0.6%
Chile	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Colombia	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Ecuador	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Peru	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Trinidad & Tobago	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Venezuela	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Other S. & Cent. America	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Total S. & Cent. America	4.8	4.8	4.9	5.0	5.1	4.9	4.7	4.9	5.5	4.9	**5.1**	3.1%	1.1%	0.8%
Austria	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Belgium	10.3	10.7	10.8	10.9	9.1	9.6	7.6	5.9	9.8	9.6	**6.4**	-32.6%	-1.3%	1.1%
Czech Republic	6.0	6.2	6.3	6.4	6.9	7.0	6.9	6.1	5.5	6.4	**6.8**	5.6%	0.8%	1.1%
Finland	5.3	5.4	5.2	5.3	5.3	5.4	5.4	5.3	5.3	5.1	**5.2**	1.5%	-0.4%	0.9%
France	99.4	92.7	97.0	100.1	96.3	95.9	98.8	99.0	91.2	90.1	**93.5**	3.7%	-1.0%	15.3%
Germany	33.7	30.5	31.8	24.4	22.5	22.0	22.0	20.8	19.2	17.3	**17.2**	-0.3%	-5.9%	2.8%
Greece	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Hungary	3.4	3.5	3.6	3.5	3.6	3.5	3.5	3.6	3.6	3.6	**3.6**	-2.3%	0.9%	0.6%
Italy	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Netherlands	0.9	1.0	0.9	0.9	0.9	0.7	0.9	0.9	0.9	0.8	**0.8**	2.7%	-2.1%	0.1%
Norway	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Poland	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Portugal	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Romania	2.5	2.7	2.6	2.7	2.6	2.6	2.6	2.6	2.6	2.6	**2.6**	-1.1%	4.1%	0.4%
Spain	13.3	11.9	13.9	13.1	13.9	12.8	13.0	13.0	13.3	13.1	**12.6**	-4.2%	0.5%	2.1%
Sweden	14.5	11.8	13.1	13.7	14.5	15.0	14.7	12.8	14.3	14.9	**15.5**	4.4%	-0.2%	2.5%
Switzerland	6.2	6.2	6.0	6.1	5.8	5.9	6.3	5.3	4.8	4.6	**5.8**	25.2%	-3.0%	1.0%
Turkey	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Ukraine	20.3	18.8	20.2	20.4	20.4	18.8	20.0	19.8	18.3	19.4	**19.1**	-1.4%	-0.8%	3.1%
United Kingdom	11.9	15.6	14.1	15.6	15.9	16.0	14.4	15.9	16.2	15.9	**14.7**	-7.5%	1.1%	2.4%
Other Europe	11.0	10.4	8.0	8.6	8.3	8.0	8.5	8.2	8.2	8.4	**8.3**	-0.4%	-2.1%	1.4%
Total Europe	238.7	227.3	233.5	231.7	225.9	223.2	224.6	219.1	213.2	211.8	**212.1**	0.1%	-1.2%	34.7%
Azerbaijan	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Belarus	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Kazakhstan	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Russian Federation	36.9	37.0	38.6	39.1	40.2	39.0	40.9	44.2	44.5	46.0	**46.3**	0.7%	2.4%	7.6%
Turkmenistan	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Uzbekistan	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Other CIS	0.6	0.6	0.6	0.6	0.5	0.5	0.6	0.6	0.5	0.6	**0.5**	-20.7%	0.3%	0.1%
Total CIS	37.5	37.6	39.1	39.7	40.7	39.6	41.5	44.9	45.0	46.6	**46.7**	0.4%	2.4%	7.6%
Iran	–	–	–	†	0.3	1.0	0.9	0.8	1.5	1.6	**1.6**	-1.0%	–	0.3%
Iraq	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Israel	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Kuwait	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Oman	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Qatar	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Saudi Arabia	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
United Arab Emirates	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Other Middle East	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Total Middle East	–	–	–	†	0.3	1.0	0.9	0.8	1.5	1.6	**1.6**	-1.0%	–	0.3%
Algeria	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Egypt	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Morocco	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
South Africa	2.9	2.9	3.1	2.9	2.9	3.2	3.1	2.8	3.6	3.6	**2.5**	-29.6%	3.4%	0.4%
Other Africa	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Total Africa	2.9	2.9	3.1	2.9	2.9	3.2	3.1	2.8	3.6	3.6	**2.5**	-29.6%	3.4%	0.4%
Australia	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Bangladesh	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
China	15.5	15.9	16.7	19.5	22.0	25.3	30.0	38.6	48.3	56.1	**66.6**	18.6%	14.9%	10.9%
China Hong Kong SAR	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
India	3.4	3.8	5.2	7.3	7.5	7.5	7.8	8.7	8.6	8.5	**8.8**	4.4%	7.7%	1.4%
Indonesia	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Japan	57.0	62.1	66.2	36.9	4.1	3.3	–	1.0	4.0	6.6	**11.1**	68.9%	-20.2%	1.8%
Malaysia	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
New Zealand	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Pakistan	0.4	0.6	0.5	0.9	1.2	1.2	1.1	1.1	1.3	1.9	**2.2**	18.0%	12.8%	0.4%
Philippines	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Singapore	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
South Korea	34.2	33.4	33.6	35.0	34.0	31.4	35.4	37.3	36.7	33.6	**30.2**	-10.1%	0.4%	4.9%
Sri Lanka	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Taiwan	9.2	9.4	9.4	9.5	9.1	9.4	9.6	8.3	7.2	5.1	**6.3**	23.3%	-5.7%	1.0%
Thailand	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Vietnam	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Other Asia Pacific	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Total Asia Pacific	119.7	125.3	131.7	109.1	78.0	78.1	83.9	95.0	106.0	111.7	**125.3**	12.1%	-1.0%	20.5%
Total World	**619.5**	**610.8**	**626.2**	**600.0**	**559.5**	**563.8**	**574.9**	**582.8**	**591.8**	**597.1**	**611.3**	**2.4%**	**-0.4%**	**100.0%**
of which: OECD	517.0	508.5	521.0	488.4	444.0	447.1	450.0	446.8	446.4	443.4	**446.1**	0.6%	-1.6%	73.0%
Non-OECD	102.5	102.3	105.3	111.7	115.5	116.7	125.0	136.0	145.3	153.7	**165.2**	7.5%	4.4%	27.0%
European Union	212.2	202.4	207.4	205.2	199.7	198.5	198.3	194.0	190.1	187.8	**187.2**	-0.3%	-1.2%	30.6%

*Based on gross generation and not accounting for cross-border electricity supply. Converted on the basis of thermal equivalence assuming 38% conversion efficiency in a thermal power station.
†Less than 0.05.
◆Less than 0.05%.
Nuclear data expressed in terawatt-hours is available at *bp.com/statisticalreview*.

36.1 Production terminology

The Red Book (NEA/OECD Uranium 2020 Resources, Production and Demand) uses production classifications developed in (IAEA (1984): Manual on the Projection of Uranium Production Capability, General Guidelines, Technical Report Series No. 238, IAEA, Vienna).

36.1.1 Production centers

A production center is a production unit consisting of one or more ore processing plants, one or more associated mines and uranium resources that are tributary to these facilities. For the purpose of describing production centers, they have been divided into four classes, as follows:

1. Existing production centers are those that currently exist in operational condition. Production projections continue until the identified resources (costs < USD 130/kgU) are exhausted.
2. Committed production centers are those that are either under construction or are firmly committed for construction.
3. Planned production centers are those for which feasibility studies are completed and regulatory approvals are at advanced stage.
4. Prospective production centers are those for which some level of feasibility study has been completed and the centers are supported by tributary RAR and Inferred resources. Indicative start-up dates should have been announced.

36.1.2 Production capacity and capability

Production capacity: Is the nominal level of production output, based on the design of the plant and facilities over an extended period, under normal commercial operating practices.

Production capability: This is an estimate of the level of production that could be practically and realistically achieved under favorable circumstances from the plant and facilities at any of the types of production centers described, given the nature of the resource's tributary to them. Projections of production capability are supported only by RAR and/or IR. The projection is presented based on those resources recoverable at costs <USD 130/kgU.

Production: Denotes the amount of uranium output, in tonnes U contained in concentrate, from an ore processing plant or production center (with mineral processing losses deducted).

36.1.3 Demand terminology

Reactor-related requirements: Refers to natural uranium acquisitions not necessarily consumption during a calendar year

36.2 Global Uranium Resources

Table G2. Changes in identified resources (recoverable) 2017-2019
(Source: NEA/OECD Uranium 2020 Resources, Production and Demand)

Resource Category	2017	2019	Change (1000 tU) [a]	% Change
Idenified (total)				
<$USD 260/kgU	7,988.6	8,070.4	81.8	1.0 %
<$USD 130/kgU	6,142.2	6,148.3	6.1	0.1 %
<$USD 80/kgU	2,079.5	2,007.6	-71.9	-3.5 %
<$USD 40/kgU [b]	1,057.7	1,080.5	22.8	2.2 %
Reasonable Assured Resources RAR				
<$USD 260/kgU	4,815.0	4,723.7	-91.3	-1.9 %
<$USD 130/kgU	3,865.0	3,791.7	-73.3	-1.9 %
<$USD 80/kgU	1,279.9	1,243.9	-36.0	-2.8 %
<$USD 40/kgU [b]	713.4	744.5	31.1	4.4 %
Inferred Resources IR				
<$USD 260/kgU	3,173.0	3,346.4	173.4	5.5 %
<$USD 130/kgU	2,277.0	2,355.7	78.7	3.5 %
<$USD 80/kgU	799.9	763.6	-36.3	-4.5 %
<$USD 40/kgU [b]	344.4	335.9	-8.5	-2.5 %

(a) Changes might not equal differences between 2017 and 2019 because of independent rounding.

(b) Resources in the cost category of <$USD 40/kgU and <USD 80/kgU should be reagrded with some caution since some countries do not report low-cost resource estimates, mainly for confidentiality reasons, whereas other countries that never, or not recently hosted uranium mining may be underestimating mining costs.

Table G2. Comparison of in situ and recoverable identified resources (as of Jan 1st 2019)
(Source: NEA/OECD Uranium 2020 Resources, Production and Demand)

Identified Resources	<$USD 40/kgU (tonnes)	<$USD 80/kgU (tonnes)	<$USD 130/kgU (tonnes)	<$USD 260/kgU (tonnes)
Total in situ (tU)	1,268,400	2,456,300	8,070,300	10,584,500
Total recoverable (tU)	1,080,500	2,007,600	6,147,800	8,070,900
Difference (tU)	187,900	448,700	1,922,500	2,513,600
% difference	17.4 %	22.4 %	31.3 %	31.1 %
% recovery	82.6 %	77.6 %	68.7 %	68.9 %

36.3 Global Identified Resources of Global Uranium Resources (IR)

Table G4.1. Identified resources (recoverable)** (as of Jan 2019, tonnes U, rounded to nearest 100 tonnes) (Source: NEA/OECD Uranium 2020 Resources, Production and Demand) – Part I

Country	Cost Ranges			
	<$USD 40/kgU (tonnes)	<$USD 80/kgU (tonnes)	<$USD 130/kgU (tonnes)	<$USD 260/kgU (tonnes)
Algeria (c, d)				19,500
Argentina	2,400	17,900	38,700	39,800
Australia			1,692,700	2,049,400
Botswana*			87,200	87,200
Brazil (d)	138,100	229,400	276,800	276,800
Canada	260,500	269,500	564,900	873,000
Central African Republic * (a, c)			32,000	32,000
Chad* (a, c, d, e)				2,400
Chile				1,400
China (People's Republic of) (d)	86,000	154,200	248,900	269,700
Congo, Dem. Rep* (a, c, d)				2,700
Czech Republic			900	119,200
Egypt (d)			400	1,900
Finland (c, d)			1,200	1,200
Gabon (a, c)			4,800	5,800
Germany (c)				7,000
Greece (a, c)				7,000
Greenland (d)				114,000
Hungary (c, d)				13,500
India (d, e)	na	na	na	195,900
Indonesia (b, d)		1,500	8,400	8,400
Iran, Islamic Republic of (b, d)			7,500	7,500
Italy (a, c)		6,100	6,100	6,100
Japan (a, c)			6,600	6,600
Jordan (d)			52,500	52,500
Kazakhstan (d)	530,600	720,200	906,800	969,200
Malawi*			6,200	14,300
Mali *(d)			8,900	8,900
Mauritania*			17,100	24,500
Mexico (d)			3,700	5,000
Mongolia		60,000	143,500	143,500

Table G4.2. Identified resources (recoverable)** (as of Jan 2019, tonnes U, rounded to nearest 100 tonnes) (Source: NEA/OECD Uranium 2020 Resources, Production and Demand) - Part II

Country	Cost Ranges			
	<$USD 40/kgU (tonnes)	<$USD 80/kgU (tonnes)	<$USD 130/kgU (tonnes)	<$USD 260/kgU (tonnes)
Namibia*			448,300	504,200
Niger		9,900	276,400	439,400
Paraguay*				3,600
Peru [a, d]		33,400	33,400	33,400
Portugal [c]		4,500	7,000	7,000
Romania* [a, c]			6,600	6,600
Russia [b]		38,000	486,000	661,900
Senegal [d]				1,100
Slovak Republic [a,b, d]		12,700	15,500	15,500
Slovenia [c, d]		5,400	9,200	9,200
Somalia* [a, c, d]				7,600
South Africa *		228,000	320,900	447,700
Spain [d,f]	8,100	28,500	28,500	28,500
Sweden* [c, d]			9,600	9,600
Tanzania* [b]		46,800	58,200	58,200
Turkey [b, d]			12,500	13,600
Ukraine		72,900	108,700	186,900
United States [d]		13,900	47,900	101,900
Uzbekistan*	54,800	54,800	132,300	132,300
Viet Nam [d]				3,900
Zambia*			31,000	31,000
Zimbabwe [a, c, d]				1,400
Total [g]	1,080,500	2,007,600	6,147,800	8,070,400

* Secretariat estimate

** In situ resources do not take into account mining and milling losses.

(a) Not reported in 2019 responses; data from previous Red Book.

(b) Assessment partially made within the last five years.

(c) Assessment not made within the last five years.

(d) Recoverable resources were adjusted by the Secretariat to estimate in situ resources using recovery factors provided by countries or estimated by the Secretariat according to the expected production method years.

(e) Cost data not provided, therefore resources are reported in the <USD 260/kgU category.

(f) Updated from previous Red Book report.

(g) Totals related to cost ranges <USD 40/kgU and <USD 80/kgU are higher than reported in the tables because certain countries do not report low-cost resource estimates, mainly for reasons of confidentiality.

Table G5.1. Identified resources (in situ)** (as of Jan 2019, tonnes U, rounded to nearest 100 tonnes) (Source: NEA/OECD Uranium 2020 Resources, Production and Demand) – Part I

Country	Cost Ranges			
	<$USD 40/kgU (tonnes)	<$USD 80/kgU (tonnes)	<$USD 130/kgU (tonnes)	<$USD 260/kgU (tonnes)
Algeria [c]				26,000
Argentina [d]	3,400	24,800	54,000	54,600
Australia [f]	na	na	2,540,500	2,934,200
Botswana* [d]			140,600	140,600
Brazil	184,300	314,600	382,300	382,300
Canada [d,f]	298,400	308,700	647,100	1,000,000
Central African Republic *			42,700	42,700
Chad* [a, e]				3,200
Chile [d]				1,900
China (People's Republic of)	107,900	192,600	316,300	344,000
Congo, Dem. Rep* [a, c]				3,600
Czech Republic [d]			1,400	197,400
Egypt			500	2,500
Finland [c]			1,500	1,500
Gabon [a, c, d]			6,400	7,700
Germany [c, d]				9,300
Greece [a, c, d]				9,300
Greenland				228,000
Hungary [c]				17,900
India [e]	na	na	na	259,500
Indonesia [b]		2,000	11,200	11,200
Iran, Islamic Republic of [b]			9,900	9,900
Italy [a, c, d]		8,100	8,100	8,100
Japan [a, c, d, f]			7,800	7,800
Jordan			70,000	70,000
Kazakhstan	596,100	809,800	1,027,600	1,102,700
Malawi* [d]			7,800	19,000
Mali *			11,800	11,800
Mauritania* [d]			19,900	29,700
Mexico			4,900	6,700
Mongolia [d]		79,200	190,500	190,500
Namibia* [d]			560,400	630,300
Niger [d]		12,200	340,700	547,400
Paraguay*				4,300
Peru [a]		47,700	47,700	47,700

Table G5.2. Identified resources (in situ)** (as of Jan 2019, tonnes U, rounded to nearest 100 tonnes) (Source: NEA/OECD Uranium 2020 Resources, Production and Demand) – Part II

Country	Cost Ranges			
	<$USD 40/kgU (tonnes)	<$USD 80/kgU (tonnes)	<$USD 130/kgU (tonnes)	<$USD 260/kgU (tonnes)
Portugal [c, d]		6,000	9,300	9,300
Romania* [a, c, d]			8,800	8,800
Russia [b, d, f]		50,600	596,800	847,500
Senegal				1,500
Slovak Republic [a,b]		15,800	19,300	19,300
Slovenia [c]		7,200	12,200	12,200
Somalia* [a, c, d]				10,200
South Africa [d, f]		313,900	440,800	614,500
Spain [f]	9,800	34,300	34,300	34,300
Sweden* [c]			12,800	12,800
Tanzania* [b, d]		58,500	72,800	72,800
Turkey [b]			15,300	16,700
Ukraine [d]		83,200	123,600	212,800
United States		18,600	67,100	135,900
Uzbekistan* [d]	68,500	68,500	171,300	171,300
Viet Nam				5,200
Zambia* [d]			34,300	34,300
Zimbabwe [a, c]				1,800
Total [g]	1,268,400	2,456,300	8,070,300	10,584,500

* Secretariat estimate

** In situ resources do not take into account mining and milling losses.

(a) Not reported in 2019 responses; data from previous Red Book.

(b) Assessment partially made within the last five years.

(c) Assessment not made within the last five years.

(d) Recoverable resources were adjusted by the Secretariat to estimate in situ resources using recovery factors provided by countries or estimated by the Secretariat according to the expected production method years.

(e) Cost data not provided, therefore resources are reported in the <USD 260/kgU category.

(f) Updated from previous Red Book report.

(g) Totals in the cost category of <$USD 40/kgU and <USD 80/kgU should be reagrded with some caution since some countries do not report low-cost resource estimates, mainly for confidentiality reasons, whereas other countries that never, or not recently hosted uranium mining may be underestimating mining costs.

36.4 Global Reasonably Assured Resources of Global Uranium Resources

Table G6.1. Reasonably assured resoruces (RAR) (recoverable) (as of Jan 2019, tonnes U, rounded to nearest 100 tonnes) (Source: NEA/OECD Uranium 2020 Resources, Production and Demand) – Part I

Country	Cost Ranges			
	<$USD 40/kgU (tonnes)	<$USD 80/kgU (tonnes)	<$USD 130/kgU (tonnes)	<$USD 260/kgU (tonnes)
Algeria (c, d)				19,500
Argentina		5,100	11,000	11,000
Australia (d)			1,183,900	1,284,800
Botswana*			20,400	20,400
Brazil (d)	138,100	155,900	155,900	155,900
Canada	258,500	258,500	461,600	652,200
Central African Republic * (a, c)			32,000	32,000
Chile				600
China (d)	37,100	64,500	119,000	122,600
Congo, Dem. Rep* (a, c, d)				1,400
Czech Republic			900	50,900
Finland (c ,d)			1,200	1,200
Gabon (a, c)			4,800	4,800
Germany (c)				3,000
Greece (a, c)				1,000
Greenland (d)				51,400
India (d, e)	na	na	na	188,000
Indonesia (b, d)		1,500	5,300	5,300
Iran, Islamic Republic of (b, d)			3,200	3,200
Italy (a, c)		4,800	4,800	4,800
Japan (a, c)			6,600	6,600
Jordan (d)			6,000	6,000
Kazakhstan (d)	272,200	343,800	445,100	464,700
Malawi*			4,400	9,700
Mali * (d)			5,000	5,000
Mauritania*			5,700	5,900
Mexico (d)			1,800	1,800
Mongolia		33,300	60,500	60,500
Namibia*			279,400	320,700
Niger		9,900	238,700	315,500
Paraguay*				2,900

Table G6.2. Reasonably assured resoruces (RAR) (recoverable) (as of Jan 2019, tonnes U, rounded to nearest 100 tonnes) (Source: NEA/OECD Uranium 2020 Resources, Production and Demand) – Part II

Country	Cost Ranges			
	<$USD 40/kgU (tonnes)	<$USD 80/kgU (tonnes)	<$USD 130/kgU (tonnes)	<$USD 260/kgU (tonnes)
Peru [a, d]		14,000	14,000	14,000
Portugal [c]		4,500	6,000	6,000
Romania* [a, c]			3,000	3,000
Russia [b]		23,300	211,200	256,600
Slovak Republic [a, b, d]		8,800	8,800	8,800
Slovenia [c, d]		1,700	1,700	1,700
Somalia* [a, c, d]				5,000
South Africa *		166,300	236,000	258,000
Spain [d, f]	8,100	19,100	19,100	19,100
Sweden* [c, d]			4,900	4,900
Tanzania* [b]		38,300	39,700	39,700
Turkey [b, d]			3,700	3,700
Ukraine		46,200	74,900	122,100
United States [d]		13,900	47,200	101,900
Uzbekistan*	30,500	30,500	50,800	50,800
Viet Nam [d]				900
Zambia*			12,800	12,800
Zimbabwe [a, c, d]				1,400
Total [g]	744,500	1,243,900	3,791,000	4,723,700

* Secretariat estimate

** In situ resources do not take into account mining and milling losses.

(a) Not reported in 2019 responses; data from previous Red Book.

(b) Assessment partially made within the last five years.

(c) Assessment not made within the last five years.

(d) Recoverable resources were adjusted by the Secretariat to estimate in situ resources using recovery factors provided by countries or estimated by the Secretariat according to the expected production method years.

(e) Cost data not provided, therefore resources are reported in the <USD 260/kgU category.

(f) Updated from previous Red Book report.

(g) Totals related to cost ranges <USD 40/kgU and <USD 80/kgU are higher than reported in the tables because certain countries do not report low-cost resource estimates, mainly for reasons of confidentiality.

Table G7.1. Reasonably Assured Resources (RAR) (in situ) (as of Jan 2017, tonnes U, rounded to nearest 100 tonnes) (Source: NEA/OECD Uranium 2018 Resources, Production and Demand)

Country	Cost Ranges			
	<$USD 40/kgU (tonnes)	<$USD 80/kgU (tonnes)	<$USD 130/kgU (tonnes)	<$USD 260/kgU (tonnes)
Algeria (c)				26 000
Argentina (d)		7 100	15 300	15 300
Australia (d)			1 877 900	2 070 000
Botswana*			22 100	22 100
Brazil	184 300	209 700	209 700	209 700
Canada (d)	341 200	366 900	543 200	784 900
Central African Republic *			42 700	42 700
Chile (d)				700
China (People's Republic of)	58 200	133 800	177 700	177 700
Congo, Dem. Rep* (a, c)				1 900
Czech Republic (d)			1 800	83 700
Finland (c)			1 500	1 500
Gabon (a, c, d)			6 400	6 400
Germany (c, d)				4 000
Greece (a, c, d)				1 300
Greenland (f)				102 800
India (e)				197 200
Indonesia (b)		2 000	7 100	7 100
Iran, Islamic Republic of (b)			1 400	1 400
Italy (a, c, d)		6 400	6 400	6 400
Japan (c, d, f)			7 800	7 800
Jordan			6 900	6 900
Kazakhstan	256 000	342 300	471 200	494 800
Malawi* (d)			5 500	13 000
Mali			6 700	6 700
Mauritania*			800	1 200
Mexico			2 400	2 400
Mongolia (d)		64 200	64 200	64 200
Namibia*			419 100	460 600
Niger*			287 400	405 200
Paraguay*				3 400

Table G7.2. Reasonably Assured Resources (RAR) (in situ) (as of Jan 2017, tonnes U, rounded to nearest 100 tonnes) (Source: NEA/OECD Uranium 2018 Resources, Production and Demand)

Country	Cost Ranges			
	<$USD 40/kgU (tonnes)	<$USD 80/kgU (tonnes)	<$USD 130/kgU (tonnes)	<$USD 260/kgU (tonnes)
Peru		20 000	20 000	20 000
Portugal (a, c, d)		6 000	8 000	8 000
Romania* (a, c, d)			4 000	4 000
Russia (b, d)		32 700	258 400	328 300
Slovak Republic (b)		10 900	10 900	10 900
Slovenia (c)		2 200	2 200	2 200
Somalia* (a, c, d)				6 700
South Africa (a, d)		239 800	338 100	369 100
Spain (d)	10 300	24 200	24 200	24 200
Sweden* (a, c)			6 500	6 500
Tanzania* (b)		47 900	49 600	49 600
Turkey (b)		9 000	9 000	9 000
Ukraine (d)		48 100	93 200	157 200
United States (f)		17 400	62 900	138 200
Uzbekistan*	46 700	46 700	72 000	72 000
Viet Nam				1 200
Zambia*			12 300	12 300
Zimbabwe (a, c)				1 800
Total (g)	896 700	1 637 300	5 156 500	6 450 200

* Secretariat estimate

** In situ resources do not take into account mining and milling losses.

(a) Not reported in 2017 responses; data from previous Red Book.

(b) Assessment partially made within the last five years.

(c) Assessment not made within the last five years.

(d) Recoverable resources were adjusted by the Secretariat to estimate in situ resources using recovery factors provided by countries or estimated by the Secretariat according to the expected production method years.

(e) Cost data not provided, therefore resources are reported in the <USD 260/kgU category.

(f) Updated from previous Red Book report.

(g) Totals related to cost ranges <USD 40/kgU and <USD 80/kgU are higher than reported in the tables because certain countries do not report low-cost resource estimates, mainly for reasons of confidentiality.

Table G8.1. Reasonably assured resoruces (RAR) (in situ) (as of Jan 2019, tonnes U, rounded to nearest 100 tonnes) (Source: NEA/OECD Uranium 2020 Resources, Production and Demand) – Part I

Country	Cost Ranges			
	<$USD 40/kgU (tonnes)	<$USD 80/kgU (tonnes)	<$USD 130/kgU (tonnes)	<$USD 260/kgU (tonnes)
Algeria (c)				26,000
Argentina (d)		7,100	15,400	15,400
Australia (f)			1,748,100	1,849,100
Botswana* (d)			32,900	32,900
Brazil	184,300	209,700	209,700	209,700
Canada (d, f)	296,200	296,200	528,800	747,000
Central African Republic *			42,700	42,700
Chile (d)				700
China (People's Republic of)	48,700	83,600	154,300	159,000
Congo, Dem. Rep* (a, c)				1,900
Czech Republic (d)			1,400	83,900
Finland (c)			1,500	1,500
Gabon (a, c, d)			6,400	6,400
Germany (c, d)				4,000
Greece (a, c, d)				1,300
Greenland (f)				102,800
India (e)	na	na	na	249,100
Indonesia (b)		2,000	7,100	7,100
Iran, Islamic Republic of (b)			4,300	4,300
Italy (a, c, d)		6,400	6,400	6,400
Japan (a,c, d, f)			7,800	7,800
Jordan			8,000	8,000
Kazakhstan	305,800	386,600	504,100	527,700
Malawi* (d)			5,500	13,000
Mali *			6,700	6,700
Mauritania* (d)			6,600	7,000
Mexico			2,500	2,500
Mongolia (d)		44,200	80,500	80,500
Namibia* (d)			349,300	400,900
Niger (d)		12,200	294,700	389,500
Paraguay*				3,400

Table G8.2. Reasonably assured resoruces (RAR) (in situ) (as of Jan 2019, tonnes U, rounded to nearest 100 tonnes) (Source: NEA/OECD Uranium 2020 Resources, Production and Demand) – Part II

Country	Cost Ranges			
	<$USD 40/kgU (tonnes)	<$USD 80/kgU (tonnes)	<$USD 130/kgU (tonnes)	<$USD 260/kgU (tonnes)
Peru [a]		20,000	20,000	20,000
Portugal [c, d]		6,000	8,000	8,000
Romania* [a, c, d]			4,000	4,000
Russia [b, d, f]		31,000	263,500	333,300
Slovak Republic [a, b]		10,900	10,900	10,900
Slovenia [c]		2,200	2,200	2,200
Somalia* [a, c, d]				6,700
South Africa [d, f]		229,400	324,600	354,600
Spain [f]	9,800	23,000	23,000	23,000
Sweden* [c]			6,500	6,500
Tanzania* [b, d]		47,900	49,600	49,600
Turkey [b]			4,300	4,300
Ukraine [d]		53,000	85,400	138,900
United States		18,600	67,100	135,900
Uzbekistan* [d]	38,100	38,100	63,500	63,500
Viet Nam				1,200
Zambia* [d]			14,100	14,100
Zimbabwe [a, c]				1,800
Total [g]	882,900	1,528,100	4,971,400	6,176,700

* Secretariat estimate

** In situ resources do not take into account mining and milling losses.

(a) Not reported in 2019 responses; data from previous Red Book.

(b) Assessment partially made within the last five years.

(c) Assessment not made within the last five years.

(d) Recoverable resources were adjusted by the Secretariat to estimate in situ resources using recovery factors provided by countries or estimated by the Secretariat according to the expected production method years.

(e) Cost data not provided, therefore resources are reported in the <USD 260/kgU category.

(f) Updated from previous Red Book report.

(g) Totals related to cost ranges <USD 40/kgU and <USD 80/kgU are higher than reported in the tables because certain countries do not report low-cost resource estimates, mainly for reasons of confidentiality.

Table G9. Reasonably assured resources (RAR) by production method (as of Jan 2019, tonnes U, rounded to nearest 100 tonnes) (Source: NEA/OECD Uranium 2020 Resources, Production and Demand)

Production Method	Cost Ranges			
	<$USD 40/kgU (tonnes)	<$USD 80/kgU (tonnes)	<$USD 130/kgU (tonnes)	<$USD 260/kgU (tonnes)
Open-pit mining	16,423	100,054	924,249	1,106,268
Undergrund mining	317,319	402,877	1,020,976	1,417,934
In situ leaching acid	319,864	439,840	532,735	591,761
In situ leaching alkaline	19,950	27,342	64,504	30,142
Co-product/by-product	71,050	255,167	1,207,544	1,394,998
Unspecified	-	18,723	41,546	182,546
Total	744,606	1,244,003	3,791,554	4,723,649

Table G10. Reasonable assured resources (RAR) by processing method (as of Jan 2019, tonnes U, rounded to nearest 100 tonnes) (Source: NEA/OECD Uranium 2020 Resources, Production and Demand)

Processing Method	Cost Ranges			
	<$USD 40/kgU (tonnes)	<$USD 80/kgU (tonnes)	<$USD 130/kgU (tonnes)	<$USD 260/kgU (tonnes)
Conventional from Open Pit	14,965	79,811	651,897	797,583
Conventional from UnderGround mining	317,319	569,214	2,107,904	2,605,877
In situ leaching acid	319,864	439,840	532,735	591,761
Insitu leaching alkaline	19,950	27,342	30,142	30,142
In-place leaching*	-	-	516	8,863
Heap leaching ** from open pit	1,134	20,243	269,932	356,275
Heap leaching ** from undergorund mining	-	-	17,770	18,670
Unspecified	71,374	107,553	180,658	314,478
Total	744,606	1,244,003	3,791,554	4,723,649

* Also known as stope leaching or block leaching

** A subset of open-pit and underground mining, since it is used in conjunction with them

36.5 Global Inferred Resources of Global Uranium Resources

Table G11.1. Inferred resources (IR) (recoverable) (as of Jan 2019, tonnes U, rounded to nearest 100 tonnes) (Source: NEA/OECD Uranium 2020 Resources, Production and Demand) - Part I

Country	Cost Ranges			
	<$USD 40/kgU (tonnes)	<$USD 80/kgU (tonnes)	<$USD 130/kgU (tonnes)	<$USD 260/kgU (tonnes)
Argentina	2,400	12,700	27,700	28,800
Australia			508,800	764,600
Botswana*			66,800	66,800
Brazil (d)		73,500	120,900	120,900
Canada	1,900	10,900	103,300	220,800
Chad * (a, c, d, e)				2,400
Chile				900
China (People's Republic of) (d)	48,900	89,700	129,900	147,100
Congo, Dem. Rep* (a, c, d)				1,300
Czech Republic				68,300
Egypt (d)			400	1,900
Gabon (a, c)				1,000
Germany (c)				4,000
Greece (a, c)				6,000
Greenland (d)				62,600
Hungary (c, d)				13,500
India (d, e)	na	na	na	8,000
Indonesia (b, d)			3,000	3,000
Iran, Islamic Republic of (b, d)			4,200	4,200
Italy (a, c)		1,300	1,300	1,300
Jordan (d)			46,500	46,500
Kazakhstan (d)	258,400	376,400	461,700	504,400
Malawi*			1,800	4,600
Mali (d)			3,900	3,900
Mauritania*			11,500	18,500
Mexico (d)			1,800	3,200
Mongolia		26,700	82,900	82,900
Namibia*			168,900	183,500
Niger			37,700	123,900
Paraguay*				700
Peru (c, d)		19,400	19,400	19,400

Table G11.2. Inferred resources (IR) (recoverable) (as of Jan 2019, tonnes U, rounded to nearest 100 tonnes) (Source: NEA/OECD Uranium 2020 Resources, Production and Demand) – Part II

Country	Cost Ranges			
	<$USD 40/kgU (tonnes)	<$USD 80/kgU (tonnes)	<$USD 130/kgU (tonnes)	<$USD 260/kgU (tonnes)
Portugal (c)			1,000	1,000
Romania* (a, c)			3,600	3,600
Russia (b)		14,700	274,800	405,300
Senegal (d)				1,100
Slovak Republic (a, b, d)		3,900	6,700	6,700
Slovenia (c, d)		3,800	7,500	7,500
Somalia* (a, c, d)				2,600
South Africa *		61,700	84,800	189,700
Spain (d, f)		9,400	9,400	9,400
Sweden* (c, d)			4,700	4,700
Tanzania* (b)		8,500	18,500	18,500
Turkey (b, d)			8,800	9,900
Ukraine		26,700	33,800	64,800
Uzbekistan*	24,300	24,300	81,500	81,500
Viet Nam (d)				3,000
Zambia*			18,200	18,200
Total (g)	335,900	763,600	2,355,700	3,346,400

* Secretariat estimate

** In situ resources do not take into account mining and milling losses.

(a) Not reported in 2019 responses; data from previous Red Book.

(b) Assessment partially made within the last five years.

(c) Assessment not made within the last five years.

(d) Recoverable resources were adjusted by the Secretariat to estimate in situ resources using recovery factors provided by countries or estimated by the Secretariat according to the expected production method years.

(e) Cost data not provided, therefore resources are reported in the <USD 260/kgU category.

(f) Updated from previous Red Book report.

(g) Totals in the cost category of <$USD 40/kgU and <USD 80/kgU should be reagrded with some caution since some countries do not report low-cost resource estimates, mainly for confidentiality reasons, whereas other countries that never, or not recently hosted uranium mining may be underestimating mining costs.

Table G12.1. Inferred resources (IR) (in situ) (as of Jan 2019, tonnes U, rounded to nearest 100 tonnes) (Source: NEA/OECD Uranium 2020 Resources, Production and Demand) - Part I

Country	Cost Ranges			
	<$USD 40/kgU (tonnes)	<$USD 80/kgU (tonnes)	<$USD 130/kgU (tonnes)	<$USD 260/kgU (tonnes)
Argentina (d)	3,400	17,700	38,600	39,200
Australia (f)			792,300	1,085,100
Botswana* (d)			107,700	107,700
Brazil		104,900	172,600	172,600
Canada (d, f)	2,200	12,500	118,300	253,000
Chad * (a, e)				3,200
Chile (d)				1,200
China (People's Republic of)	59,200	109,000	162,000	185,000
Congo, Dem. Rep* (a, c)				1,700
Czech Republic (d)				113,500
Egypt			500	2,500
Gabon (a, c, d)				1,300
Germany (c, d)				5,300
Greece (a, c, d)				8,000
Greenland (f)				125,100
Hungary (c)				17,900
India (e)	na	na	na	10,500
Indonesia (b)			4,100	4,100
Iran, Islamic Republic of (b)			5,500	5,500
Italy (a, c, d)		1,700	1,700	1,700
Jordan			62,000	62,000
Kazakhstan	290,300	423,200	523,500	575,000
Malawi* (d)			2,300	6,000
Mali *			5,200	5,200
Mauritania* (d)			13,300	22,700
Mexico			2,500	4,300
Mongolia (d)		35,100	110,000	110,000
Namibia* (d)			211,200	229,400
Niger* (d)			46,000	157,900
Paraguay*				900

Table G12.2. Inferred resources (IR) (in situ) (as of Jan 2019, tonnes U, rounded to nearest 100 tonnes) (Source: NEA/OECD Uranium 2020 Resources, Production and Demand) – Part II

Country	Cost Ranges			
	<$USD 40/kgU (tonnes)	<$USD 80/kgU (tonnes)	<$USD 130/kgU (tonnes)	<$USD 260/kgU (tonnes)
Peru [a]		27,700	27,700	27,700
Portugal [c, d]		1,300	1,300	1,300
Romania* [a, c, d]			4,800	4,800
Russia [b, d, f]		19,600	333,400	514,200
Senegal [c]				1,500
Slovak Republic [a, b]		4,900	8,400	8,400
Slovenia [c]		5,000	10,000	10,000
Somalia* [a, c, d]				3,500
South Africa [d, f]		84,500	116,200	259,900
Spain [f]		11,300	11,300	11,300
Sweden* [c]			6,300	6,300
Tanzania* [b, d]		10,600	23,200	23,200
Turkey [b]			10,900	12,400
Ukraine [d]		30,200	38,200	73,900
Uzbekistan* [d]	30,400	30,400	107,800	107,800
Viet Nam				4,000
Zambia* [d]			20,100	20,100
Total [g]	385,500	929,600	3,098,900	4,407,800

* Secretariat estimate

** In situ resources do not take into account mining and milling losses.

(a) Not reported in 2019 responses; data from previous Red Book.

(b) Assessment partially made within the last five years.

(c) Assessment not made within the last five years.

(d) Recoverable resources were adjusted by the Secretariat to estimate in situ resources using recovery factors provided by countries or estimated by the Secretariat according to the expected production method years.

(e) Cost data not provided, therefore resources are reported in the <USD 260/kgU category.

(f) Updated from previous Red Book report.

(g) Totals in the cost category of <$USD 40/kgU and <USD 80/kgU should be reagrded with some caution since some countries do not report low-cost resource estimates, mainly for confidentiality reasons, whereas other countries that never, or not recently hosted uranium mining may be underestimating mining costs.

Table G13. Inferred resources (IR) by production method (as of Jan 2019, tonnes U, rounded to nearest 100 tonnes) (Source: NEA/OECD Uranium 2020 Resources, Production and Demand)

Production Method	Cost Ranges			
	<$USD 40/kgU (tonnes)	<$USD 80/kgU (tonnes)	<$USD 130/kgU (tonnes)	<$USD 260/kgU (tonnes)
Open-pit mining	2,430	59,045	526,256	688,332
Undergrund mining	1,925	65,124	546,794	901,061
In situ leaching acid	324,791	495,203	614,750	729,251
In situ leaching alkaline	6,790	8,470	9,233	9,233
Co-product/by-product		94,580	583,181	815,616
Unspecified		41,130	75,890	203,185
Total	335,936	763,552	2,356,104	3,346,678

Table G14. Inferred resources (IR) by processing method (as of Jan 2019, tonnes U, rounded to nearest 100 tonnes) (Source: NEA/OECD Uranium 2020 Resources, Production and Demand)

Processing Method	Cost Ranges			
	<$USD 40/kgU (tonnes)	<$USD 80/kgU (tonnes)	<$USD 130/kgU (tonnes)	<$USD 260/kgU (tonnes)
Conventional from Open Pit	2,430	41,332	338,867	559,066
Conventional from underground mining	1,925	126,780	1,040,918	1,512,741
In situ leaching acid	324,791	495,203	614,751	729,252
Insitu leaching alkaline	6,790	8,470	9,233	9,233
In-place leaching*	-	-	2,068	13,594
Heap leaching ** from open pit	-	19,417	134,667	139,116
Heap leaching ** from undergorund mining	-	-	6,675	11,714
Unspecified	-	72,350	208,925	371,962
Total	335,936	763,552	2,356,104	3,346,678

* Also known as srope leaching or block leaching
** A subset of open-pit and underground mining, since it is used in conjunction with them

Table G15. Inferred resources (IR) by deposit type (as of Jan 2019, tonnes U, rounded to nearest 100 tonnes)
(Source: NEA/OECD Uranium 2020 Resources, Production and Demand)

Deposit type	Cost Ranges			
	<$USD 40/kgU (tonnes)	<$USD 80/kgU (tonnes)	<$USD 130/kgU (tonnes)	<$USD 260/kgU (tonnes)
Proterozoic Unconformity	1,925	10,945	138,626	230,349
Sandstone	333,531	533,157	792,213	1,093,036
Polymetallic Fe-oxide breccia complex	-	-	428,506	532,127
Paleo-quartz-pebble conglomerate [(a)]	-	72,456	85,161	130,091
Granite-related	-	9,421	61,308	77,695
Metamorphite	-	720	2,988	9,294
Intrusive	-	-	122,368	245,605
Volcanic-related	480	45,411	138,489	153,300
Metasomatite	-	33,949	376,764	506,197
Surficial deposits	-	-	67,288	115,975
Carbonate	-	-	3,863	3,862
Collapse breccia	-	19,008	19,008	19,008
Phosphate	-	30,010	37,137	47,137
Lignite-coal	-	-	2,010	72,785
Black Shale	-	-	32,900	32,900
Unspecifed		8,475	47,475	77,317
Total	335,936	763,552	2,356,104	3,346,678

(a) In South Africa, Paleo-quartz-pebble conglomerate resources include tailings resources.

Table G16. Inferred Resources (IR) by production method (as of Jan 2017, tonnes U, rounded to nearest 100 tonnes)
(Source: NEA/OECD Uranium 2018 Resources, Production and Demand)

Production Method	Cost Ranges			
	<$USD 40/kgU (tonnes)	<$USD 80/kgU (tonnes)	<$USD 130/kgU (tonnes)	<$USD 260/kgU (tonnes)
Open-pit mining	2 430	46 665	431 091	567 678
Undergrund mining	16 785	110 100	567 310	925 081
In situ leaching acid	320 427	498 265	630 252	727 534
In situ leaching alkaline	4 760	8 470	9 240	9 240
Co-product/by-product		94 580	526 475	728 360
Unspecified		41 652	112 833	215 228
Total	344 402	799 732	2 277 201	3 173 121

36.6 Additional, Prognosticated, Undiscovered and Unconventional Resources

Table G17. Additional identified resources (a) (rounded to nearest 100 tU)
(Source: NEA/OECD Uranium 2018 Resources, Production and Demand)

Country	Deposit/project	RAR and Inferred Resources
Bulgaria	ISL mineable deposits	7 900
Cameroon	Poli (Kitongo)	11 130
	Lolodorf	11 000
Columbia	Berlin	8 200
Egypt	Gabal Gutter	2 000
	Abu Zenima	100
Guinea	Firawa	7 500
Guyana	Kurupung	6 200
Mauritana [(b)]	Tiris	6 800
Peru	Kihitian	11 200
	Triunfador	1 200

Total 73 230

(a) Amount not reported in RAR and IR national totals

(b) Additional resource as September 2017, not the resource for the entire deposit

Source: NEA/IAEA estimate based on publicly available data.

Table G18. Reported undiscovered resources (in 1000 tU as of Jan 2017)
(Source: NEA/OECD Uranium 2018 Resources, Production and Demand)

Country	Prognosticated resources			Speculative resources			Total SR
	Cost ranges			Cost ranges			
	<$USD 80/kgU (tonnes)	<$USD 130/kgU (tonnes)	<$USD 260/kgU (tonnes)	<$USD 130/kgU (tonnes)	<$USD 260/kgU (tonnes)	Cost range unassigned	
Argentina (d)	NA	13,8	13,8	NA	79,5	NA	79,5
Brazil (a)	300,0	300,0	300,0	NA	NA	500,0	500,0
Bolivia (a)	0,0	0,0	0,0	0,0	0,0	1,7	1,7
Bulgaria (b)	NA	NA	25,0	NA	NA	NA	NA
Canada (d)	50,0	150,0	150,0	700,0	700,0	0,0	700,0
Chile (a)	0,0	0,0	2,3	0,0	0,0	2,4	2,4
China (People's Republic of) (b)	3,6	3,6	3,6	4,1	4,1	NA	4,1
Columbia (b)	NA	11,0	11,0	217,0	217,0	NA	217,0
Czech Republic	0,0	0,2	223,0	0,0	0,0	17,0	17,0
Germany (a)	NA	NA	NA	NA	NA	74,0	74,0
Greece (b)	6,0	6,0	6,0	NA	NA	NA	NA
Hungary (a)	0,0	0,0	13,4	0,0	0,0	0,0	0,0
India	NA	NA	114,5	NA	NA	50,9	50,9
Indonesia	0,0	0,0	30,2	0,0	0,0	0,0	0,0
Iran, Islamic Republic of (c)	0,0	12,4	12,4	0,0	0,0	33,2	33,2
Italy (b)	0,0	0,0	0,0	10,0	10,0	NA	10,0
Jordan (a)	0,0	0,0	0,0	0,0	50,0	NA	50,0
Kazakhstan	194,1	229,1	230,6	266,9	300,0	NA	300,0
Mauritania*	0,0	0,0	0,0	NA	NA	19,6	19,6
Mexico (b)	NA	3,0	3,0	NA	NA	10,0	10,0
Mongolia (a)	21,0	21,0	21,0	1 390,0	1 390,0	NA	1 390,0
Namibia*	0,0	0,0	57,0	0,0	0,0	110,7	110,7
Niger (b)	0,0	13,6	13,6	0,0	51,3	0,0	51,3
Peru (a)	6,6	20,0	20,0	19,7	19,7	0,0	19,7
Poland (b)	0,0	0,0	0,0	0,0	0,0	20,0	20,0
Portugal (b)	1,0	1,5	1,5	NA	NA	NA	NA
Romania* (b)	NA	3,0	3,0	3,0	3,0	NA	3,0
Russia	115,1	115,1	143,9	390,1	591,1	NA	591,1
Senegal	0,0	0,0	0,0	0,0	0,0	1,5	1,5
Slovak Republic (b)	0,0	3,7	10,9	0,0	0,0	0,0	0,0
Slovenia (b)	0,0	1,1	1,1	0,0	0,0	0,0	0,0
South Africa (b)	0,0	74,0	159,0	243,0	411,0	280,0	691,0
Ukraine (a)	0,0	8,4	22,5	0,0	120,0	255,0	375,0
United States	NA	NA	NA	NA	NA	NA	NA
Uzbekistan*	24,8	24,8	24,8	0,0	0,0	0,0	0,0
Venezuela (b)	NA	NA	NA	0,0	0,0	163,0	163,0
Viet Nam	NA	NA	81,2	NA	NA	321,6	321,6
Zimbabwe (b)	0,0	0,0	0,0	25,0	25,0	NA	25,0
Total (g)	722,2	1 015,3	1 698,3	3 268,8	3 971,7	1 860,6	5 832,3

NA = Data not available
* Secretariat estimate
** In situ resources do not take into account mining and milling losses.
(a) Not reported in 2017 responses; but data not updated within the last 5 years
(b) Not reported in 2017 responses; data from previous Red Book.
(c) Reported in 2017 responses, but only partially assessed within the last five years

Table G19. Unconventional uranium resource (1000 tU) reported in 1965-2003 Red Books, with updated data* from 2011-2019 in parentheses (Source: NEA/OECD Uranium 2020 Resources, Production and Demand)

Country	Phosphate rocks	Non-ferrous ores	Monazite	Carbonatite	Black schist/shales, lignite	Other
Algeria	(28[a])					
Australia					(0.15 [a])	
Brazil	28-70	2		13		
Canada					(47.6 [a])	
Central African Republic	(36.4 [a])					
Chile	0.6 - 2.8 (0.4 [b])	4.5-5.2 (0.8[b])				
China				(13 [a])	(30 [a])	
Columbia	20-60					
Czech Republic					(0.11 [a])	
Egypt**	35-100 (210 [a])					
Finland	1[a]			2.5 (2.5[a])	3.0-9.0 (24)	
France					(0.36 [a])	
Germany					(204 [a])	
Greece	0.5				(4 [a])	
India	1.7-2.5	6.6-22.9			4	
Indonesia			(27)			
Iraq	(546[a])					
Iran, Islamic Republic of						(53)
Isreal	(33 [a])					
Jordan	100-123.4 (165.5)					
Kazakhstan	58***				(61 [a])	
Korea					(36.2 [a])	
Kyrgyzstan				(0.47 [a])	(0.32 [a])	
Mexico	100-151 (240[a])	1		(0.14 [a])		
Morocco	6,526				(8,500 [a])	
New Zealand	(12.2 [a])					
Peru	20 (41.6[a])	0.14-1.41				
Poland					(151.6 [a])	
Russia					(42.9 [a])	
Saudi Arabia	(187.1[a])					
South Africa	(180 b)				(81.2 [a])	
Sweden	(42.3[a])				300 (1,054)	
Syrian Arab Republic	60-80					
Tanzania	(0.35 [a])					
Thailand	0.5-1.5					(132)
Tunisia	(50 [a])					
Turkmenistan					(50 [a])	
Ukraine					(0.59 [a])	
United States	14-33 (576.5a)	1.8		(0.26 [a])	(19 014 [a])	
Venezuela	42					
Viet Nam	(3[a])				0.5	

* Updated data from publicly availbale sources and information provided by countires in the Red Book questionaire.

** Includes an unknown quantity of uranium contained in monazite.

*** Production of estimated 6 000 tU between 1959 and 1992 has been deducted from reported total.

(a) Secretariat estimate based on UDEPO which may include mined resources

(b) Not reported in 2019 questionaire reponses; data from previous Red Books.

(c) Including all measured, indicated and inferred resources at the Talvivaara black schist-hosted Ni-Zn-Cu-Co deposit

Nation state stocks of Uranium

Table G20. Uranium stocks in countries responding to the 2017 Red Book questionnaire
(Source: NEA/OECD Uranium 2018 Resources, Production and Demand)

Country	Natural Uranium (tonnes natural U-equivalent as of 1 Jan 2017)	Enriched Uranium (tonnes natural U-equivalent as of 1 Jan 2017)
Argentina[(a)]	N/A	N/A
Australia[(b)]	N/A	N/A
Belgium	N/A	N/A
Brazil	0	0
Bulgaria[(c)]	0	81
Canada[(b)]	N/A	0
China (People's Rep. of)	N/A	N/A
Czech Republic[(d)]	<100	0
Finland[(e)]	N/A	N/A
France[(f)]	N/A	N/A
Germany	N/A	N/A
Hungary[(g)]	4	0
India	N/A	N/A
Iran, Islamic Rep. Of	N/A	N/A
Japan	N/A	N/A
Kazakhstan	N/A	N/A
Korea[(c, h)]	2 000	6 000
Mexico	N/A	N/A
Netherlands	N/A	N/A
Niger	N/A	N/A
Portugal[(c)]	168	0
Russia	N/A	N/A
Slovak Republic[(c)]	0	228
South Africa	N/A	N/A
Spain[(i)]	N/A	608
Switzerland[(j)]	662	1 487
Turkey	2	0
Ukraine	N/A	N/A
United Kingdom	N/A	N/A
United States[(k)]	>41 796	>26 062
World Total	>44 732	>34 466

(a) Commercial data are not available. A minimum of two years' inventory is required from the plant's operator.

(b) Government stocks are zero in all categories. Commercial data are not available.

(c) Data from the 2016 edition of the Red Book.

(d) CEZ maintains strategic and working inventories in various forms, including fuel assemblies, amounting to about two years of requirements. Data reported for uranium stocks in the table include only producer stocks.

(e) The nuclear power utilities maintain reserves of fuel assemblies sufficient for 7-12 months of use.

(f) A minimum strategic inventory, amounting to a few years of forward fuel requirements, is maintained by EDF.

(g) Inventory from mine water treatment only.

(h) A strategic inventory is maintained along with about one year of forward consumption in pipeline inventory.

(i) Regulations require a strategic inventory of at least 608 tU to be maintained jointly by nuclear utilities.

(j) Utilities also hold 68 t (U-equivalent) of reprocessed uranium.

(k) Natural uranium hexafluoride (UF6) and enriched uranium in fuel assemblies held in storage prior to loading in the reactor is not included. Government stocks also include 30 000 t (U-equivalent) of depleted uranium. Data from producers (5 889 tU) is also not included.

37 APPENDIX H - HYDROELECTRICITY ENERGY

Table H1. Global hydroelectricity energy consumption (Mtoe) (BP Statistical Review of World Energy 2019)

Consumption*

Million tonnes oil equivalent	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Growth rate per annum 2018	Growth rate per annum 2007-17	Share 2018
Canada	85.4	83.4	79.5	85.0	86.0	88.7	86.6	86.5	87.6	89.7	**87.6**	-2.3%	0.8%	9.2%
Mexico	8.9	6.0	8.4	8.2	7.2	6.3	8.8	7.0	6.9	7.2	**7.3**	1.7%	1.5%	0.8%
US	56.8	61.4	58.2	71.5	62.0	60.3	57.9	55.8	59.7	67.2	**65.3**	-2.7%	2.0%	6.9%
Total North America	151.1	150.9	146.1	164.7	155.3	155.3	153.2	149.2	154.2	164.1	**160.3**	-2.3%	1.3%	16.9%
Argentina	8.4	9.2	9.2	9.0	8.3	9.2	9.2	9.5	8.7	9.4	**9.4**	0.3%	1.0%	1.0%
Brazil	83.6	88.5	91.3	96.9	94.0	88.5	84.5	81.4	86.2	83.9	**87.7**	4.5%	-0.1%	9.2%
Chile	5.5	5.7	4.9	4.6	4.6	4.5	5.2	5.3	4.5	4.8	**5.2**	8.5%	-0.5%	0.6%
Colombia	10.4	9.2	9.2	11.0	10.8	10.0	10.1	10.1	10.6	13.0	**12.8**	-1.2%	2.6%	1.4%
Ecuador	2.6	2.1	2.0	2.5	2.8	2.5	2.6	3.0	3.6	4.5	**4.7**	3.0%	8.3%	0.5%
Peru	4.3	4.5	4.5	4.9	5.0	5.1	5.0	5.4	5.4	6.6	**7.0**	5.8%	4.0%	0.7%
Trinidad & Tobago	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Venezuela	19.6	19.4	17.3	18.8	18.5	18.9	17.8	16.6	14.0	18.0	**16.3**	-9.3%	-0.4%	1.7%
Other S. & Cent. America	19.5	19.2	20.2	20.7	21.3	22.0	20.8	20.7	22.5	22.8	**22.3**	-2.0%	1.6%	2.4%
Total S. & Cent. America	153.9	157.8	158.6	168.4	165.3	160.6	155.3	151.9	155.3	163.0	**165.5**	1.5%	0.6%	17.4%
Austria	8.7	9.3	8.7	7.7	9.9	9.5	9.3	8.4	9.0	8.7	**8.5**	-2.2%	0.3%	0.9%
Belgium	0.1	0.1	0.1	†	0.1	0.1	0.1	0.1	0.1	0.1	**0.1**	5.4%	-3.6%	◆
Czech Republic	0.5	0.5	0.6	0.5	0.5	0.6	0.4	0.4	0.5	0.4	**0.4**	-13.0%	-1.1%	◆
Finland	3.9	2.9	2.9	2.8	3.8	2.9	3.0	3.8	3.6	3.3	**3.0**	-10.0%	0.4%	0.3%
France	14.4	12.9	14.2	10.1	13.3	16.0	14.2	12.3	13.6	11.1	**14.5**	30.5%	-1.6%	1.5%
Germany	4.6	4.3	4.7	4.0	5.0	5.2	4.4	4.3	4.6	4.6	**3.8**	-16.1%	-0.5%	0.4%
Greece	0.7	1.2	1.7	0.9	1.0	1.4	1.0	1.4	1.3	0.9	**1.3**	44.4%	4.3%	0.1%
Hungary	†	0.1	†	0.1	†	†	0.1	0.1	0.1	†	**0.1**	0.5%	0.5%	◆
Italy	9.4	11.1	11.6	10.4	9.5	11.9	13.2	10.0	9.2	7.8	**10.4**	33.4%	0.5%	1.1%
Netherlands	†	†	†	†	†	†	†	†	†	†	**†**	19.1%	-5.5%	◆
Norway	31.5	28.3	26.4	27.2	32.1	29.0	30.6	31.1	32.2	32.1	**31.3**	-2.4%	0.6%	3.3%
Poland	0.5	0.5	0.7	0.5	0.5	0.6	0.5	0.4	0.5	0.6	**0.4**	-23.0%	0.9%	◆
Portugal	1.5	1.9	3.7	2.6	1.3	3.1	3.5	2.0	3.6	1.3	**2.8**	109.4%	-5.2%	0.3%
Romania	3.9	3.5	4.5	3.3	2.7	3.3	4.2	3.8	4.1	3.3	**4.0**	21.2%	-1.0%	0.4%
Spain	5.3	6.0	9.5	6.9	4.6	8.3	8.9	6.4	8.2	4.2	**8.0**	87.4%	-3.6%	0.8%
Sweden	15.6	14.8	15.0	15.2	17.9	13.9	14.4	17.0	14.0	14.7	**14.0**	-4.7%	-0.2%	1.5%
Switzerland	8.2	8.1	8.2	7.3	8.7	8.7	8.6	8.7	7.8	7.7	**7.9**	2.1%	-0.3%	0.8%
Turkey	7.5	8.1	11.7	11.8	13.1	13.4	9.2	15.2	15.2	13.2	**13.5**	2.2%	5.0%	1.4%
Ukraine	2.6	2.7	3.0	2.5	2.4	3.1	1.9	1.2	1.7	2.0	**2.2**	13.6%	-1.5%	0.2%
United Kingdom	1.2	1.2	0.8	1.3	1.2	1.1	1.3	1.4	1.3	1.3	**1.2**	-7.8%	1.6%	0.1%
Other Europe	14.1	15.9	19.0	13.6	14.0	17.3	16.7	16.1	16.8	14.9	**17.9**	19.9%	2.0%	1.9%
Total Europe	134.2	133.4	147.0	128.9	141.6	149.7	145.7	143.9	147.4	132.3	**145.3**	9.8%	0.4%	15.3%
Azerbaijan	0.5	0.5	0.8	0.6	0.4	0.3	0.3	0.4	0.4	0.4	**0.4**	1.2%	-3.0%	◆
Belarus	†	†	†	†	†	†	†	†	†	0.1	**0.1**	12.9%	27.7%	◆
Kazakhstan	1.7	1.6	1.8	1.8	1.7	1.7	1.9	2.1	2.6	2.5	**2.3**	-7.6%	3.2%	0.2%
Russian Federation	37.3	39.4	37.7	36.9	37.0	41.0	39.2	38.0	41.8	41.9	**43.0**	2.6%	0.5%	4.5%
Turkmenistan	†	†	†	–	–	–	–	–	–	–	**–**	–	-100.0%	–
Uzbekistan	1.0	1.5	1.9	1.3	1.4	1.4	1.4	1.4	1.2	1.7	**1.6**	-10.3%	1.7%	0.2%
Other CIS	6.5	6.4	6.9	7.6	7.6	7.4	7.2	6.9	6.9	7.7	**8.0**	4.0%	0.2%	0.8%
Total CIS	47.0	49.4	49.1	48.1	48.2	51.9	50.0	48.8	53.1	54.3	**55.4**	2.0%	0.5%	5.8%
Iran	1.7	1.5	2.3	2.4	2.8	3.3	3.3	3.0	3.5	3.9	**2.4**	-37.5%	-0.4%	0.3%
Iraq	0.7	0.6	0.8	0.8	1.0	1.0	0.6	0.6	0.8	0.5	**0.7**	42.8%	-7.1%	0.1%
Israel	†	†	†	†	†	†	†	†	†	†	**†**	–	5.8%	◆
Kuwait	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Oman	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Qatar	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Saudi Arabia	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
United Arab Emirates	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Other Middle East	0.7	0.6	0.8	1.0	1.0	0.9	0.6	0.2	0.3	0.3	**0.3**	-4.9%	-10.6%	◆
Total Middle East	3.1	2.7	3.9	4.1	4.8	5.3	4.5	3.8	4.6	4.7	**3.4**	-26.9%	-2.5%	0.4%
Algeria	0.1	0.1	†	0.1	0.1	†	†	†	†	†	**†**	108.9%	-13.0%	◆
Egypt	3.4	3.1	2.9	2.9	2.9	3.0	3.1	3.1	3.1	3.0	**3.1**	0.6%	-0.6%	0.3%
Morocco	0.2	0.6	0.8	0.5	0.4	0.6	0.4	0.4	0.3	0.3	**0.4**	42.9%	2.8%	◆
South Africa	0.3	0.3	0.3	0.7	0.2	0.2	0.4	0.2	0.2	0.2	**0.2**	5.0%	-11.2%	◆
Other Africa	18.0	18.5	20.3	20.8	21.5	22.7	24.1	23.5	22.9	24.7	**26.4**	6.9%	3.5%	2.8%
Total Africa	22.0	22.6	24.3	25.0	25.1	26.6	28.0	27.2	26.4	28.2	**30.1**	6.6%	2.7%	3.2%
Australia	2.7	2.9	3.1	4.4	3.9	4.3	3.3	3.2	4.0	3.1	**3.9**	27.6%	0.4%	0.4%
Bangladesh	0.2	0.1	0.2	0.2	0.2	0.2	0.1	0.2	0.2	0.2	**0.2**	-14.0%	3.2%	◆
China	144.1	139.3	161.0	155.7	195.2	205.8	237.8	252.2	261.0	263.6	**272.1**	3.2%	9.2%	28.7%
China Hong Kong SAR	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
India	26.1	24.1	24.6	29.8	26.2	29.9	31.5	30.2	29.0	30.7	**31.6**	2.9%	1.0%	3.3%
Indonesia	2.6	2.6	3.9	2.8	2.9	3.8	3.4	3.1	4.2	4.2	**3.7**	-11.9%	5.1%	0.4%
Japan	16.8	15.6	19.7	18.3	17.2	17.7	18.1	19.0	18.1	17.9	**18.3**	2.2%	0.6%	1.9%
Malaysia	1.8	1.6	1.4	1.8	2.1	2.6	3.0	3.5	4.6	5.2	**5.5**	4.7%	14.5%	0.6%
New Zealand	5.1	5.5	5.6	5.7	5.2	5.2	5.5	5.6	5.9	5.7	**6.0**	4.5%	0.6%	0.6%
Pakistan	6.1	6.4	6.7	6.9	6.7	7.0	7.3	7.4	7.8	6.9	**8.1**	18.1%	-0.4%	0.9%
Philippines	2.2	2.2	1.8	2.2	2.3	2.3	2.1	2.0	1.8	2.2	**2.1**	-2.3%	1.2%	0.2%
Singapore	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
South Korea	0.7	0.6	0.8	1.0	0.9	1.0	0.6	0.5	0.6	0.6	**0.7**	4.0%	-2.5%	0.1%
Sri Lanka	0.9	0.9	1.3	1.0	0.7	1.6	1.0	1.4	1.0	0.9	**1.4**	58.6%	0.1%	0.2%
Taiwan	1.0	0.8	0.9	0.9	1.3	1.2	1.0	1.0	1.5	1.2	**1.0**	-18.0%	2.1%	0.1%
Thailand	1.6	1.6	1.2	1.8	1.9	1.2	1.2	0.9	0.8	1.1	**1.7**	62.1%	-5.2%	0.2%
Vietnam	5.9	6.8	6.2	9.3	11.9	13.0	13.8	12.9	14.5	16.0	**18.3**	13.9%	12.2%	1.9%
Other Asia Pacific	7.8	7.7	9.3	10.6	10.8	12.1	12.0	11.3	13.1	13.6	**14.2**	4.7%	6.3%	1.5%
Total Asia Pacific	225.5	218.5	247.7	252.5	289.4	308.9	341.9	354.1	368.1	373.2	**388.9**	4.2%	6.8%	41.0%
Total World	**736.8**	**735.4**	**776.8**	**791.8**	**829.7**	**858.3**	**878.7**	**878.9**	**909.1**	**919.9**	**948.8**	**3.1%**	**2.8%**	**100.0%**
of which: OECD	301.1	298.3	306.8	313.6	315.1	319.7	314.8	311.1	317.8	314.6	**321.3**	2.1%	0.8%	33.9%
Non-OECD	435.7	437.1	470.0	478.2	514.6	538.6	563.9	567.8	591.3	605.3	**627.5**	3.7%	4.0%	66.1%
European Union	75.2	75.9	85.2	70.8	76.1	84.0	84.8	76.9	78.8	67.4	**78.0**	15.7%	-0.5%	8.2%

*Based on gross primary hydroelectric generation and not accounting for cross-border electricity supply. Converted on the basis of thermal equivalence assuming 38% conversion efficiency in a thermal power station.
†Less than 0.05.
◆Less than 0.05%.
Hydroelectricity data expressed in terawatt-hours is available at *bp.com/statisticalreview*.

38 APPENDIX I - RENEWABLE ENERGY & BIOFUELS

Table I1. Global renewable energy consumption (Mtoe) (Source: BP Statistical Review of World Energy 2019)

Renewables consumption*

												Growth rate per annum		Share
Million tonnes oil equivalent	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	**2018**	2018	2007-17	2018
Canada	2.7	3.5	4.3	4.7	5.2	6.9	7.6	8.5	9.5	9.5	**10.3**	7.7%	13.4%	1.8%
Mexico	1.8	1.8	2.0	2.0	2.4	2.6	3.1	3.7	4.1	4.3	**4.8**	11.6%	8.4%	0.9%
US	29.7	33.9	39.3	45.7	51.7	60.2	67.2	71.5	83.1	94.5	**103.8**	9.8%	14.3%	18.5%
Total North America	34.2	39.3	45.6	52.5	59.3	69.8	77.9	83.6	96.7	108.4	**118.8**	9.6%	13.9%	21.2%
Argentina	0.4	0.4	0.5	0.5	0.6	0.7	0.7	0.7	0.6	0.7	**0.9**	26.8%	6.3%	0.2%
Brazil	4.7	5.4	7.6	7.9	9.1	10.6	13.3	16.0	19.1	21.4	**23.6**	10.6%	17.6%	4.2%
Chile	0.8	0.7	0.8	1.0	1.4	1.6	1.5	2.0	2.5	3.3	**3.5**	7.6%	18.2%	0.6%
Colombia	0.1	0.2	0.3	0.3	0.3	0.3	0.4	0.4	0.5	0.5	**0.5**	7.5%	13.6%	0.1%
Ecuador	†	†	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	**0.1**	0.8%	9.4%	◆
Peru	0.1	0.1	0.2	0.2	0.2	0.3	0.4	0.4	0.4	0.4	**0.7**	50.3%	16.6%	0.1%
Trinidad & Tobago	†	†	†	†	†	†	†	†	†	†	**†**	–	-15.7%	◆
Venezuela	–	–	†	†	†	†	†	†	†	†	**†**	–	–	◆
Other S. & Cent. America	1.6	1.8	2.0	2.1	2.6	2.9	3.4	4.3	4.9	5.2	**6.1**	17.0%	13.9%	1.1%
Total S. & Cent. America	7.8	8.7	11.3	12.0	14.3	16.4	19.7	23.9	28.2	31.5	**35.4**	12.2%	16.4%	6.3%
Austria	1.4	1.4	1.5	1.5	1.7	1.9	2.0	2.3	2.5	2.8	**2.8**	-1.9%	7.4%	0.5%
Belgium	0.9	1.2	1.4	1.9	2.3	2.6	2.7	3.2	3.2	3.5	**3.8**	8.4%	17.5%	0.7%
Czech Republic	0.4	0.5	0.7	1.2	1.3	1.5	1.6	1.7	1.7	1.8	**1.7**	-0.9%	19.4%	0.3%
Finland	2.4	2.0	2.6	2.6	2.6	2.9	2.9	3.1	3.3	3.8	**4.3**	13.2%	5.1%	0.8%
France	2.3	2.9	3.5	4.4	5.5	5.9	6.6	7.9	8.4	9.4	**10.6**	13.0%	17.4%	1.9%
Germany	16.5	17.2	19.1	24.1	27.4	29.3	32.3	38.4	38.3	44.4	**47.3**	6.6%	11.3%	8.4%
Greece	0.6	0.6	0.7	0.9	1.3	1.8	1.7	2.0	2.1	2.2	**2.4**	5.6%	17.3%	0.4%
Hungary	0.5	0.6	0.6	0.6	0.6	0.6	0.6	0.7	0.7	0.7	**0.8**	9.9%	6.9%	0.1%
Italy	3.7	4.6	5.8	8.4	11.4	13.4	14.1	14.3	14.8	15.3	**14.9**	-2.5%	16.3%	2.7%
Netherlands	2.1	2.4	2.5	2.8	2.8	2.7	2.6	3.1	3.3	3.9	**4.2**	7.2%	8.8%	0.8%
Norway	0.3	0.3	0.3	0.4	0.4	0.5	0.6	0.6	0.5	0.7	**0.9**	32.7%	9.2%	0.2%
Poland	1.0	1.4	1.8	2.4	3.4	3.3	4.0	4.7	4.7	4.9	**4.4**	-9.7%	21.5%	0.8%
Portugal	1.8	2.3	2.8	2.8	3.1	3.6	3.6	3.6	3.7	3.8	**3.9**	2.6%	10.5%	0.7%
Romania	†	†	0.1	0.4	0.6	1.2	1.5	2.2	2.0	2.2	**2.0**	-11.8%	74.2%	0.3%
Spain	8.8	10.7	12.3	12.6	15.0	16.8	16.1	15.6	15.4	15.7	**16.0**	1.7%	8.4%	2.9%
Sweden	2.8	3.2	3.6	4.0	4.4	4.8	5.0	6.1	6.1	6.8	**6.6**	-2.9%	10.3%	1.2%
Switzerland	0.3	0.3	0.3	0.4	0.4	0.5	0.6	0.6	0.7	0.8	**0.9**	11.2%	11.6%	0.2%
Turkey	0.3	0.5	0.9	1.3	1.7	2.2	2.7	3.7	5.2	6.6	**8.5**	29.8%	47.3%	1.5%
Ukraine	0.1	†	0.1	0.1	0.2	0.3	0.4	0.4	0.4	0.4	**0.6**	38.8%	19.3%	0.1%
United Kingdom	3.8	4.5	5.1	6.7	8.1	11.0	13.3	17.4	17.6	21.1	**23.9**	13.1%	20.4%	4.3%
Other Europe	4.2	4.5	5.4	6.5	7.2	8.0	8.9	9.7	9.8	11.4	**11.7**	2.8%	11.3%	2.1%
Total Europe	54.1	61.2	71.0	85.9	101.5	114.7	123.8	141.5	144.5	162.3	**172.2**	6.1%	13.1%	30.7%
Azerbaijan	–	†	†	–	–	†	†	†	†	†	**†**	40.2%	–	◆
Belarus	†	†	†	†	†	†	†	†	†	0.1	**0.1**	23.8%	34.6%	◆
Kazakhstan	–	–	–	†	†	†	†	†	0.1	0.1	**0.1**	56.8%	–	◆
Russian Federation	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.3	**0.3**	10.5%	8.8%	0.1%
Turkmenistan	–	–	†	†	†	†	†	†	†	†	**†**	–	–	◆
Uzbekistan	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Other CIS	†	†	†	†	†	†	†	†	†	†	**†**	11.2%	30.1%	◆
Total CIS	0.1	0.1	0.1	0.2	0.1	0.2	0.2	0.3	0.4	0.5	**0.6**	24.0%	14.9%	0.1%
Iran	†	0.1	†	0.1	0.1	0.1	0.1	0.1	0.1	0.1	**0.1**	28.2%	8.8%	◆
Iraq	–	–	–	–	–	†	†	†	†	†	**†**	–	–	◆
Israel	†	†	†	0.1	0.1	0.1	0.2	0.3	0.4	0.4	**0.5**	10.9%	68.2%	0.1%
Kuwait	–	–	–	–	–	†	†	†	†	†	**†**	–	–	◆
Oman	–	–	–	–	–	†	†	†	†	†	**†**	57.5%	–	◆
Qatar	–	–	–	†	†	†	†	†	†	†	**†**	–	–	◆
Saudi Arabia	†	†	†	†	†	†	†	†	†	†	**†**	9.2%	–	◆
United Arab Emirates	–	†	†	†	†	†	0.1	0.1	0.1	0.1	**0.2**	76.9%	–	◆
Other Middle East	†	†	†	†	†	†	†	0.2	0.4	0.5	**0.8**	48.5%	67.3%	0.1%
Total Middle East	0.1	0.1	0.1	0.2	0.2	0.3	0.4	0.7	1.0	1.3	**1.7**	34.2%	42.1%	0.3%
Algeria	–	–	†	†	†	†	†	†	0.1	0.1	**0.1**	17.2%	–	◆
Egypt	0.2	0.2	0.3	0.4	0.4	0.4	0.3	0.4	0.6	0.6	**0.8**	28.1%	15.1%	0.1%
Morocco	0.1	0.1	0.1	0.2	0.2	0.3	0.4	0.6	0.8	0.8	**1.1**	38.9%	28.6%	0.2%
South Africa	0.1	0.1	0.1	0.1	0.1	0.2	0.6	1.4	1.8	2.4	**2.8**	16.3%	36.8%	0.5%
Other Africa	0.7	0.7	0.8	0.9	1.0	1.2	1.5	2.0	2.1	2.2	**2.4**	11.0%	13.2%	0.4%
Total Africa	1.0	1.2	1.4	1.6	1.7	2.0	2.8	4.4	5.3	6.1	**7.2**	18.5%	20.4%	1.3%
Australia	1.7	1.7	1.9	2.5	3.0	3.7	4.1	4.9	5.5	5.8	**7.2**	24.1%	13.5%	1.3%
Bangladesh	†	†	†	†	†	†	†	†	0.1	0.1	**0.1**	12.3%	38.6%	◆
China	6.4	11.0	15.9	22.8	29.4	42.3	51.1	64.1	81.7	111.4	**143.5**	28.8%	41.4%	25.6%
China Hong Kong SAR	†	†	†	†	†	†	†	†	†	†	**†**	-0.1%	61.2%	◆
India	5.4	6.3	7.7	9.5	11.2	12.7	14.3	14.7	18.1	21.7	**27.5**	26.9%	17.5%	4.9%
Indonesia	1.9	2.1	2.1	2.2	2.2	2.2	2.3	2.4	2.6	3.0	**3.3**	10.2%	6.6%	0.6%
Japan	6.1	6.1	6.7	7.0	7.7	9.3	11.8	15.4	18.8	22.4	**25.4**	13.5%	13.7%	4.5%
Malaysia	†	0.3	0.3	0.3	0.4	0.3	0.3	0.3	0.3	0.3	**0.3**	10.9%	224.8%	0.1%
New Zealand	1.3	1.6	1.8	2.0	2.0	2.0	2.3	2.4	2.4	2.4	**2.4**	-1.7%	7.8%	0.4%
Pakistan	0.3	0.2	0.2	0.3	0.3	0.4	0.5	0.5	0.7	0.9	**1.2**	41.9%	13.4%	0.2%
Philippines	2.4	2.4	2.3	2.3	2.4	2.2	2.4	2.8	3.1	3.1	**3.2**	2.7%	2.8%	0.6%
Singapore	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	**0.3**	11.8%	8.1%	◆
South Korea	0.3	0.4	0.5	0.6	0.9	1.2	2.1	2.7	3.1	4.0	**5.0**	24.8%	37.0%	0.9%
Sri Lanka	†	†	†	†	†	0.1	0.1	0.1	0.1	0.1	**0.1**	5.6%	51.3%	
Taiwan	0.5	0.6	0.6	0.8	0.8	0.9	0.9	1.0	1.0	1.2	**1.5**	21.8%	8.9%	0.3%
Thailand	0.5	0.5	0.8	0.9	1.2	1.6	2.0	2.3	2.8	3.4	**4.0**	19.1%	19.8%	0.7%
Vietnam	†	†	†	†	†	†	†	0.1	0.1	0.1	**0.1**	39.8%	15.5%	◆
Other Asia Pacific	†	†	†	†	0.1	0.1	0.1	0.1	0.2	0.2	**0.3**	32.2%	25.6%	0.1%
Total Asia Pacific	26.8	33.4	41.1	51.3	61.7	79.2	94.5	114.0	140.7	180.2	**225.4**	25.0%	23.2%	40.2%
Total World	**124.1**	**144.0**	**170.6**	**203.6**	**238.8**	**282.5**	**319.5**	**368.5**	**416.8**	**490.2**	**561.3**	**14.5%**	**16.4%**	**100.0%**
of which: OECD	98.1	110.7	127.8	150.5	174.2	199.9	220.6	248.8	269.9	304.3	**330.4**	8.6%	13.4%	58.9%
Non-OECD	26.0	33.3	42.8	53.1	64.6	82.6	98.9	119.7	146.9	185.9	**230.8**	24.1%	24.5%	41.1%
European Union	52.2	59.0	68.4	82.7	97.6	109.9	118.3	134.9	136.4	152.4	**159.6**	4.8%	12.8%	28.4%

*Based on gross generation from renewable sources including wind, geothermal, solar, biomass and waste, and not accounting for cross-border electricity supply. Converted on the basis of thermal equivalence assuming 38% conversion efficiency in a thermal power station.
†Less than 0.05.
◆Less than 0.05%.
Renewables data expressed in terawatt-hours is available at *bp.com/statisticalreview.*

Table I2. Global biofuels production (kbbls/day) (Source: BP Statistical Review of World Energy 2020)

Renewables: Biofuels production*

Thousand barrels of oil equivalent per day	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Growth rate per annum 2019	2008-18	Share 2019
Canada	14	16	19	20	19	21	22	23	25	25	**29**	14.4%	9.4%	1.6%
Mexico	–	†	†	†	†	†	†	†	†	†	**†**	–	–	◆
US	445	526	585	557	582	617	634	673	696	717	**697**	-2.7%	6.2%	37.9%
Total North America	460	542	604	577	601	638	656	696	722	742	**726**	-2.1%	6.3%	39.4%
Argentina	19	32	42	43	38	49	38	53	58	51	**46**	-9.9%	16.1%	2.5%
Brazil	286	316	270	276	321	337	362	340	342	413	**444**	7.6%	3.6%	24.1%
Colombia	5	8	10	11	12	12	12	12	11	14	**13**	-4.6%	18.7%	0.7%
Other S. & Cent. America	4	4	5	5	7	8	8	10	10	11	**12**	7.2%	2.1%	0.7%
Total S. & Cent. America	315	360	327	335	378	406	421	415	422	489	**516**	5.4%	4.6%	28.0%
Austria	7	7	7	7	7	6	7	8	7	7	**7**	-1.7%	3.7%	0.4%
Belgium	3	7	8	8	8	11	7	7	8	8	**9**	7.9%	–	0.5%
Finland	4	6	4	5	6	7	8	2	6	5	**6**	4.9%	12.8%	0.3%
France	44	43	42	49	48	51	53	49	52	58	**51**	-13.1%	4.1%	2.7%
Germany	47	59	58	54	58	65	60	60	62	64	**64**	0.6%	3.1%	3.5%
Italy	14	15	11	6	9	10	10	10	12	13	**14**	12.2%	0.8%	0.8%
Netherlands	5	7	13	24	28	34	36	29	37	36	**35**	-1.8%	37.8%	1.9%
Poland	8	8	8	12	13	14	15	17	17	17	**18**	5.5%	12.1%	1.0%
Portugal	4	5	6	5	5	6	6	6	6	6	**7**	20.2%	8.2%	0.4%
Spain	17	19	16	12	14	19	21	22	29	34	**30**	-13.4%	17.0%	1.6%
Sweden	3	4	4	4	4	4	4	4	3	4	**4**	26.3%	3.6%	0.2%
United Kingdom	4	5	3	6	9	7	6	10	14	13	**11**	-14.9%	9.2%	0.6%
Other Europe	20	20	22	26	28	28	32	33	35	39	**40**	2.5%	8.9%	2.2%
Total Europe	180	205	201	218	237	262	265	257	289	304	**296**	-2.6%	7.6%	16.1%
Total CIS	†	1	1	1	†	†	†	†	†	†	**†**	–	12.1%	◆
Total Middle East	†	†	†	†	†	†	†	†	†	†	**†**	–	–	◆
Total Africa	5	6	6	4	4	5	7	7	8	9	**9**	6.6%	25.5%	0.5%
Australia	4	3	4	4	5	5	4	4	2	3	**3**	6.3%	-0.7%	0.2%
China	31	30	37	39	44	49	42	40	49	47	**50**	6.6%	5.3%	2.7%
India	2	4	5	5	5	5	10	12	11	19	**24**	24.9%	20.9%	1.3%
Indonesia	3	4	27	33	41	59	24	54	50	91	**123**	35.7%	27.1%	6.7%
South Korea	4	6	5	7	7	7	8	8	8	8	**8**	-3.2%	11.3%	0.4%
Thailand	12	16	17	24	30	34	36	31	37	40	**43**	8.1%	14.9%	2.3%
Other Asia Pacific	8	8	16	22	28	34	36	34	33	35	**43**	21.6%	17.0%	2.3%
Total Asia Pacific	65	69	111	133	160	193	161	183	191	243	**294**	21.0%	14.6%	15.9%
Total World	**1025**	**1183**	**1250**	**1268**	**1381**	**1505**	**1511**	**1560**	**1631**	**1787**	**1842**	**3.0%**	**6.8%**	**100.0%**
of which: OECD	646	755	811	803	846	908	929	961	1016	1052	**1027**	-2.3%	6.7%	55.8%
Non-OECD	378	428	439	465	535	597	581	599	615	736	**814**	10.6%	7.1%	44.2%
European Union	179	204	199	216	235	260	262	254	285	299	**291**	-2.8%	7.6%	15.8%
Biofuels production by fuel type														
Biogasoline														
Canada & Mexico	13	15	17	17	17	17	17	17	18	19	**22**	11.9%	8.2%	1.9%
US	417	507	531	502	506	545	564	585	607	613	**601**	-2.0%	5.7%	52.6%
Brazil	263	281	231	236	278	287	304	284	279	334	**357**	6.9%	2.1%	31.3%
Other S. & Cent. America	6	7	9	10	13	16	18	21	22	24	**24**	1.0%	8.0%	2.1%
Europe	31	36	41	47	53	53	58	54	57	59	**57**	-3.7%	8.7%	4.9%
CIS	–	–	–	–	†	†	†	†	†	†	**†**	–	–	◆
Middle East	†	†	†	†	†	†	†	†	†	†	**†**	–	–	◆
Africa	5	6	6	4	4	5	6	6	5	6	**6**	0.5%	20.8%	0.5%
Asia Pacific	31	32	40	42	48	55	59	54	61	67	**76**	13.3%	8.8%	6.6%
Total World	**765**	**883**	**875**	**858**	**921**	**978**	**1027**	**1021**	**1050**	**1122**	**1143**	**1.8%**	**4.8%**	**100.0%**
of which: OECD	463	560	591	569	579	617	641	657	683	692	**681**	-1.7%	5.9%	59.6%
Non-OECD	302	323	283	290	342	361	386	363	367	430	**462**	7.5%	3.3%	40.4%
European Union	30	36	41	47	51	52	57	53	56	57	**55**	-3.8%	8.6%	4.8%
Biodiesel														
Canada & Mexico	2	2	2	2	2	4	5	6	7	6	**7**	22.0%	15.7%	1.0%
US	29	19	54	55	76	71	70	87	89	104	**96**	-7.2%	10.6%	13.8%
Brazil	24	35	39	40	43	50	58	56	63	79	**87**	10.3%	16.5%	12.4%
Other S. & Cent. America	22	37	48	49	43	53	40	54	57	52	**47**	-9.8%	15.8%	6.8%
Europe	149	168	160	171	184	209	207	204	232	246	**240**	-2.4%	7.4%	34.3%
CIS	†	1	1	1	†	†	†	†	†	†	**†**	–	12.1%	0.1%
Middle East	–	–	–	–	–	–	–	–	–	–	**–**	–	–	–
Africa	–	–	–	†	†	†	1	2	2	3	**3**	19.5%	–	0.5%
Asia Pacific	34	37	71	91	111	138	102	130	130	176	**218**	24.0%	18.0%	31.2%
Total World	**260**	**300**	**375**	**409**	**460**	**526**	**483**	**539**	**581**	**665**	**699**	**5.1%**	**11.6%**	**100.0%**
of which: OECD	183	195	220	234	267	291	288	304	333	359	**347**	-3.4%	8.3%	49.6%
Non-OECD	77	105	155	175	193	236	195	235	248	306	**352**	15.0%	17.6%	50.4%
European Union	148	168	159	169	183	209	205	202	229	242	**236**	-2.6%	7.3%	33.7%

Source: includes data from F.O. Lichts; US Energy Information Administration (March 2020).

*Includes biogasoline (such as ethanol) and biodiesel. Volumes have been adjusted for energy content.
†Less than 0.5.
◆Less than 0.05%.
Annual changes and shares of total are calculated using thousand barrels a day oil equivalent figures.

Table I3. Global biofuels consumption (kbbls/day) (Source: BP Statistical Review of World Energy 2020)

Renewables: Biofuels consumption*

Thousand barrels of oil equivalent per day	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Growth rate per annum 2019	Growth rate per annum 2008-18	Share 2019
Canada	15	16	25	29	33	34	34	34	35	37	**38**	2.1%	10.5%	2.1%
Mexico	2	2	2	2	2	3	3	4	4	4	**4**	1.4%	8.4%	0.2%
US	438	504	541	539	583	591	615	661	662	655	**655**	-0.1%	5.5%	36.9%
Total North America	456	522	567	570	618	629	651	699	701	696	**696**	0.1%	5.7%	39.2%
Argentina	–	10	14	17	19	23	25	26	30	29	**30**	2.1%	n/a	1.7%
Brazil	253	269	246	232	273	301	357	324	341	395	**437**	10.6%	5.6%	24.6%
Colombia	†	†	1	1	1	1	1	1	1	1	**1**	2.8%	11.5%	◆
Other S. & Cent. America	9	11	12	14	15	16	17	17	18	18	**19**	4.7%	8.8%	1.1%
Total S. & Cent. America	262	290	272	264	308	340	399	368	389	443	**486**	9.8%	6.4%	27.4%
Austria	10	10	10	10	8	10	12	10	9	9	**10**	1.4%	1.9%	0.5%
Belgium	2	7	7	7	6	8	5	8	9	9	**9**	◆	n/a	0.5%
Finland	2	2	4	4	4	8	8	3	7	6	**6**	-1.4%	15.8%	0.3%
France	45	44	44	48	49	53	53	53	54	53	**56**	4.5%	2.3%	3.1%
Germany	51	52	54	57	51	54	50	50	51	54	**54**	0.1%	0.4%	3.0%
Italy	21	26	25	28	24	20	25	25	25	26	**15**	-42.6%	7.2%	0.8%
Netherlands	7	4	6	6	6	7	6	5	8	12	**14**	15.8%	8.0%	0.8%
Poland	12	12	13	14	14	13	12	8	11	17	**18**	6.7%	7.6%	1.0%
Portugal	4	6	6	5	5	5	7	5	5	5	**5**	-1.4%	7.5%	0.3%
Spain	6	27	32	39	17	18	19	21	25	32	**25**	-22.1%	23.6%	1.4%
Sweden	6	9	11	12	12	16	19	25	28	27	**28**	3.3%	15.8%	1.6%
United Kingdom	19	22	20	17	20	22	18	18	18	24	**31**	27.4%	5.0%	1.8%
Other Europe	19	23	27	31	38	37	37	43	50	53	**56**	6.1%	12.8%	3.1%
Total Europe	205	244	258	279	255	272	272	276	300	327	**325**	-0.5%	6.6%	18.3%
Total CIS	†	1	1	1	†	†	†	†	†	†	**†**	0.5%	12.7%	◆
Total Middle East	†	†	†	†	†	†	†	†	†	†	**†**	1.7%	-4.0%	◆
Total Africa	†	†	†	†	†	†	1	1	1	1	**2**	19.1%	59.1%	0.1%
Australia	20	31	33	29	28	26	24	20	23	26	**25**	-2.3%	6.3%	1.4%
China	29	29	34	39	46	61	36	42	43	50	**44**	-10.4%	6.5%	2.5%
India	†	†	1	1	1	1	2	3	2	2	**2**	-0.5%	6.6%	0.1%
Indonesia	3	3	5	10	15	27	13	44	38	55	**111**	102.0%	57.1%	6.3%
South Korea	5	7	6	7	7	7	8	8	8	13	**13**	0.7%	14.4%	0.7%
Thailand	12	13	14	18	23	28	31	32	35	38	**45**	16.9%	15.4%	2.5%
Other Asia Pacific	4	9	10	12	15	19	23	25	26	26	**26**	1.7%	29.1%	1.5%
Total Asia Pacific	74	91	103	116	135	170	138	174	175	209	**267**	27.5%	14.0%	15.0%
Total World	**997**	**1148**	**1201**	**1229**	**1317**	**1412**	**1463**	**1518**	**1567**	**1676**	**1776**	**6.0%**	**6.8%**	**100.0%**
of which: OECD	683	805	864	883	905	934	957	1003	1032	1060	**1056**	-0.4%	6.1%	59.4%
Non-OECD	314	343	337	346	412	477	506	515	535	617	**720**	16.8%	8.2%	40.6%
European Union	203	241	255	274	244	266	266	265	284	313	**311**	-0.7%	6.2%	17.5%
Biofuels consumption by fuel type														
Biogasoline														
US	420	490	491	489	503	512	531	545	552	549	**554**	0.8%	4.1%	49.4%
Canada & Mexico	16	16	22	26	29	32	32	33	33	35	**36**	3.3%	9.0%	3.2%
Brazil	230	234	208	191	230	251	299	268	277	316	**349**	10.5%	4.0%	31.1%
Other S. & Cent. America	7	9	10	12	15	17	19	21	23	24	**24**	3.3%	14.4%	2.2%
Europe	45	56	58	58	55	55	56	54	57	59	**64**	8.8%	4.7%	5.7%
CIS	–	–	–	–	–	–	–	–	–	–	**–**	n/a	n/a	–
Middle East	†	†	†	†	†	†	†	†	†	†	**†**	1.7%	-4.0%	◆
Africa	†	†	†	†	†	†	†	†	†	†	**†**	4.3%	19.2%	◆
Asia Pacific	48	61	66	66	73	77	77	86	95	94	**94**	-0.2%	9.8%	8.4%
Total World	**766**	**867**	**857**	**843**	**905**	**945**	**1015**	**1007**	**1037**	**1077**	**1122**	**4.1%**	**4.8%**	**100.0%**
of which: OECD	502	596	606	604	616	627	646	657	670	673	**682**	1.3%	4.5%	60.8%
Non-OECD	264	271	250	240	289	318	369	350	367	404	**439**	8.8%	5.2%	39.2%
European Union	45	56	58	58	53	53	54	51	54	56	**61**	9.2%	4.2%	5.4%
Biodiesel														
US	18	15	49	50	80	79	83	116	111	106	**101**	-4.5%	20.1%	15.4%
Canada & Mexico	1	2	4	5	5	6	4	5	6	6	**5**	-5.7%	27.7%	0.8%
Brazil	23	35	38	40	43	50	58	56	63	79	**87**	11.0%	16.9%	13.3%
Other S. & Cent. America	3	12	16	20	20	22	23	23	25	24	**25**	2.9%	29.1%	3.8%
Europe	160	187	200	220	200	217	217	222	243	268	**261**	-2.6%	7.0%	39.9%
CIS	†	1	1	1	†	†	†	†	†	†	**†**	0.5%	12.7%	0.1%
Middle East	–	–	–	–	–	–	–	–	–	–	**–**	n/a	n/a	–
Africa	–	–	–	–	–	†	1	1	1	1	**1**	20.0%	n/a	0.2%
Asia Pacific	26	30	36	49	63	93	61	89	80	115	**173**	50.1%	19.4%	26.4%
Total World	**231**	**281**	**344**	**386**	**412**	**467**	**448**	**511**	**530**	**599**	**655**	**9.2%**	**12.1%**	**100.0%**
of which: OECD	181	210	258	280	289	307	311	346	362	386	**374**	-3.3%	9.6%	57.1%
Non-OECD	50	72	86	106	122	159	137	165	168	213	**281**	31.9%	19.3%	42.9%
European Union	158	185	197	216	191	213	212	214	230	257	**250**	-2.8%	6.7%	38.1%

*Includes biogasoline (such as ethanol) and biodiesel. Volumes have been adjusted for energy content.
†Less than 0.5.
◆Less than 0.05%.
Annual changes and shares of total are calculated using thousand barrels of oil equivalent per day figures.

Table I4. Global renewable energy generation by source (TWh) (Source: BP Statistical Review of World Energy 2019)

Renewable energy: Generation by source*

Terawatt-hours	Wind	Solar	Other renewables‡	2017 Total	Wind	Solar	Other renewables‡	2018 Total	2018 Growth rate: Wind	Solar	Other renewables‡	Total
Canada	29.1	3.3	9.7	42.1	32.2	3.5	9.6	**45.3**	10.7%	7.7%	-1.4%	**7.7%**
Mexico	10.6	1.2	7.3	19.1	12.6	2.2	6.5	**21.4**	18.9%	89.0%	-11.5%	**11.6%**
US	256.9	78.1	82.8	417.8	277.7	97.1	83.7	**458.5**	8.1%	24.4%	1.0%	**9.8%**
Total North America	296.6	82.5	99.9	479.0	322.5	102.9	99.7	**525.2**	8.8%	24.7%	-0.1%	**9.6%**
Argentina	0.6	†	2.4	3.0	1.4	0.1	2.3	**3.8**	131.0%	558.6%	-3.6%	**26.8%**
Brazil	42.4	0.8	51.3	94.5	48.5	3.1	52.9	**104.5**	14.4%	277.1%	3.2%	**10.6%**
Chile	3.6	3.9	6.9	14.5	3.7	5.1	6.7	**15.5**	1.7%	31.4%	-2.8%	**7.6%**
Colombia	†	–	2.0	2.0	†	†	2.1	**2.1**	1314.2%	–	4.9%	**7.5%**
Ecuador	0.1	†	0.4	0.5	0.1	†	0.4	**0.5**	9.3%	1.4%	-0.7%	**0.8%**
Peru	1.1	0.3	0.6	1.9	1.5	0.7	0.7	**2.9**	39.1%	159.5%	16.8%	**50.3%**
Trinidad & Tobago	–	†	–	†	–	†	–	**†**	–	–	–	**–**
Venezuela	–	†	–	†	–	†	–	**†**	–	–	–	**–**
Other S. & Cent. America	8.4	2.4	12.2	22.9	10.7	3.3	12.9	**26.8**	27.4%	37.3%	5.9%	**17.0%**
Total S. & Cent. America	56.1	7.5	75.8	139.4	65.9	12.4	78.0	**156.3**	17.3%	66.7%	3.0%	**12.2%**
Austria	6.6	1.3	4.6	12.5	5.9	1.6	4.8	**12.2**	-10.3%	24.4%	2.6%	**-1.9%**
Belgium	6.5	3.3	5.8	15.6	7.5	4.0	5.4	**16.9**	14.7%	20.8%	-5.8%	**8.4%**
Czech Republic	0.6	2.2	5.0	7.7	0.6	2.3	4.7	**7.7**	3.1%	6.6%	-4.8%	**-0.9%**
Finland	4.8	†	11.8	16.7	5.9	0.2	12.9	**18.9**	22.1%	272.0%	8.6%	**13.2%**
France	24.3	9.2	8.0	41.5	28.2	10.2	8.5	**46.8**	15.8%	10.9%	6.6%	**13.0%**
Germany	105.7	39.4	51.1	196.2	111.6	46.2	51.4	**209.2**	5.6%	17.2%	0.7%	**6.6%**
Greece	5.5	4.0	0.3	9.8	6.3	3.8	0.3	**10.4**	13.8%	-5.0%	-3.8%	**5.6%**
Hungary	0.8	0.3	2.1	3.2	0.6	0.6	2.4	**3.6**	-19.8%	68.7%	10.8%	**9.9%**
Italy	17.7	24.4	25.6	67.7	17.5	23.2	25.3	**66.0**	-1.5%	-4.7%	-1.0%	**-2.5%**
Netherlands	10.6	2.2	4.6	17.4	10.5	3.2	4.9	**18.6**	-0.2%	45.2%	6.0%	**7.2%**
Norway	2.9	†	0.2	3.1	3.9	0.1	0.2	**4.1**	35.8%	58.2%	-15.1%	**32.7%**
Poland	14.9	0.2	6.5	21.6	12.8	0.3	6.3	**19.5**	-13.8%	81.2%	-2.4%	**-9.7%**
Portugal	12.2	1.0	3.4	16.7	12.7	1.0	3.4	**17.1**	3.3%	2.8%	0.1%	**2.6%**
Romania	7.4	1.9	0.5	9.8	6.5	1.7	0.5	**8.6**	-12.3%	-9.8%	-12.1%	**-11.8%**
Spain	49.1	14.3	6.1	69.5	50.8	12.5	7.4	**70.7**	3.5%	-12.6%	21.4%	**1.7%**
Sweden	17.6	0.2	12.1	29.9	16.8	0.4	11.9	**29.0**	-4.5%	62.2%	-1.8%	**-2.9%**
Switzerland	0.1	1.7	1.8	3.7	0.1	2.0	2.0	**4.1**	–	16.3%	7.4%	**11.2%**
Turkey	17.9	2.9	8.3	29.0	19.8	7.9	10.0	**37.7**	10.7%	173.1%	21.0%	**29.8%**
Ukraine	1.0	0.8	0.2	1.9	1.1	1.3	0.2	**2.6**	15.7%	69.7%	33.7%	**38.8%**
United Kingdom	50.0	11.5	31.9	93.4	57.1	12.9	35.6	**105.6**	14.2%	12.1%	11.7%	**13.1%**
Other Europe	0.3	0.4	0.2	0.9	0.5	0.4	0.2	**1.2**	80.8%	14.8%	18.3%	**37.8%**
Total Europe	384.3	124.5	208.2	717.1	404.4	139.1	217.6	**761.1**	5.2%	11.7%	4.5%	**6.1%**
Azerbaijan	†	†	0.1	0.1	0.1	†	0.1	**0.2**	271.9%	5.5%	-4.8%	**40.2%**
Belarus	0.1	0.1	0.1	0.3	0.1	0.1	0.1	**0.4**	21.6%	51.1%	3.0%	**23.8%**
Kazakhstan	0.3	0.1	–	0.4	0.5	0.1	†	**0.7**	64.0%	27.9%	–	**56.8%**
Russian Federation	0.1	0.5	0.5	1.1	0.2	0.6	0.5	**1.3**	62.4%	6.9%	-0.9%	**10.5%**
Turkmenistan	–	†	–	†	–	†	–	**†**	–	–	–	**–**
Uzbekistan	–	–	–	–	–	–	–	**–**	–	–	–	**–**
Other CIS	†	†	†	†	†	†	†	**†**	-2.5%	46.3%	–	**11.2%**
Total CIS	0.6	0.8	0.7	2.0	1.0	0.9	0.7	**2.5**	63.5%	14.9%	-0.4%	**24.0%**
Iran	0.3	†	†	0.3	0.4	†	†	**0.4**	23.8%	157.5%	–	**28.2%**
Iraq	–	0.1	–	0.1	–	0.1	–	**0.1**	–	–	–	**–**
Israel	0.1	1.6	0.1	1.8	0.1	1.8	0.1	**2.0**	–	12.4%	–	**10.9%**
Kuwait	†	0.1	–	0.1	†	0.1	–	**0.1**	–	–	–	**–**
Oman	–	†	–	†	–	†	–	**†**	–	57.5%	–	**57.5%**
Qatar	–	†	0.1	0.1	–	†	0.1	**0.1**	–	–	–	**–**
Saudi Arabia	–	0.1	–	0.1	–	0.2	–	**0.2**	–	9.2%	–	**9.2%**
United Arab Emirates	†	0.5	†	0.5	†	0.9	†	**1.0**	◆	77.9%	–	**76.9%**
Other Middle East	0.5	2.0	†	2.4	0.6	3.0	†	**3.6**	25.7%	53.9%	–	**48.5%**
Total Middle East	0.9	4.4	0.3	5.5	1.1	6.1	0.3	**7.4**	21.4%	38.8%	–	**34.2%**
Algeria	†	0.5	–	0.5	†	0.6	–	**0.6**	-47.4%	19.6%	–	**17.2%**
Egypt	2.4	0.3	–	2.7	2.4	1.0	–	**3.5**	-0.4%	294.2%	–	**28.1%**
Morocco	3.0	0.4	–	3.5	3.8	1.0	–	**4.8**	26.6%	128.8%	–	**38.9%**
South Africa	5.9	4.3	0.5	10.6	6.9	4.9	0.5	**12.4**	17.5%	15.4%	9.8%	**16.3%**
Other Africa	1.4	1.2	7.0	9.6	1.5	1.5	7.6	**10.6**	5.3%	30.6%	8.9%	**11.0%**
Total Africa	12.8	6.6	7.5	26.9	14.7	9.0	8.2	**31.9**	14.8%	36.6%	8.9%	**18.5%**
Australia	13.2	9.0	3.5	25.7	16.3	12.1	3.5	**31.9**	23.3%	34.9%	-0.1%	**24.1%**
Bangladesh	†	0.3	†	0.3	†	0.3	†	**0.3**	–	12.9%	–	**12.3%**
China	295.0	117.8	79.6	492.4	366.0	177.5	90.7	**634.2**	24.1%	50.7%	14.0%	**28.8%**
China Hong Kong SAR	†	†	0.1	0.1	†	†	0.1	**0.1**	–	-9.3%	–	**-0.1%**
India	52.6	21.5	21.6	95.8	60.3	30.7	30.5	**121.5**	14.6%	42.8%	40.9%	**26.9%**
Indonesia	–	†	13.4	13.4	0.2	†	14.5	**14.8**	–	-36.8%	8.9%	**10.2%**
Japan	6.1	61.8	30.9	98.8	6.8	71.7	33.7	**112.1**	11.1%	15.9%	9.0%	**13.5%**
Malaysia	–	0.4	1.0	1.3	–	0.5	1.0	**1.5**	–	26.7%	4.9%	**10.9%**
New Zealand	2.1	0.1	8.4	10.6	2.0	0.1	8.3	**10.5**	-4.4%	30.3%	-1.3%	**-1.7%**
Pakistan	1.2	1.1	1.6	3.9	1.7	2.1	1.7	**5.5**	43.1%	100.5%	2.8%	**41.9%**
Philippines	1.1	1.2	11.3	13.6	1.2	1.2	11.5	**13.9**	5.4%	4.0%	2.3%	**2.7%**
Singapore	–	0.2	0.8	1.1	–	0.3	0.9	**1.2**	–	25.0%	8.2%	**11.8%**
South Korea	2.2	7.1	8.3	17.6	2.4	9.3	10.2	**21.9**	10.8%	32.5%	21.9%	**24.8%**
Sri Lanka	0.4	0.1	0.1	0.6	0.3	0.2	0.1	**0.6**	-17.4%	38.1%	57.2%	**5.6%**
Taiwan	1.7	1.7	1.9	5.3	1.7	2.7	2.0	**6.4**	-2.5%	61.6%	8.2%	**21.8%**
Thailand	0.5	4.5	9.9	14.9	0.8	4.7	12.3	**17.8**	45.0%	5.3%	24.0%	**19.1%**
Vietnam	0.3	†	0.1	0.3	0.3	0.1	0.1	**0.5**	23.4%	803.3%	–	**39.8%**
Other Asia Pacific	0.3	0.5	0.2	0.9	0.5	0.6	0.2	**1.2**	58.0%	22.8%	8.3%	**32.2%**
Total Asia Pacific	376.7	227.2	192.6	796.6	460.5	314.2	221.3	**996.0**	22.2%	38.3%	14.9%	**25.0%**
Total World	**1128.0**	**453.5**	**585.0**	**2166.5**	**1270.0**	**584.6**	**625.8**	**2480.4**	**12.6%**	**28.9%**	**7.0%**	**14.5%**
of which: OECD	695.1	285.7	363.9	1344.8	745.8	337.2	377.3	**1460.3**	7.3%	18.0%	3.7%	**8.6%**
Non–OECD	432.9	167.8	221.0	821.7	524.1	247.4	248.6	**1020.1**	21.1%	47.5%	12.4%	**24.1%**
European Union	362.0	119.1	192.4	673.5	378.8	127.8	199.0	**705.5**	4.6%	7.3%	3.4%	**4.8%**

*Based on gross generation and not accounting for cross–border electricity supply.
‡Includes electricity generated from: geothermal, biomass and other sources of renewable energy (not already itemized).
†Less than 0.05.
◆Less than 0.05%.
A more extensive time series of renewables by source is available at *bp.com/statisticalreview*.

39 APPENDIX J – NUMBER OF ICE VEHICLES IN TRANSPORT FLEET

Table J1 (Part 1 of 3). Number of ICE vehicles in the global fleet.
(This includes cars, vans, buses, and freight and other trucks; but excludes motorcycles and other two-wheelers.)

Country or Region	Motor vehicles per 1000 people	Total vehicle fleet	Refence/Source	Date of Estimate
Global	**205**	**1 416 528 615**		
United States	811	268 913 221	U.S. Dept of Transportation (2017)	2017
European Union	543	261 019 964	ACEA (2018)	2015/2016
China	179	232 312 300	National Bureau of Statistic of China 2019	2018
Japan	615	77 938 515	Japan Dept Transport (2017)	2018
Brazil	350	74 454 951	Balconista (2019)	2019
Russia	373	54 779 626	ЕМИСС (2019)	2018
United Kingdom	579	39 240 439	ACEA (2018)	2016
Mexico	297	37 353 597	The World Bank (2014)	2015
India	22	28 860 000	CEIC (2015)	2015
Canada	650	23 846 147	Statistics Canada (2019)	2017
Indonesia	87	22 512 918	UK Dept of Transport (2015)	2015
South Korea	411	20 989 885	UK Dept of Transport (2015)	2015
Australia	730	19 200 000	Australian Bureau of Statistics (2018)	2018
Thailand	226	15 490 503	UK Dept of Transport (2015)	2015
Turkey	199	16 320 927	ACEA (2018)	2015
Iran	178	14 130 000	UK Dept of Transport (2015)	2015
Argentina	316	13 726 226	UK Dept of Transport (2015)	2015
Malaysia	433	13 308 716	UK Dept of Transport (2015)	2015
Nigeria	64	11 458 370	Nigeria National Bureau of Statistics (2017)	2017
Pakistan	17	10 000 000	UK Dept of Transport (2015)	2015
South Africa	174	9 600 412	UK Dept of Transport (2015)	2015
Ukraine	219	9 290 000	MIUS (2019)	2018
Taiwan	333	7 842 423	Taiwan MTOC (2016)	2016
Syria	368	6 900 000	UK Dept of Transport (2015)	2012
Saudi Arabia	209	6 600 000	UK Dept of Transport (2015)	2015
Colombia	116	5 800 000	ANDEMOS (2018) & Columbian National Census (2018)	2018
Egypt	62	5 733 810	UK Dept of Transport (2015)	2015
Algeria	140	5 570 000	UK Dept of Transport (2015)	2015
Switzerland	539	5 003 551	Switzerland Federal Statistical Office FSO (2018)	2018
Venezuela	145	4 510 000	UK Dept of Transport (2015)	2015
Chile	230	4 444 941	UK Dept of Transport (2015)	2015
Kazakhstan	251	4 397 354	UK Dept of Transport (2015)	2015
New Zealand	860	4 240 000	New Zealand MIA (2018)	2018
Iraq	105	3 900 000	CEIC (2015)	2015
Philippines	38	3 822 544	UK Dept of Transport (2015)	2015
Morocco	103	3 570 000	CEIC (2015)	2015
Belarus	369	3 501 981	UK Dept of Transport (2015)	2015
Israel	384	3 373 139	Israel Central Bureau of Statistics. (2018)	2017
Norway	616	3 236 944	ACEA (2018)	2015
Libya	439	2 740 000	UK Dept of Transport (2011)	2015
Peru	78	2 444 478	UK Dept of Transport (2015)	2015
Ecuador	141	2 267 344	UK Dept of Transport (2015)	2015
Vietnam	23	2 170 000	UK Dept of Transport (2015)	2015
United Arab Emirates	234	2 140 000	UK Dept of Transport (2015)	2015
Serbia	288	2 052 067	Serbian Statistical Office (2016)	2015
Congo, Democratic Republic of the	25	1 900 000	UK Dept of Transport (2015)	2015

Table J1 (Part 2 of 3). Number of ICE vehicles in the global fleet.
(This includes cars, vans, buses, and freight and other trucks; but excludes motorcycles and other two-wheelers.)

Country or Region	Motor vehicles per 1000 people	Total vehicle fleet	Reference/Source	Date of Estimate
Kuwait	477	1 876 188	UK Dept of Transport (2015)	2015
Guatemala	115	1 862 535	UK Dept of Transport (2015)	2015
Dominican Republic	153	1 610 551	UK Dept of Transport (2015)	2015
Afghanistan	47	1 572 663	UK Dept of Transport (2015)	2015
Sri Lanka	70	1 469 821	UK Dept of Transport (2015)	2015
Tunisia	129	1 450 000	UK Dept of Transport (2015)	2015
Kenya	29	1 381 473	UK Dept of Transport (2015)	2015
Kyrgyzstan	223	1 330 000	UK Dept of Transport (2015)	2015
Azerbaijan	135	1 301 926	UK Dept of Transport (2015)	2015
Jordan	123	1 130 000	UK Dept of Transport (2015)	2015
Costa Rica	224	1 076 041	UK Dept of Transport (2015)	2015
Myanmar	20	1 065 897	CEIC (2015)	2017
Georgia	281	1 043 900	UK Dept of Transport (2015)	2015
Qatar	411	1 020 000	UK Dept of Transport (2015)	2015
Yemen	37	1 000 000	UK Dept of Transport (2015)	2015
Oman	233	980 000	UK Dept of Transport (2015)	2015
Uruguay	280	960 000	UK Dept of Transport (2015)	2015
Singapore	170	957 006	Singapore Land Transport Authority (2018)	2018
Zimbabwe	60	940 000	UK Dept of Transport (2015)	2015
Cote d'Ivoire	41	940 000	UK Dept of Transport (2015)	2015
Bosnia and Herzegovina	258	910 969	UK Dept of Transport (2015)	2015
Ghana	32	890 000	UK Dept of Transport (2015)	2015
Angola	32	880 000	UK Dept of Transport (2015)	2015
Ethiopia	9	831 000	2Merkato Business Portal (2017)	2017
Bolivia	72	770 000	UK Dept of Transport (2015)	2015
Moldova	201	715 480	UK Dept of Transport (2015)	2015
Lebanon	117	683 000	Al-akhbar (2019)	2018
Panama	171	677 356	UK Dept of Transport (2015)	2015
Hong Kong	92	674 253	UK Dept of Transport (2015)	2015
Senegal	44	660 000	UK Dept of Transport (2015)	2015
Madagascar	27	660 000	UK Dept of Transport (2015)	2015
Paraguay	98	652 886	CEIC (2015)	2015
Bangladesh	4	620 000	UK Dept of Transport (2015)	2015
Bahrain	422	578 471	UK Dept of Transport (2015)	2015
Uganda	12	490 000	UK Dept of Transport (2015)	2015
Armenia	167	489 346	Armenia vehicle statistics (2018)	2018
Albania	167	481 114	UK Dept of Transport (2015)	2015
Nicaragua	79	480 000	UK Dept of Transport (2015)	2015
Cuba	42	480 000	UK Dept of Transport (2015)	2015
North Macedonia	206	425 764	UK Dept of Transport (2015)	2015
Mozambique	14	400 000	UK Dept of Transport (2015)	2015
Trinidad and Tobago	292	397 000	UK Dept of Transport (2015)	2015
Botswana	177	391 686	UK Dept of Transport (2015)	2015
Tanzania	7	380 000	UK Dept of Transport (2015)	2015
Zambia	23	370 000	UK Dept of Transport (2015)	2015
Cameroon	15	347 000	UK Dept of Transport (2015)	2015
Brunei	721	300 897	UK Dept of Transport (2015)	2015

Table J1 (Part 3 of 3). Number of ICE vehicles in the global fleet.
(This includes cars, vans, buses, and freight and other trucks; but excludes motorcycles and other two-wheelers.)

Country or Region	Motor vehicles per 1000 people	Total vehicle fleet	Reference/Source	Date of Estimate
Burkina Faso	16	297 000	UK Dept of Transport (2015)	2015
Iceland	824	278 924	UK Dept of Transport (2015)	2016
El Salvador	41	260 000	UK Dept of Transport (2015)	2015
Benin	24	252 000	UK Dept of Transport (2015)	2015
Mauritius	192	236 853	UK Dept of Transport (2015)	2015
Mali	12	203 000	UK Dept of Transport (2015)	2015
Montenegro	326	202 322	Montenegrin Statistical Office (2017)	2016
Togo	27	198 000	UK Dept of Transport (2015)	2015
Suriname	349	193 000	UK Dept of Transport (2015)	2015
Jamaica	66	190 000	UK Dept of Transport (2015)	2015
Honduras	18	160 000	CEIC (2015)	2017
Malawi	8	139 000	UK Dept of Transport (2015)	2015
Barbados	387	110 000	UK Dept of Transport (2015)	2015
Haiti	7	80 000	UK Dept of Transport (2015)	2015
Liberia	14	63 000	UK Dept of Transport (2015)	2015
Burundi	6	63 000	UK Dept of Transport (2015)	2015
Belize	139	50 000	UK Dept of Transport (2015)	2015
Mauritania	10	41 000	UK Dept of Transport (2015)	2015

39.1 Chinese Vehicle Fleet in 2018

Table J2. Chinese passenger vehicle class specifications
(Source: National Bureau of Statistic of China in 2019 http://www.stats.gov.cn/tjsj/ndsj/2019/indexch.htm)
(People's Republic of China public safety industry standard
http://www.jxjdcjc.com/ueditor/php/upload/file/20170818/1503017721116112.pdf)

Size	Vehicle Length (mm)	Number of passenger(s) (number)	Other
Large	>= 6000	>=20	
Medium	<6000	10-19	
Small	<6000	=<9 (excluding mini passenger vehicles)	
Mini	=< 3500		Engine capacity =< 1000mL

Table J3. Chinese goods vehicle class specifications
(Source: National Bureau of Statistic of China in 2019 http://www.stats.gov.cn/tjsj/ndsj/2019/indexch.htm)
(People's Republic of China public safety industry standard
http://www.jxjdcjc.com/ueditor/php/upload/file/20170818/1503017721116112.pdf)

Size	**Vehicle Length (mm)**	**Total weight (kg)**
Heavy duty		>= 12000
Medium	>=6000	4500 >= Medium < 12000
Light	< 6000	< 4500
Mini	=< 3500	=< 1800

Table J4. Number of vehicles in the Chinese fleet between years 1978 to 2018, by class
(Source: National Bureau of Statistic of China in 2019 http://www.stats.gov.cn/tjsj/ndsj/2019/indexch.htm)

Year	Total Number of Civilian feelt of cars (10 000)	Passenger Vehicle (10 000)	Large	Medium Size	Small	Mini	Goods Vehicle (10 000)	Heavy Duty	Medium	Light	Mini	Other Vehicle Type (10 000)
1978	135,84	25,90					100,17					
1980	178,29	35,08					129,9					
1985	321,12	79,45					223,2					
1990	551,36	162,19					368,48					
1995	1 040,00	417,90					585,43					
2000	1 608,91	853,73					716,32					
2005	3 159,66	2 132,46	82,13	131,65	1 618,35	300,32	955,55	168,07	236,66	484,51	66,31	71,66
2006	3 697,35	2 619,57	87,34	137,00	2 083,40	311,83	986,30	174,01	235,39	532,13	44,76	91,49
2007	4 358,36	3 195,99	93,82	140,52	2 646,47	315,18	1 054,06	186,74	243,46	587,22	36,63	108,31
2008	5 099,61	3 838,92	100,39	143,19	3 271,14	324,19	1 126,07	200,84	249,73	644,96	30,54	134,62
2009	6 280,61	4 845,09	107,95	145,80	4 246,90	344,44	1 368,60	315,08	262,21	765,33	25,97	66,92
2010	7 801,83	6 124,13	116,44	146,07	5 498,36	363,25	1 597,55	394,80	269,75	911,88	21,12	80,14
2011	9 356,32	7 478,37	126,54	147,41	6 827,54	376,88	1 787,99	460,58	267,80	1 042,07	17,54	89,96
2012	10 933,09	8 943,01	128,13	131,78	8 302,63	380,47	1 894,75	472,51	229,20	1 179,65	13,40	95,33
2013	12 670,14	10 561,78	131,38	117,06	9 951,46	361,87	2 010,62	501,97	196,40	1 300,02	12,23	97,75
2014	14 598,11	12 326,70	139,61	112,06	11 748,19	326,84	2 125,46	533,67	188,09	1 385,77	17,93	145,95
2015	16 284,45	14 095,88	140,07	89,66	13 580,48	285,66	2 065,62	530,05	148,87	1 375,79	10,90	122,95
2016	18 574,54	16 278,24	146,03	83,82	15 813,84	234,55	2 171,89	569,48	138,69	1 455,29	8,43	124,41
2017	20 906,67	18 469,54	152,94	78,95	18 038,69	198,96	2 338,85	635,41	130,68	1 566,30	6,46	98,28
2018	23 231,21	20 555,40	158,33	75,40	20 135,22	186,46	2 567,82	709,53	124,39	1 728,53	5,37	108,00

Table J5. Number of vehicles in the Chinese fleet 2018, by class, and estimated km driven
(Source: National Bureau of Statistic of China in 2019 http://www.stats.gov.cn/tjsj/ndsj/2019/indexch.htm)

Vehicle Class in China	Vehicle Mass According to Chinese Classification	Number of Vehicles in China in 2018 (number)	Vehicle Class in U.S. Dept of Transport Classification System	Proportion of vehicles in Chinese fleet, reclassified with U.S. dept transport Classification System	Average km traveled in 2018 by Vehicle Class in U.S. Dept Transport system (km)	Estimated total km driven by class in 2018 Chinese Fleet (projected from US dept of Transport) (km)
Passenger Vehicle		**205 554 000**	Passenger Car	203 689 500	18 298	3,72716E+12
Large		1 583 300				
Medium Size		754 000				
Small		201 352 200				
Mini		1 864 600	Motorcycle	1 864 600	3 792	7069842142
Goods Vehicle		**25 678 200**				
Heavy Duty	>= 12000 kg	7 095 300	Class 8 Truck	7 095 300	102 077	7,2427E+11
Medium	4500 >= Medium < 12000	1 243 900	Transit Bus + School Bus + Refuse Truck + Paratransit Shuttle + Delivery Truck	1 243 900	34 327	42699324241
Light	< 4500 kg	17 285 300	Light Truck/Van + Light-Duty Vehicle + Other Vehicle Type	18 419 000	18 908	3,4827E+11
Mini	=< 1800 kg	53 700				
Other Vehicle Type		**1 080 000**				
	Total	232 312 300		232 312 300		4,85E+12
		232.3 Trillion Vehicles		232.3 Trillion Vehicles		4.85 Trillion km

Table J6-1. Estimated average annual gasoline consumption per vehicle by nation state, compared to the United States

Nation	Daily gasoline consumption by nation per capita (liters per capita)	Annual gasoline consumption, by nation per capita (liters per capita)	Human Population in 2016 (both sexes combined) (number)	Annual gasoline consumption by nation state (in 2016) (liters)	Number of vehicles in nation fleet (number)	Average annual gasoline consumption per vehicle (liters)	Ratio of EU-28 Nation compared to USA (USA:EU28 Nation)	Ratio of China compared to USA (USA:China)	Ratio of RoW Nation compared to USA (USA:Nation)
	Gasoline consumption per capita around the world (https://www.globalpetrolprices.com/articles/52/)		(UN World Population Data 2017)	(Consumption per capita times nation population)	(Appendix J, & ACEA 2018 for EU-28)	(annual nation consumption divided by number of vehicles)			
United States of America	4.39	1602.35	319,929,162	5.13E+11	268,913,221	1,906			1
Canada	3.62	1321.30	35,949,709	4.75E+10	23,846,147	1,992			1.04
Kuwait	2.84	1036.60	3,935,794	4.08E+09	1,876,188	2,175			1.14
Saudi Arabia	2.60	949.00	31,557,144	2.99E+10	6,600,000	4,538			2.38
Oman	2.53	923.45	4,199,810	3.88E+09	980,000	3,957			2.08
Qatar	2.48	905.20	2,481,539	2.25E+09	1,020,000	2,202			1.16
Luxembourg	2.43	886.95	566,741	5.03E+08	422,291	1,190	0.62		
Australia	2.40	876.00	23,799,556	2.08E+10	19,200,000	1,086			0.57
Brunei Darussalam	2.36	861.40	417,542	3.60E+08	300,897	1,195			0.63
Libya	2.03	740.95	6,234,955	4.62E+09	2,740,000	1,686			0.88
United Arab Emirates	1.98	722.70	9,154,302	6.62E+09	2,140,000	3,092			1.62
New Zealand	1.91	697.15	4,614,532	3.22E+09	4,240,000	759			0.40
Bahrain	1.86	678.90	1,371,855	9.31E+08	578,471	1,610			0.84
Iceland	1.58	576.70	330,243	1.90E+08	278,924	683			0.36
Bahamas	1.53	558.45	386,838	2.16E+08					
Venezuela (Bolivarian Republic of)	1.45	529.25	31,155,134	1.65E+10	4,510,000	3,656			1.92
Trinidad & Tobago	1.44	525.60	1,360,092	7.15E+08	397,000	1,801			0.94
Lebanon	1.41	514.65	5,851,479	3.01E+09	683,000	4,409			2.31
Switzerland	1.35	492.75	8,319,769	4.10E+09	5,003,551	819			0.43
Israel	1.26	459.90	8,064,547	3.71E+09	3,373,139	1,100			0.58
Japan	1.22	445.30	127,974,958	5.70E+10	77,938,515	731			0.05
Sweden	1.12	408.80	9,763,565	3.99E+09	5,398,128	739	0.39		
Malaysia	1.08	394.20	30,723,155	1.21E+10	13,308,716	910			0.48
Finland	1.07	390.55	5,481,966	2.14E+09	3,048,059	702	0.37		
Mexico	1.01	368.65	125,890,949	4.64E+10	37,353,597	1,242			0.65
Ireland	1.00	365.00	4,700,107	1.72E+09	2,409,983	712	0.37		
Greece	0.97	354.05	11,217,800	3.97E+09	6,235,761	637	0.33		
Denmark	0.94	343.10	5,688,695	1.95E+09	2,936,247	665	0.35		
Slovenia	0.92	335.80	2,074,788	6.97E+08	1,284,382	542	0.28		
Russian Federation	0.91	332.15	143,888,004	4.78E+10	54,779,626	872			0.46
Netherlands	0.91	332.15	16,938,499	5.63E+09	9,528,197	590	0.31		
Germany	0.84	306.60	81,707,789	2.51E+10	49,285,424	508	0.27		
Kazakhstan	0.84	306.60	17,749,648	5.44E+09	4,397,354	1,238			0.65
Turkmenistan	0.83	302.95	5,565,284	1.69E+09					
United Kingdom	0.80	292.00	65,397,080	1.91E+10	39,240,439	487	0.26		
Austria	0.76	277.40	8,678,657	2.41E+09	5,288,596	455	0.24		
Iran (Islamic Republic of)	0.73	266.45	79,360,487	2.11E+10	14,130,000	1,497			0.79
Norway	0.73	266.45	5,199,836	1.39E+09	3,236,944	428			0.22
Iraq	0.72	262.80	36,115,649	9.49E+09	3,900,000	2,434			1.28

Table J6-2. Estimated average annual gasoline consumption per vehicle by nation state, compared to the United States

Nation	Daily gasoline consumption by nation per capita (liters per capita)	Annual gasoline consumption, by nation per capita (liters per capita)	Human Population in 2016 (both sexes combined) (number)	Annual gasoline consumption by nation state (in 2016) (liters)	Number of vehicles in nation fleet (number)	Average annual gasoline consumption per vehicle (liters)	Ratio of EU-28 Nation compared to USA (USA:EU28 Nation)	Ratio of China compared to USA (USA:China)	Ratio of RoW Nation compared to USA (USA:Nation)
Estonia	0.70	255.50	1,315,321	3.36E+08	816,206	412			0.22
Panama	0.67	244.55	3,969,249	9.71E+08	677,356	1,433			0.75
Ecuador	0.67	244.55	16,144,368	3.95E+09	2,267,344	1,741			0.91
Jordan	0.65	237.25	9,159,302	2.17E+09	1,130,000	1,923			1.01
Malta	0.65	237.25	427,616	1.01E+08					
Nambia	0.64	233.60	2,425,561	5.67E+08					
Botswana	0.61	222.65	2,209,197	4.92E+08	391,686	1,256			0.66
Jamaica	0.61	222.65	2,871,934	6.39E+08	190,000	3,365			1.77
South Africa	0.60	219.00	55,291,225	1.21E+10	9,600,412	1,261			0.66
South Korea (Republic of Korea)	0.60	219.00	50,593,662	1.11E+10	20,989,885	528			0.28
Singapore	0.60	219.00	5,535,262	1.21E+09	957,006	1,267			0.66
Costa Rica	0.59	215.35	4,807,852	1.04E+09	1,076,041	962			0.50
Kyrgyzstan	0.59	215.35	5,865,401	1.26E+09	1,330,000	950			0.50
Czech Republic	0.58	211.70	10,603,762	2.24E+09	6,119,478	367	0.19		
Italy	0.58	211.70	59,504,212	1.26E+10	42,862,046	294	0.15		
Chile	0.57	208.05	17,762,681	3.70E+09	4,444,941	831			0.44
Uruguay	0.52	189.80	3,431,552	6.51E+08	960,000	678			0.36
Mongolia	0.51	186.15	2,976,877	5.54E+08					
Coatia	0.51	186.15	4,236,016	7.89E+08	1,724,267	457	0.24		
Azerbaijan	0.50	182.50	9,617,484	1.76E+09	1,301,926	1,348			0.71
Argentina	0.50	182.50	43,417,765	7.92E+09	13,726,226	577			0.30
Hungary	0.47	171.55	9,783,925	1.68E+09	3,821,432	439	0.23		
Belize	0.47	171.55	359,288	6.16E+07	50,000	1,233			0.65
France	0.44	160.60	64,457,201	1.04E+10	38,651,953	268	0.14		
Belarus	0.43	156.95	9,485,772	1.49E+09	3,501,981	425			0.22
Dominican Republic	0.42	153.30	10,528,394	1.61E+09	1,610,551	1,002			0.53
Brazil	0.42	153.30	205,962,108	3.16E+10	74,454,951	424			0.22
Belgium	0.40	146.00	11,287,940	1.65E+09	6,538,095	252	0.13		
Latvia	0.40	146.00	1,992,663	2.91E+08	753,373	386	0.20		
Portugal	0.39	142.35	10,418,473	1.48E+09	5,824,700	255	0.13		
Slovakia	0.39	142.35	5,439,318	7.74E+08	2,461,598	315	0.17		
Spain	0.39	142.35	46,397,664	6.60E+09	28,026,696	236	0.12		
Poland	0.37	135.05	38,265,226	5.17E+09	25,329,863	204	0.11		
Georgia	0.35	127.75	3,951,524	5.05E+08	1,043,900	484			0.25
Algeria	0.35	127.75	39,871,528	5.09E+09	5,570,000	914			0.48
Indonesia	0.34	124.10	258,162,113	3.20E+10	22,512,918	1,423			0.75
Bolivia (Plurinational State of)	0.31	113.15	10,724,705	1.21E+09	770,000	1,576			0.83
Thailand	0.29	105.85	68,657,600	7.27E+09	15,490,503	469			0.25
Colombia	0.28	102.20	48,228,697	4.93E+09	5,800,000	850			0.45
El Salvador	0.27	98.55	6,312,478	6.22E+08	260,000	2,393			1.26

Table J6-3. Estimated average annual gasoline consumption per vehicle by nation state, compared to the United States

Nation	Daily gasoline consumption by nation per capita (liters per capita)	Annual gasoline consumption, by nation per capita (liters per capita)	Human Population in 2016 (both sexes combined) (number)	Annual gasoline consumption by nation state (in 2016) (liters)	Number of vehicles in nation fleet (number)	Average annual gasoline consumption per vehicle (liters)	Ratio of EU-28 Nation compared to USA (USA:EU28 Nation)	Ratio of China compared to USA (USA:China)	Ratio of RoW Nation compared to USA (USA:Nation)
Maldives	0.27	98.55	418,403	4.12E+07					
Ukraine	0.26	94.90	44,657,704	4.24E+09	12,834,673	330			0.17
Bulgaria	0.26	94.90	7,177,396	6.81E+08					
Romania	0.25	91.25	19,876,621	1.81E+09	6,408,904	283	0.15		
Syrian Arab Republic	0.25	91.25	18,734,987	1.71E+09	6,900,000	248			0.13
Honduras	0.24	87.60	8,960,829	7.85E+08					
Egypt	0.23	83.95	93,778,172	7.87E+09	5,733,810	1,373			0.72
China	0.22	80.30	1,397,028,553	1.12E+11	232,312,300	483		0.25	
Guatemala	0.22	80.30	16,252,429	1.31E+09	1,862,535	701			0.37
Serbia	0.21	76.65	8,851,280	6.78E+08	2,052,067	331			0.17
Yemen	0.21	76.65	26,916,207	2.06E+09	1,000,000	2,063			1.08
Paraguay	0.21	76.65	6,639,119	5.09E+08	652,886	779			0.41
Viet Nam	0.21	76.65	93,571,567	7.17E+09	2,170,000	3,305			1.73
China, Hong Kong SAR	0.21	76.65	7,245,701	5.55E+08	674,253	824			0.43
Macedonia TFYR	0.20	73.00	2,079,308	1.52E+08	425,764	357			0.19
Peru	0.19	69.35	31,376,671	2.18E+09	2,444,478	890			0.47
Fiji	0.18	65.70	892,149	5.86E+07					
Angola	0.18	65.70	27,859,305	1.83E+09	880,000	2,080			1.09
Republic of Moldova	0.18	65.70	4,065,980	2.67E+08	715,480	373			0.20
Lithuania	0.17	62.05	2,931,926	1.82E+08	1,295,630	140			0.07
Tunisia	0.17	62.05	11,273,661	7.00E+08	1,450,000	482			0.25
Armenia	0.17	62.05	2,916,950	1.81E+08	489,346	370			0.19
Nigeria	0.17	62.05	181,181,744	1.12E+10	11,458,370	981			0.51
Nicaragua	0.15	54.75	6,082,035	3.33E+08	480,000	694			0.36
Ghana	0.15	54.75	27,582,821	1.51E+09	890,000	1,697			0.89
Uzbekistan	0.15	54.75	30,976,021	1.70E+09					
Cuba	0.14	51.10	11,461,432	5.86E+08	480,000	1,220			0.64
Gambia	0.14	51.10	1,977,590	1.01E+08					
Sri Lanka	0.14	51.10	20,714,040	1.06E+09	1,469,821	720			0.38
Afghanistan	0.14	51.10	33,736,494	1.72E+09	1,572,663	1,096			0.58
Albania	0.13	47.45	2,923,352	1.39E+08	481,114	288			0.15
Gabon	0.13	47.45	1,930,175	9.16E+07					
Philippines	0.11	40.15	101,716,359	4.08E+09	3,822,544	1,068			0.56
Solomon Islands	0.11	40.15	587,482	2.36E+07					
State of Palestine	0.11	40.15	4,662,884	1.87E+08					
Turkey	0.09	32.85	78,271,472	2.57E+09	16,320,927	158			0.08
Sudan	0.09	32.85	38,647,803	1.27E+09					
Togo	0.08	29.20	7,416,802	2.17E+08	198,000	1,094			0.57
Pakistan	0.07	25.55	189,380,513	4.84E+09	10,000,000	484			0.25
Morocco	0.06	21.90	34,803,322	7.62E+08	3,570,000	213			0.11

Table J6-4. Estimated average annual gasoline consumption per vehicle by nation state, compared to the United States

Nation	Daily gasoline consumption by nation per capita (liters per capita)	Annual gasoline consumption, by nation per capita (liters per capita)	Human Population in 2016 (both sexes combined) (number)	Annual gasoline consumption by nation state (in 2016) (liters)	Number of vehicles in nation fleet (number)	Average annual gasoline consumption per vehicle (liters)	Ratio of EU-28 Nation compared to USA (USA:EU28 Nation)	Ratio of China compared to USA (USA:China)	Ratio of RoW Nation compared to USA (USA:Nation)
Cameroon	0.06	21.90	22,834,522	5.00E+08	347,000	1,441			0.76
Cape Verde	0.06	21.90	532,913	1.17E+07					
Zambia	0.06	21.90	16,100,587	3.53E+08	370,000	953			0.50
Kenya	0.05	18.25	47,236,259	8.62E+08	1,381,473	624			0.33
Liberia	0.05	18.25	4,499,621	8.21E+07	63,000	1,303			0.68
Haiti	0.05	18.25	10,711,061	1.95E+08	80,000	2,443			1.28
India	0.05	18.25	1,309,053,980	2.39E+10	28,860,000	828			0.43
Zimbabwe	0.04	14.60	15,777,451	2.30E+08	940,000	245			0.13
Senegal	0.03	10.95	14,976,994	1.64E+08	660,000	248			0.13
Papua New Ginea	0.03	10.95	7,919,825	8.67E+07					
Burkina Faso	0.03	10.95	18,110,624	1.98E+08	297,000	668			0.35
Uganda	0.03	10.95	40,144,870	4.40E+08	490,000	897			0.47
North Korea (Dem. People's Republic of Korea)	0.03	10.95	25,243,917	2.76E+08					
Guinea	0.03	10.95	12,091,533	1.32E+08					
Mozambique	0.03	10.95	28,010,691	3.07E+08	400,000	767			0.40
Ivory Coast (Côte d'Ivoire)	0.03	10.95	23,108,472	2.53E+08	940,000	269			0.14
United Republic of Tanzania	0.02	7.30	53,879,957	3.93E+08	380,000	1,035			0.54
Mauritania	0.02	7.30	4,182,341	3.05E+07	41,000	745			0.39
Malawi	0.02	7.30	17,573,607	1.28E+08	139,000	923			0.48
Rwanda	0.02	7.30	11,629,553	8.49E+07					
Mali	0.02	7.30	17,467,905	1.28E+08	203,000	628			0.33
Nepal	0.02	7.30	28,656,282	2.09E+08					
Niger	0.02	7.30	19,896,965	1.45E+08					
Lao People's Democratic Republic	0.01	3.65	6,663,967	2.43E+07					
Ethiopia	0.01	3.65	99,873,033	3.65E+08	831,000	439			0.23
Bangladesh	0.01	3.65	161,200,886	5.88E+08	620,000	949			0.50
						1	0.210	0.253	0.622
						USA	EU-28	China	RoW

40 APPENDIX K – RAIL TRANSPORT PASSENGERS AND FREIGHT

Table K1. Global Tonnes carried in rail transport per year.
(Countries with more than ten million tonnes carried per year.)

Rank	Country	Million tonnes	Reference/Source	Date of Estimate
	Global	**12 545**		
1	China	3 358	China Rail (2015)	2015
2	United States	1 710	Statistica (2016)	2011
3	Australia	1 298	Australian Railway Association (2010)	2014
4	India	1 221	Economic Times (2019)	2018
5	Russia	1 218	ЕМИСС (2019)	2015
6	Brazil	460	UIC (2015)	2014
7	Ukraine	457	UIC (2015)	2011
8	Canada	310	UIC (2015)	2011
9	Kazakhstan	295	UIC (2015)	2012
10	Poland	225	UTK (2019)	2015
11	Germany	221	UIC (2015)	2014
12	South Africa	197	UIC (2015)	2011
13	Belarus	141	UIC (2015)	2014
14	United Kingdom	110,1	Amusan (2015)	2014
15	Mexico	105	UIC (2015)	2010
16	Uzbekistan	82	UIC (2015)	2014
17	Austria	74	UIC (2015)	2014
18	Sweden	65	Rail Traffic (2015)	2015
19	France	63	UIC (2015)	2011
20	Colombia	59	UIC (2015)	2014
21	Czech Republic	57	UIC (2015)	2014
22	Latvia	57	UIC (2015)	2014
23	Switzerland	50	UIC (2015)	2014
24	Lithuania	49	UIC (2015)	2014
25	Romania	44	UIC (2015)	2014
26	South Korea	40	UIC (2015)	2013
27	Italy	38	UIC (2015)	2014
28	Finland	37	UIC (2015)	2014
29	Belgium	37	UIC (2015)	2009
30	Slovakia	36	UIC (2015)	2014
31	Morocco	37	UIC (2015)	2011
32	Iran	33	UIC (2015)	2013
33	Japan	31	UIC (2015)	2010
34	Turkmenistan	27	UIC (2015)	2012
35	Turkey	26	UIC (2015)	2014
36	Estonia	26	UIC (2015)	2012
37	Spain	25	UIC (2015)	2014
38	Chile	25	UIC (2015)	2013
39	Argentina	24	UIC (2015)	2010
40	Azerbaijan	23	UIC (2015)	2012
41	Georgia	20	UIC (2015)	2012
42	Indonesia	20	UIC (2015)	2010
43	Mongolia	18	UIC (2015)	2011
44	Slovenia	17	UIC (2015)	2014
45	Bosnia and Herzegovina	13	UIC (2015)	2014
46	Malaysia	12	UIC (2015)	2011
47	Bulgaria	12	UIC (2015)	2014
48	Taiwan	11	UIC (2015)	2012
49	Thailand	11	UIC (2015)	2011
50	Croatia	10	UIC (2015)	2014
51	Tunisia	10	UIC (2015)	2012

Table K2.1 (1 of 2). Global Tonne-kilometres of rail transport per year.
(Countries with more than one billion tonne-kilometres (tkm) travelled per year)

Rank	Country	Billion tkm	Reference/Source	Date of Estimate
	Global	**11 067**		
1	Russia	3 176	Russia Rail (2017)	2017
2	China	2 696	China Rail (2014)	2014
3	United States	2 326	Statistica (2016)	2016
4	India	666	UIC (2015)	2014
5	Canada	352	UIC (2015)	2011
6	Brazil	267	UIC (2015)	2014
—	European Union	261	UIC (2015)	2014
7	Ukraine	237	UIC (2015)	2011
8	Kazakhstan	236	UIC (2015)	2012
9	Australia	198	Australian Railway Association (2010)	2008
10	South Africa	135	UIC (2015)	2014
11	Mexico	81	International Transport Forum (2014)	2014
12	Germany	75	UIC (2015)	2014
13	Belarus	45	UIC (2015)	2014
14	Poland	32	UIC (2015)	2014
15	France	32	UIC (2015)	2014
16	United Kingdom	24,4	Rail Delivery Group (2015)	2014
17	Uzbekistan	22	UIC (2015)	2012
18	Iran	22	UIC (2015)	2013
19	Sweden	21,1	Railway transport (2014)	2014
20	Japan	21	International Transport Forum (2014)	2014
21	Austria	16	UIC (2015)	2014
22	Latvia	15	UIC (2015)	2014
23	Lithuania	14	UIC (2015)	2014
24	Argentina	12	UIC (2015)	2010
25	Turkmenistan	12	UIC (2015)	2012
26	Colombia	12	UIC (2015)	2009
27	Turkey	11	UIC (2015)	2014
28	South Korea	10	UIC (2015)	2013
29	Italy	10	UIC (2015)	2014
30	Czech Republic	10	UIC (2015)	2014
31	Romania	10	UIC (2015)	2014
32	Finland	9,6	UIC (2015)	2014

Table K2.2 (2 of 2). Global Tonne-kilometres of rail transport per year.
(Countries with more than one billion tonne-kilometres (tkm) travelled per year)

Rank	Country	Billion tkm	Reference/Source	Date of Estimate
33	Switzerland	9	UIC (2015)	2014
34	Azerbaijan	8	UIC (2015)	2014
35	Spain	8	UIC (2015)	2014
36	Mauritania	8	UIC (2015)	2010
37	Indonesia	7	UIC (2015)	2010
38	Netherlands	6	IRG-Rail (2015)	2013
39	Morocco	6	UIC (2015)	2011
40	Belgium	5	UIC (2015)	2014
41	Estonia	5	UIC (2015)	2012
42	Norway	4	IRG-Rail (2015)	2013
43	Chile	4	UIC (2015)	2009
44	Vietnam	4	UIC (2015)	2012
45	Malaysia	3	UIC (2015)	2011
46	Serbia	3	UIC (2015)	2014
47	Thailand	3	UIC (2015)	2011
48	Gabon	2	UIC (2015)	2014
49	Croatia	2	UIC (2015)	2014
50	Denmark	2	IRG-Rail (2015)	2013
51	Tunisia	2	UIC (2015)	2010
52	Egypt	2	UIC (2015)	2010
53	Kenya	1,7	The CEO Magazine (2015)	2014
54	Israel	1,4	Israel Central Bureau of Statistics (2017)	2016
55	Algeria	1	UIC (2015)	2012
56	Cameroon	1	UIC (2015)	2011

Table K3. Global Passengers carried in rail transport per year.
(Countries with more than 20 million passengers per year.)

Rank	Country	Million Passengers	Reference/Source	Date of Estimate
	Global	**32 355**		
1	Japan	9 090	International Union of Railways (2015)	2015
2	India	8 116	Indian Railways (2017)	2017
3	Germany	2 007	International Union of Railways (2015)	2015
4	France	1 762	SNCF Mobilités (2017) & QMNIL (2017)	2017
5	United Kingdom	1 731	UK Office of Rail and Road (2016)	2016
6	China	1 544	China Rail (2014)	2014
7	Russia	1 020	Moscow Metro (2015)	2015
8	Italy	622	International Union of Railways (2015)	2015
9	Spain	571	International Union of Railways (2015)	2015
10	Egypt	550	International Union of Railways (2019)	2019
11	United States	527,78	Amtrak (2018) & American Public Transportation Association (2017)	2017
12	South Africa	500	International Union of Railways (2019)	2019
13	Switzerland	488	International Union of Railways (2015)	2015
14	Ukraine	399	International Union of Railways (2015)	2014
15	Indonesia	393	International Union of Railways (2019)	2019
16	Netherlands	320	International Union of Railways (2015)	2015
17	Poland	280	UTK (2015)	2015
18	Taiwan	277	International Union of Railways (2015)	2015
19	Austria	248	International Union of Railways (2015)	2015
20	Belgium	232	International Union of Railways (2015)	2015
21	Denmark	192	DSB (2016)	2015
22	Czech Republic	179	Czech Statistical Office (2016)	2016
23	South Korea	127,84	International Union of Railways (2019)	2019
24	Portugal	126,28	International Union of Railways (2019)	2019
25	Hungary	119	International Union of Railways (2019)	2019
26	Turkey	101	International Union of Railways (2019)	2019
27	Belarus	92	International Union of Railways (2015)	2014
28	Finland	83	VR (2019) & Helsinki Commuter Traffic (2018)	2018
29	Bangladesh	77,81	International Union of Railways (2019)	2019
30	Slovakia	72,47	International Union of Railways (2019)	2017
31	Israel	64,6	Weissman, S., (2017)	2017
32	Romania	61	International Union of Railways (2015)	2015
33	Pakistan	52,39	International Union of Railways (2019)	2019
34	Thailand	50	General Electric (2017)	2017
35	Ireland	47,9	Irish Times (2019)	2018
36	Malaysia	44,51	International Union of Railways (2019)	2019
37	Tunisia	41	International Union of Railways (2015)	2011
38	Algeria	39	International Union of Railways (2019)	2019
39	Morocco	35	International Union of Railways (2019)	2019
40	Iran	28,09	International Union of Railways (2019)	2019
41	Kazakhstan	22,9	International Union of Railways (2019)	2019
42	Philippines	21.84	International Union of Railways (2019)	2019
43	Uzbekistan	21.59	International Union of Railways (2019)	2019
44	Luxembourg	20	International Union of Railways (2015)	2015

Table K4. Global Passenger-kilometres of rail transport per year.
(Countries with more than five billion passenger-kilometres (tkm) travelled per year)

Rank	Country/Region	Billion passenger-kilometres	Reference/Source	Date of Estimate
	Global	**3 823**		
1	China	1 346	China Rail (2017)	2017
2	India	1 161	OECD (2017)	2017
3	Japan	431,8	OECD (2017)	2016
4	Russia	123,1	OECD (2017)	2017
5	France	110,5	OECD (2017)	2017
6	Germany	95,5	OECD (2017)	2017
7	United Kingdom	80,2	OECD (2017)	2017
8	South Korea	77,8	OECD (2017)	2016
9	Italy	52,2	OECD (2017)	2017
10	Ukraine	37,1	OECD (2017)	2015
11	Spain	27,5	OECD (2017)	2017
12	Switzerland	20,8	OECD (2017)	2017
13	Pakistan	20,3	OECD (2017)	2015
14	Poland	20,3	OECD (2017)	2015
15	Taiwan	19,8	OECD (2017)	2015
16	Indonesia	18,5	OECD (2017)	2015
17	Netherlands	18,4	OECD (2017)	2017
18	Kazakhstan	16,6	OECD (2017)	2011
19	Iran	16,3	OECD (2017)	2014
20	Australia	15,7	OECD (2017)	2015
21	Sweden	13,3	OECD (2017)	2017
22	Austria	12,6	OECD (2017)	2017
23	United States	10,6	OECD (2017)	2017
24	Belgium	10,2	OECD (2017)	2017
25	Czech Republic	9,5	OECD (2017)	2017
26	Belarus	9,0	OECD (2017)	2013
27	Argentina	8,4	OECD (2017)	2017
28	Hungary	7,7	OECD (2017)	2017
29	Thailand	7,5	OECD (2017)	2011
30	Bangladesh	7,3	OECD (2017)	2010
31	Denmark	6,7	OECD (2017)	2016
32	Romania	5,7	OECD (2017)	2015
33	Morocco	5,3	OECD (2017)	2014

40.1 Number of diesel freight locomotives

Table K5 shows that there is an estimated 104 894 diesel freight locomotives in the major economies within the global fleet. This table shows the number of diesel locomotives in each of the top 15 ranked economies in context of freight carried (tonne-km). While this is only part of the world fleet of diesel freight trains, this number will probably represent a majority share of the true number of diesel locomotives in the global fleet.

Table K5. 1.1 Number of diesel freight locomotives

Rank	Country	Number of Diesel Locomotives	Date of Assessment (average 2016)	Reference
	Global Estimate	**104 894**		
1	Europe EU-28	22 100	2014	Railway Statistics 2014 Report by the International Union of Railways
2	China	21 000	2018	Statistica.com https://www.statista.com/statistics/276290/china-railways-train-fleet-by-type-of-carriage/
3	United States	20 366	2015	Statistica.com https://www.statista.com/statistics/495660/locomotive-and-transit-railcars-in-selected-countries-worldwide/
4	Russia	18 250	2015	Railway Statistics 2014 Report by the International Union of Railways
5	India	6086	2018	Statistica (2020): Number of locomotives in the railway fleet across India in financial year 2018, by type, https://www.statista.com/statistics/1029182/india-rolling-stock-number-by-type/#:~:text=The%20Indian%20Railways%20had%20a,sectors%20worldwide%20under%20single%20management.
6	Brazil	4 955	2016	SCI (2017): Diesel locomotives – Global market trends, Forecast, Fleet, Suppliers, and Procurement Projects, https://www.sci.de/fileadmin/user_upload/MC_Studien_Flyer/Flyer_Diesel_Locomotives.pdf
7	Ukraine	4 371	2020	Railway Statistics 2014 Report by the International Union of Railways
8	Canada	2 400	2015	Statistica.com https://www.statista.com/statistics/495660/locomotive-and-transit-railcars-in-selected-countries-worldwide/
9	Australia	1 850	2013	ENVIRON (2013): Locomotive Emissions Project Scoping Study of Potential Measures to Reduce Emissions from New and In-Service Locomotives in NSW and Australia, Prepared by NSW EPA, ENVIRON Australia Pty Ltd, https://www.epa.nsw.gov.au/~/media/EPA/Corporate%20Site/resources/air/locoemissrep.ashx
10	Kazakhstan	1 300	2019	Gadimova, N. (2019): Kazakhstan Modernizes Its Railway Fleet Thanks To French Locomotives, Caspian News, https://caspiannews.com/news-detail/kazakhstan-modernizes-its-railway-fleet-thanks-to-french-locomotives-2019-5-29-49/
11	South Africa	988	2014	Barrow, K., (2014 March): Transnet South Africa orders 1064 locomotives, International Rail Journal, https://www.railjournal.com/locomotives/transnet-south-africa-orders-1064-locomotives/
12	Belarus	825	2014	Railway Statistics 2014 Report by the International Union of Railways
13	United Kingdom	244	2015	Railway Statistics 2014 Report by the International Union of Railways
14	Argentina	81	2016	SCI (2017): Diesel locomotives – Global market trends, Forecast, Fleet, Suppliers, and Procurement Projects, https://www.sci.de/fileadmin/user_upload/MC_Studien_Flyer/Flyer_Diesel_Locomotives.pdf
15	Colombia	78	2016	SCI (2017): Diesel locomotives – Global market trends, Forecast, Fleet, Suppliers, and Procurement Projects, https://www.sci.de/fileadmin/user_upload/MC_Studien_Flyer/Flyer_Diesel_Locomotives.pdf

41 APPENDIX L – INTERNAL ENERGY FLOWS INSIDE MAJOR ECONOMIES

This appendix has the internal energy flows inside economies that are grouped in context of how they may be modelled.

41.1 Global System

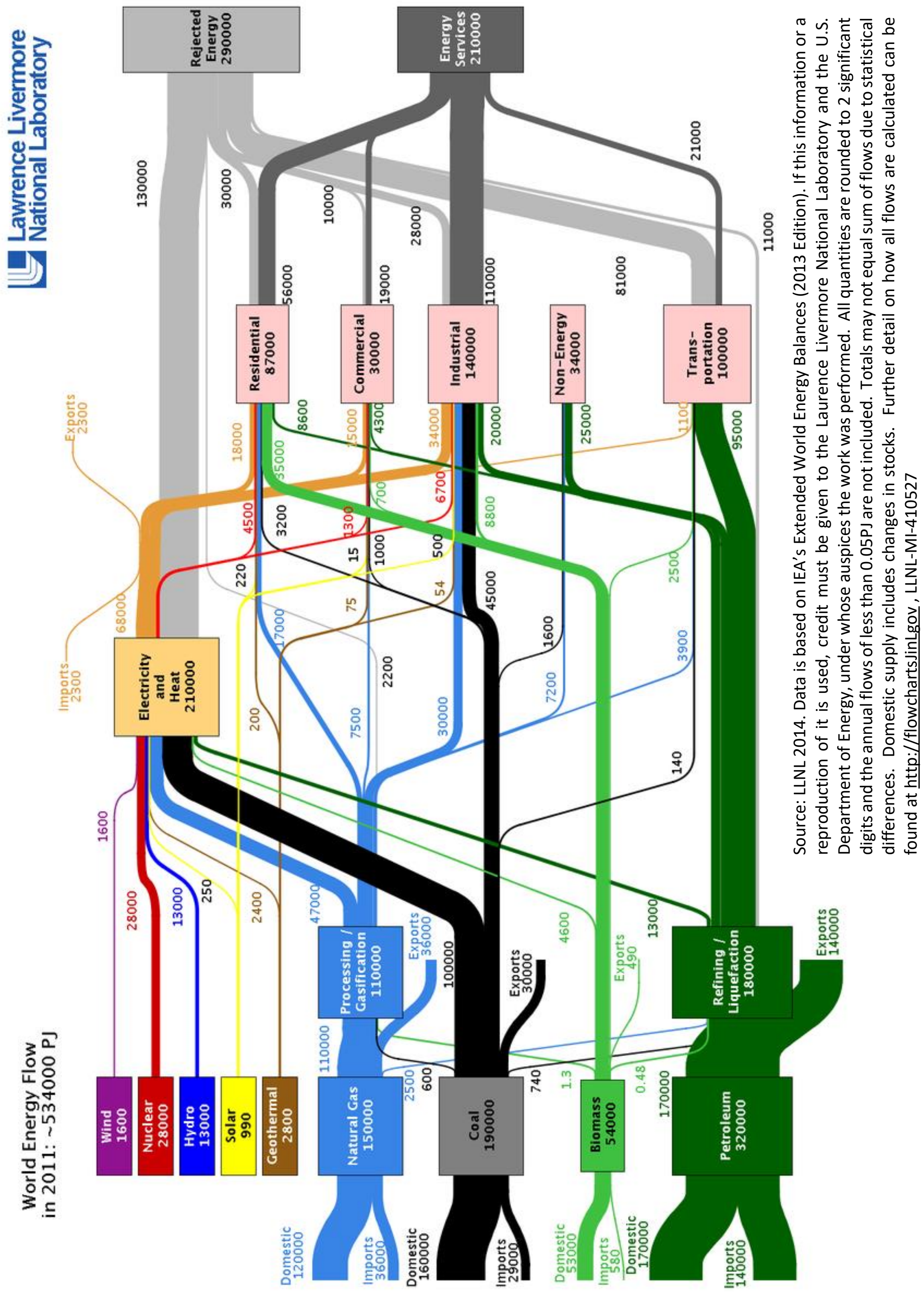


Figure L1. Global energy flow between energy source and application
(Source: Lawrence Livermore National Laboratory Energy Flow Charts)
(Copyright License: https://creativecommons.org/licenses/by-nc-sa/4.0/)

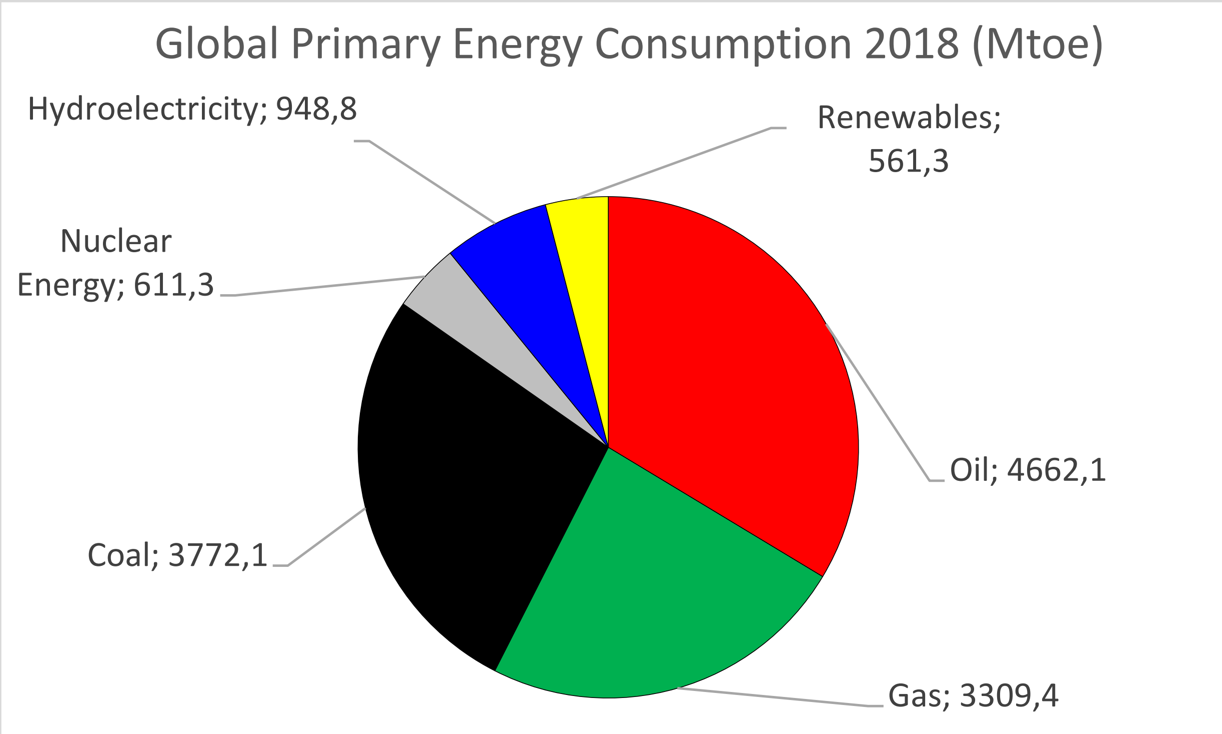


Figure L2. Global primary energy consumption by raw material source
(Source: BP Statistical Review of World Energy 2019 & Appendix A)

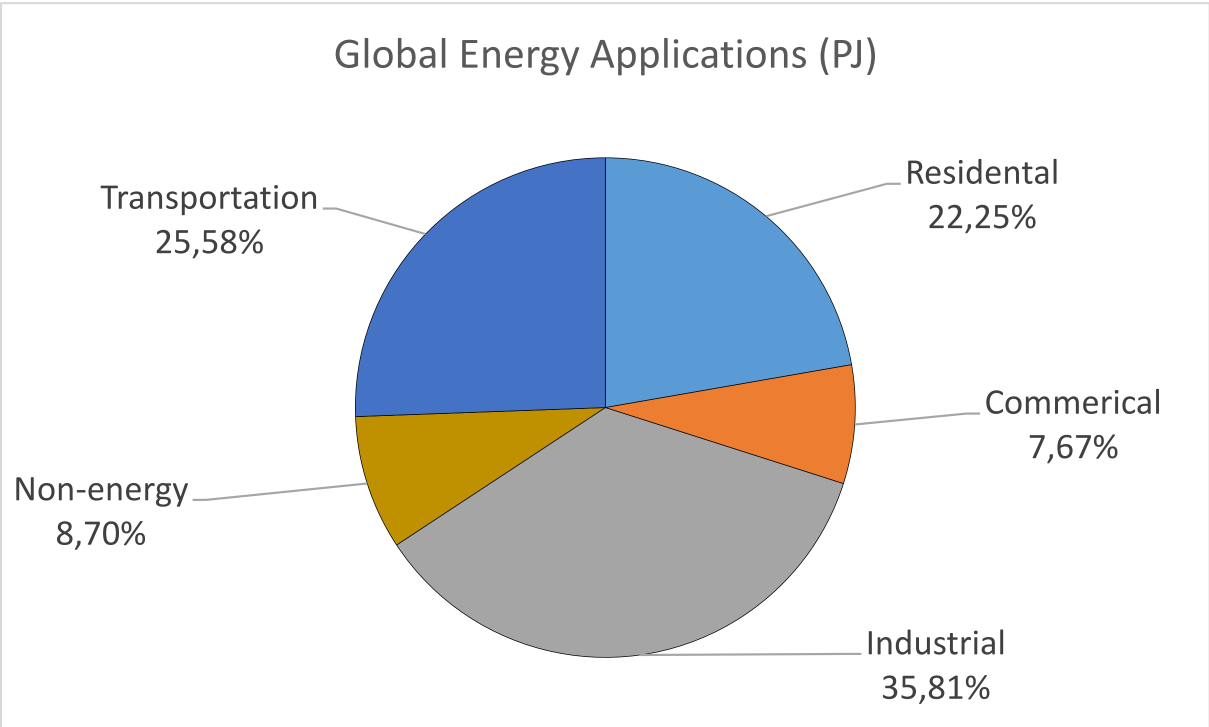


Figure L3. Global energy applications
(Source: Lawrence Livermore National Laboratory 2017, EIA 2017)

41.2 United States

The United States is in a class of its own. Since World War II, it was the largest economy, the largest consumer of energy, the largest producer of energy raw materials (up until 1970) and the largest supplier of industrial goods. It also has the current world reserve currency, the dollar. It is simultaneously a developed nation, the largest consumer, a world class energy producer and an industrial manufacturer.

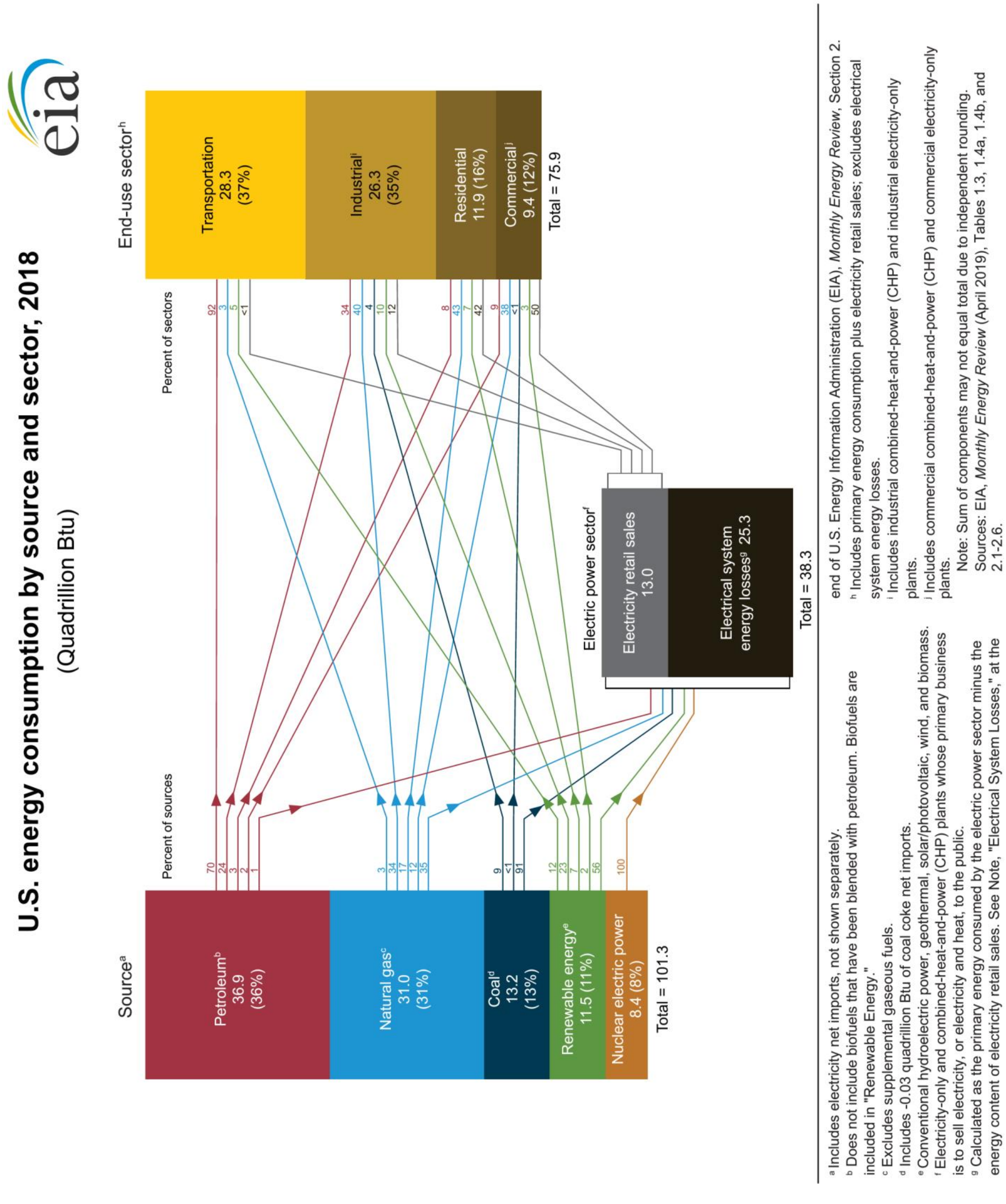


Figure L4. United States energy consumption
(Source: EIA 2019)
(Copyright License: https://www.eia.gov/about/copyrights_reuse.php)

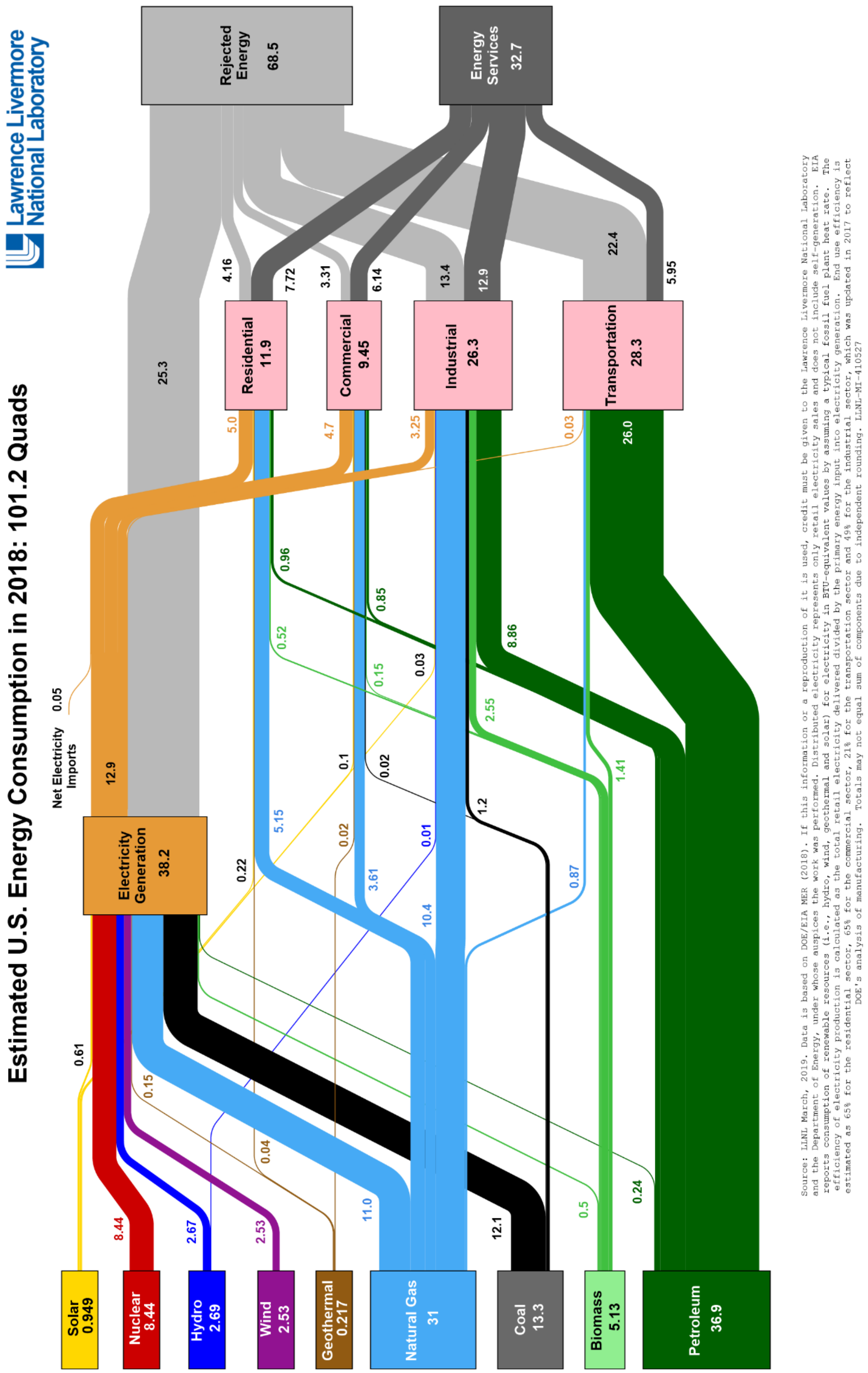


Figure L5. United States energy flow between energy source and application
(Source: Lawrence Livermore National Laboratory 2019, EIA 2019)

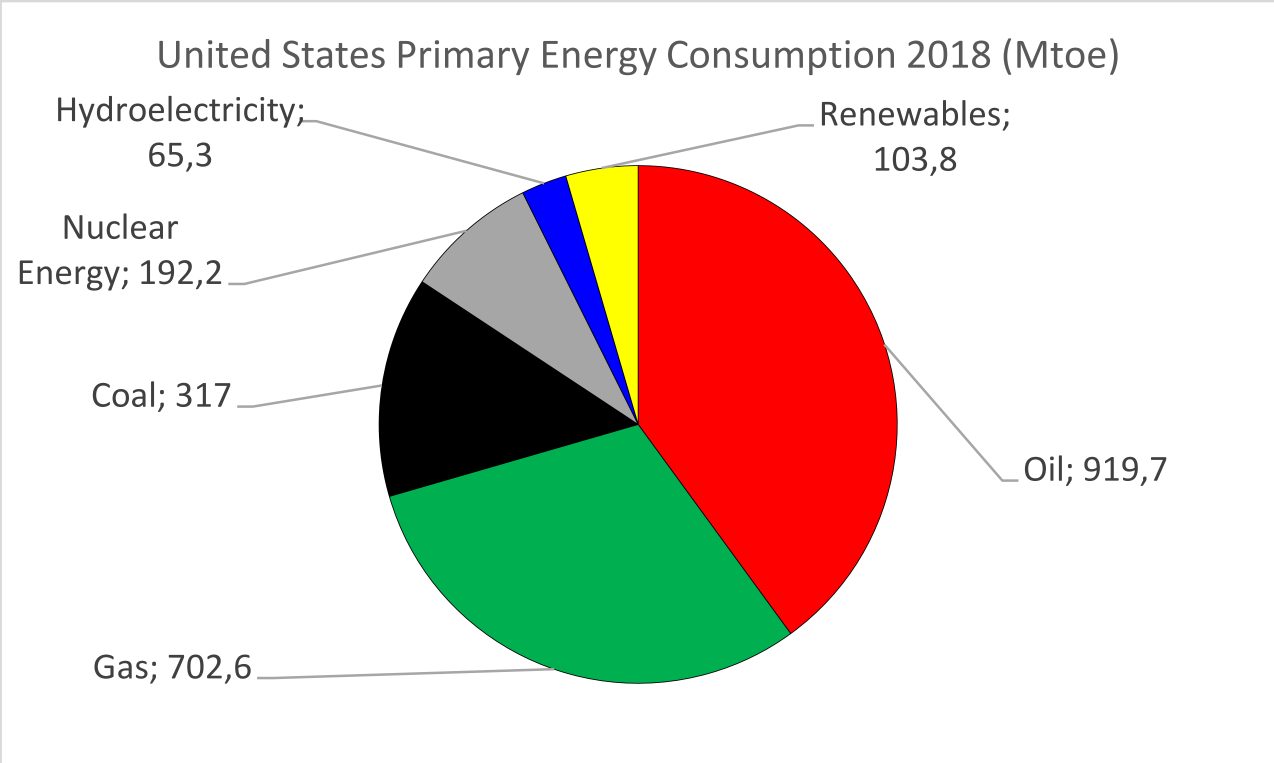


Figure L6. United States primary energy consumption by raw material source
(Source: BP Statistical Review of World Energy 2019 & Appendix A)

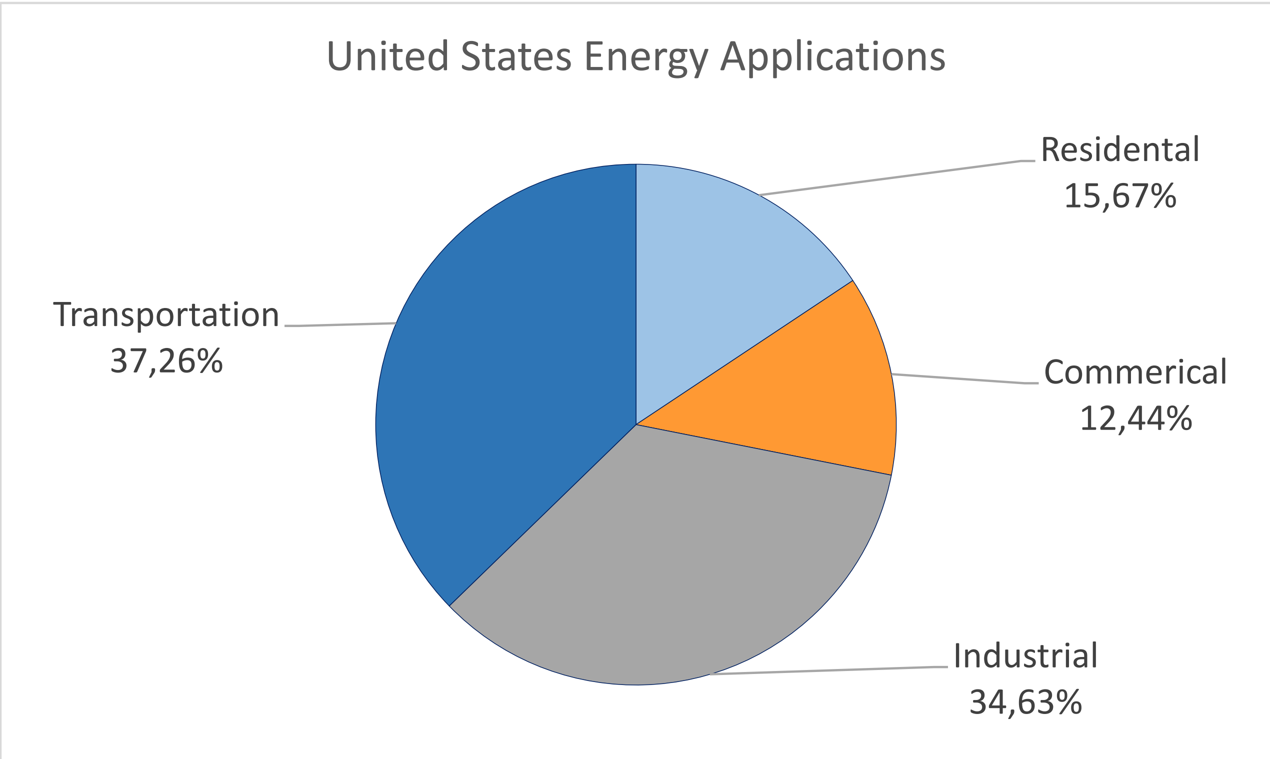


Figure L7. United States energy applications
(Source: Lawrence Livermore National Laboratory 2017, EIA 2017)

41.3 European Union EU-28

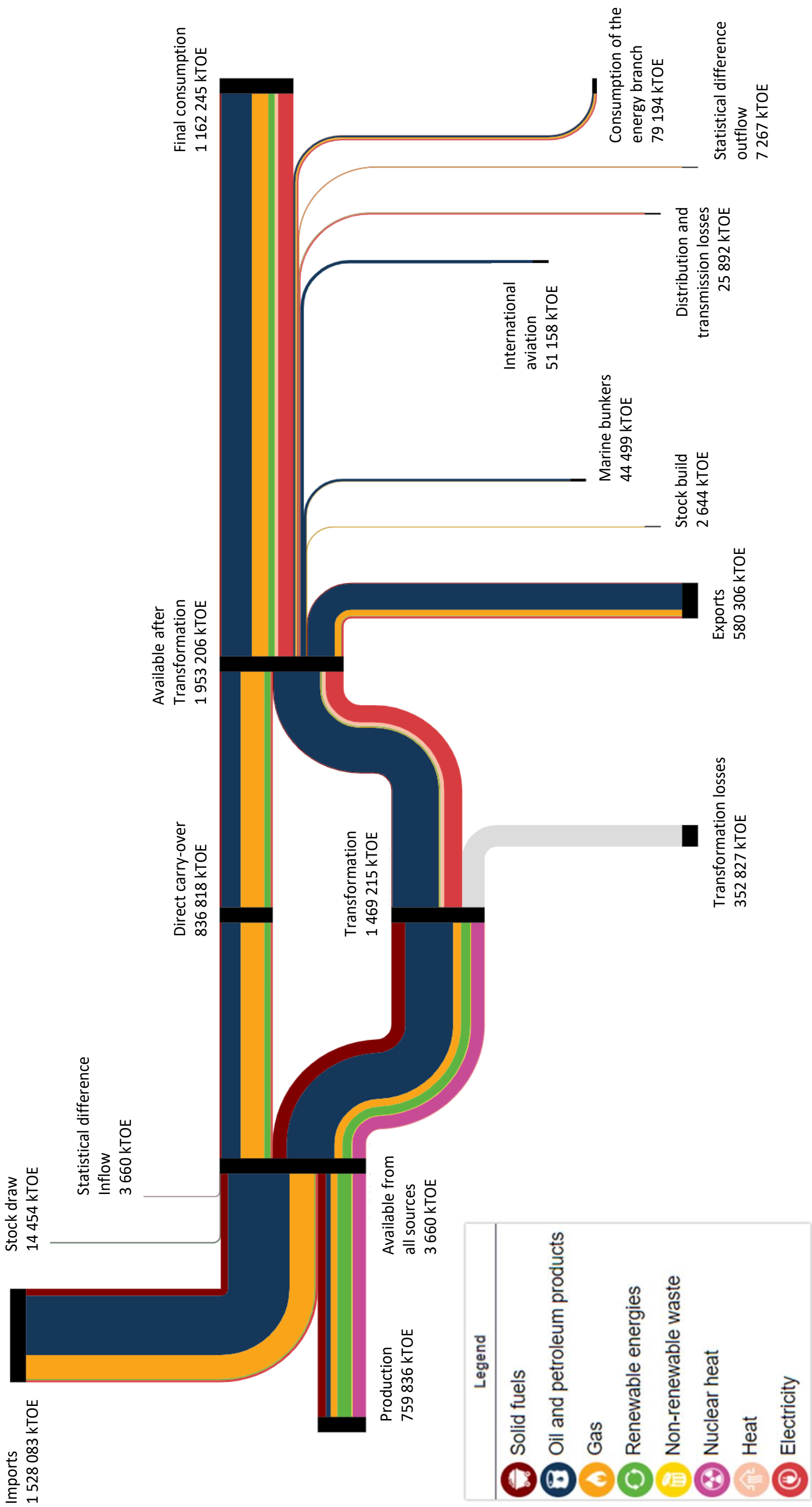


Figure L8: Energy balance flow for European Union EU-28 in 2017
(Source: European Commission Eurostat)
(https://ec.europa.eu/eurostat/web/products-eurostat-news/-/WDN-20190329-1)

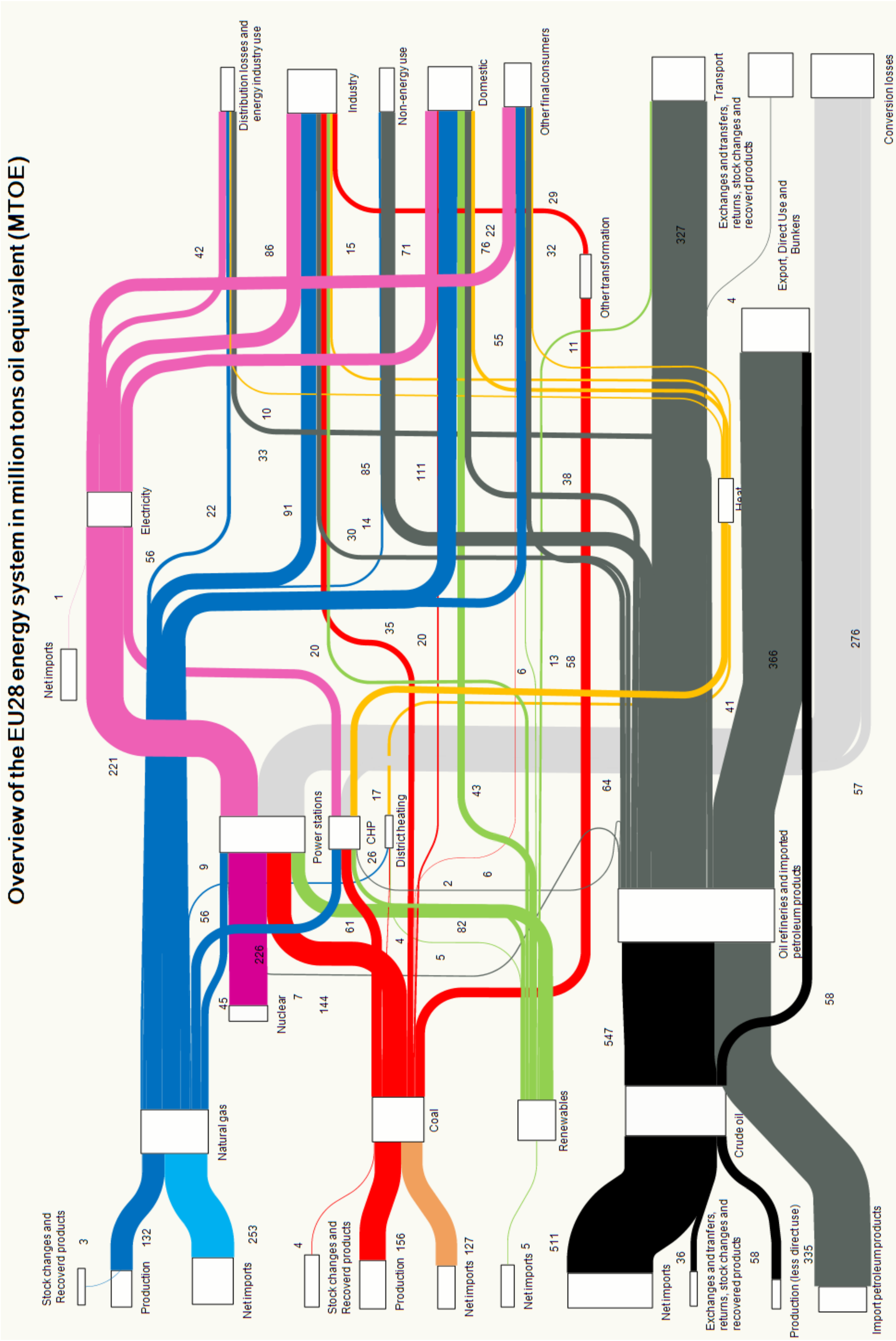


Figure L9: Composition of the primary energy entering the energy system of the EU-28 in 2013
(Source: European Environmental Agency, https://www.eea.europa.eu/)

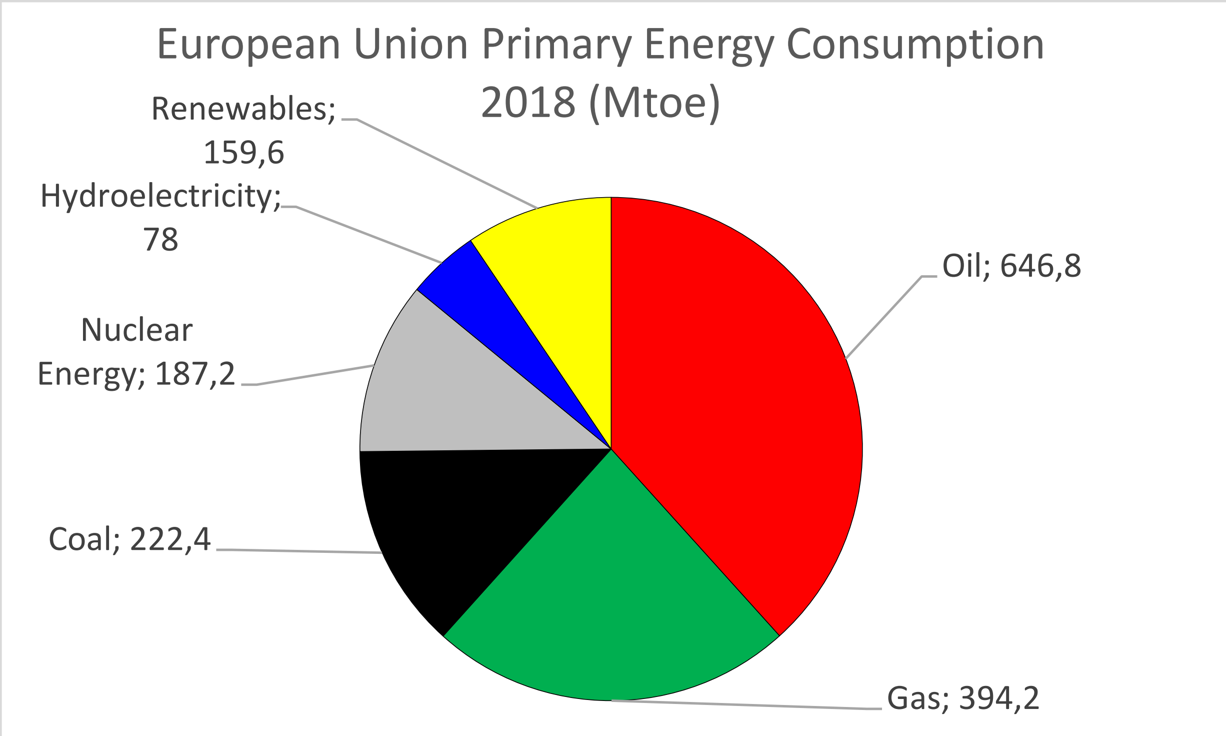


Figure L10. European EU-28 primary energy consumption by raw material source
(Source: BP Statistical Review of World Energy 2019 & Appendix A)

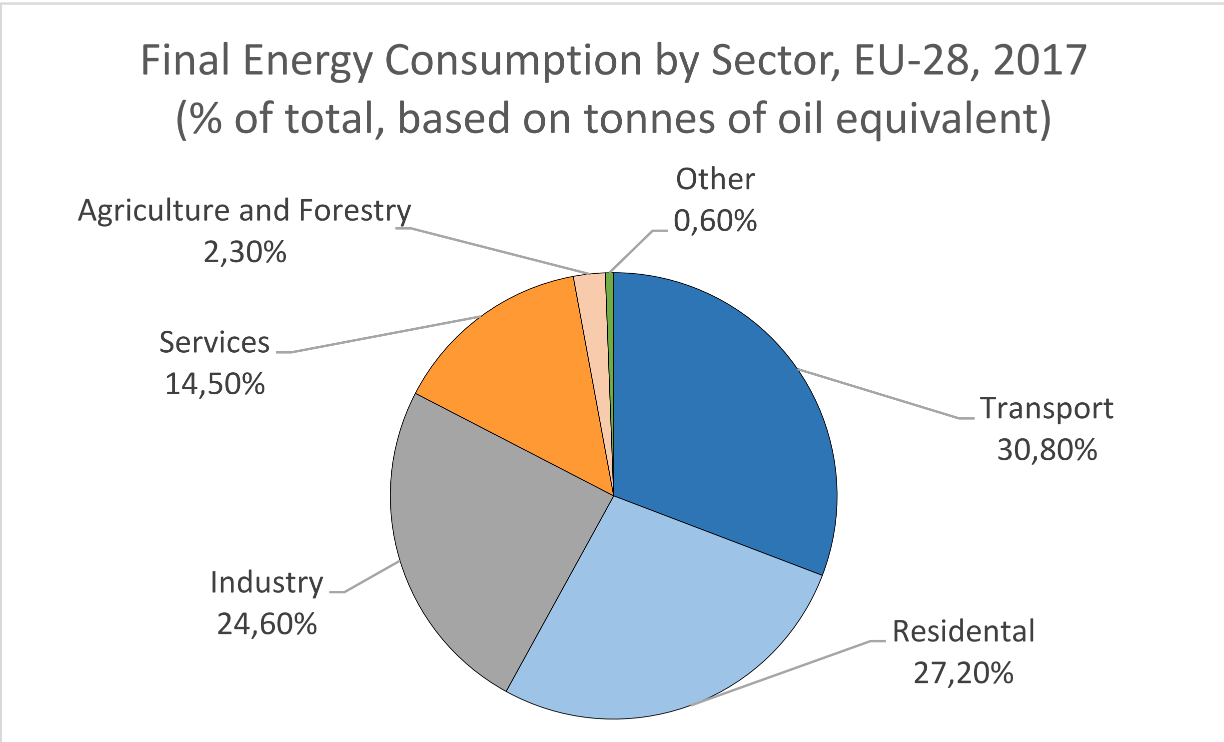


Figure L11: Final energy consumption by sector, EU-28, 2017
(% of total, based on tonnes of oil equivalent)
Source: Eurostat (nrg_bal_s)

41.4 Emerging Economies

These economies are developing into ‘first world’ complexity. A case can be made that when these economies do this, an unprecedented strain on natural resources will result. Nation states like China, Poland and Hungary can also be placed in this classification but each of those nations are classed as industrial production states.

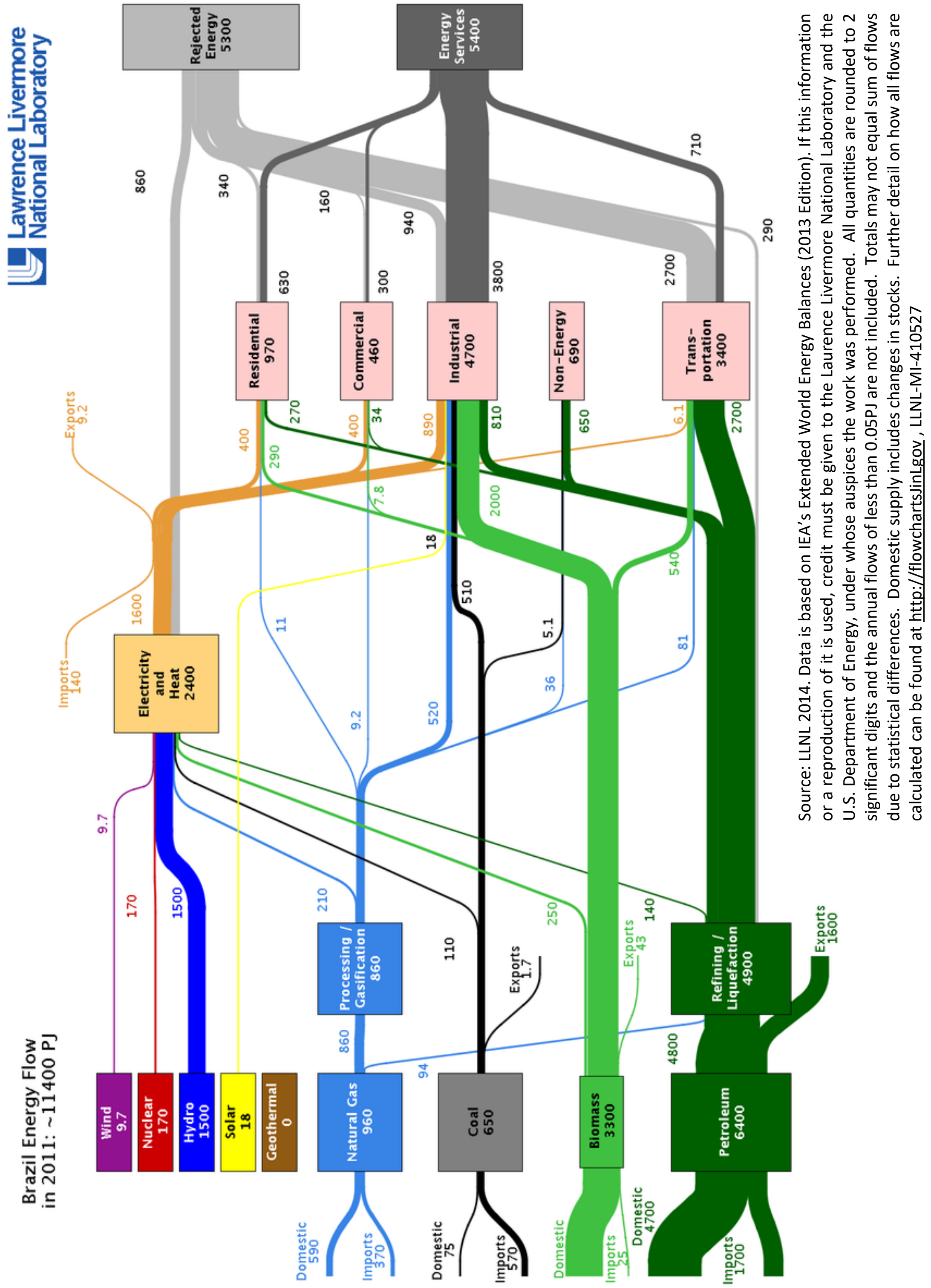


Figure L12. Brazil energy flow between energy source and application
(Source: Lawrence Livermore National Laboratory Energy Flow Charts)

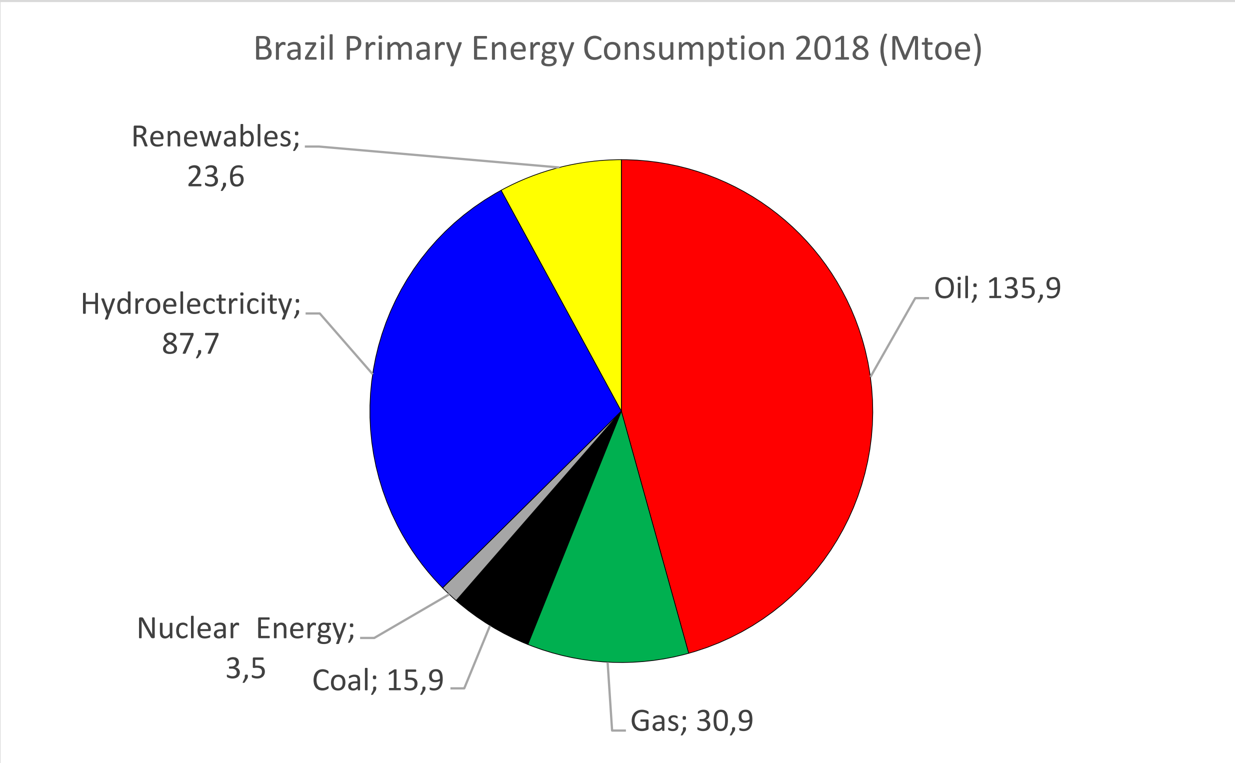


Figure L13. Brazil primary energy consumption by raw material source
(Source: BP Statistical Review of World Energy 2019 & Appendix A)

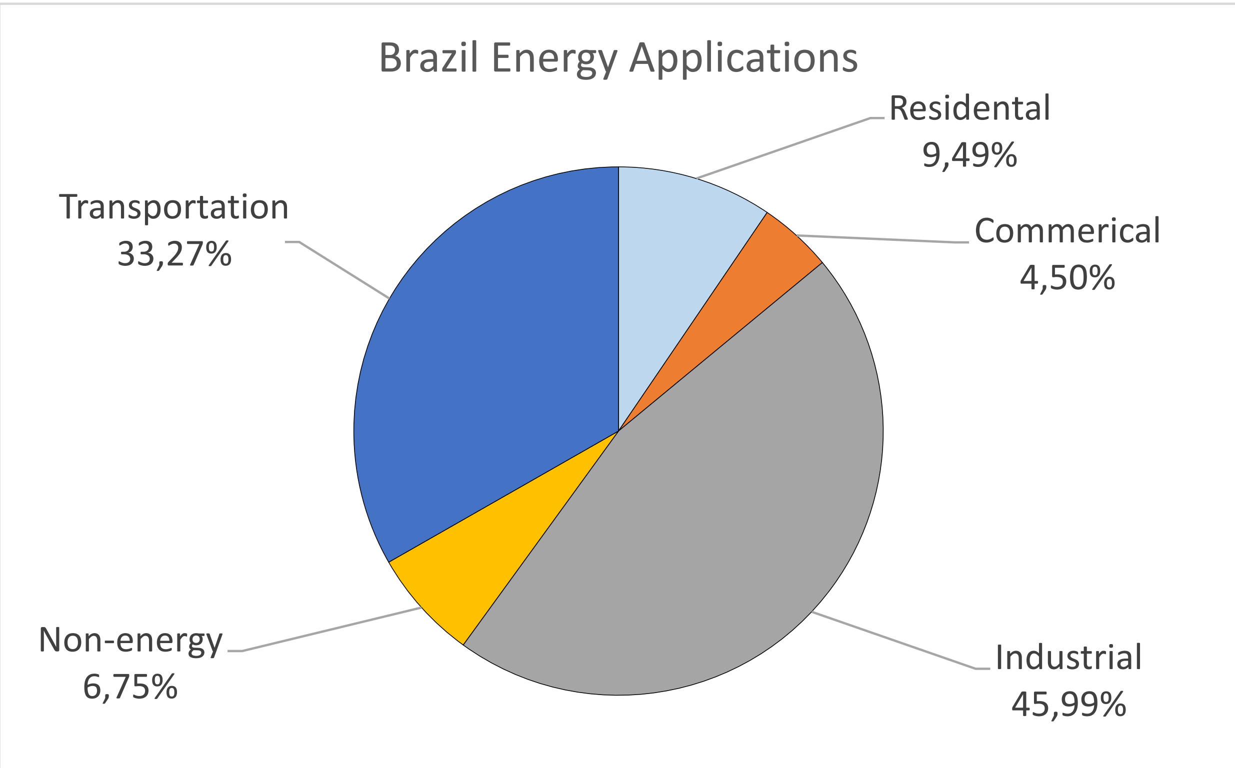


Figure L14. Brazil energy applications
(Source: Lawrence Livermore National Laboratory 2017, EIA 2017)

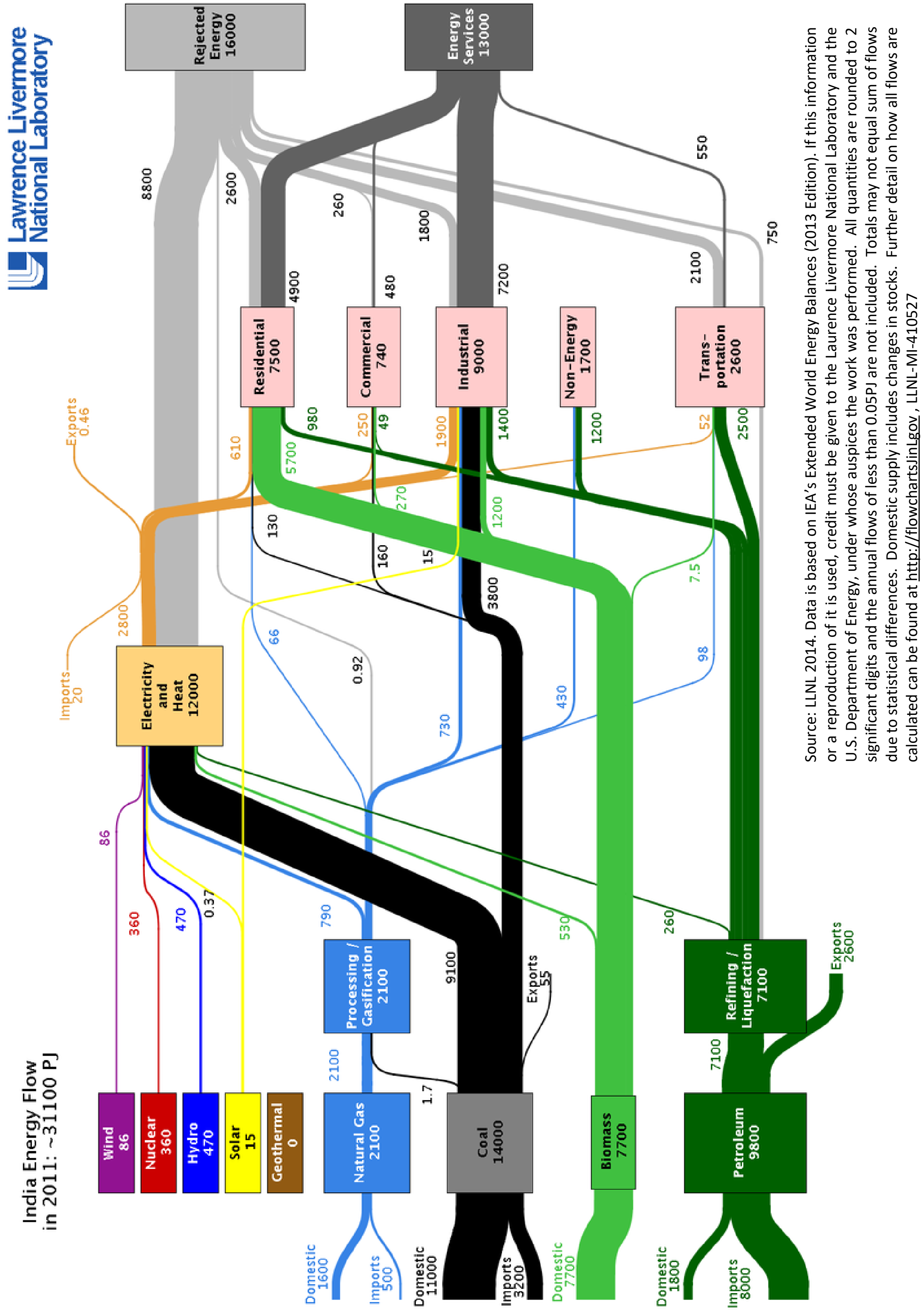


Figure L15. India energy flow between energy source and application
(Source: Lawrence Livermore National Laboratory Energy Flow Charts)

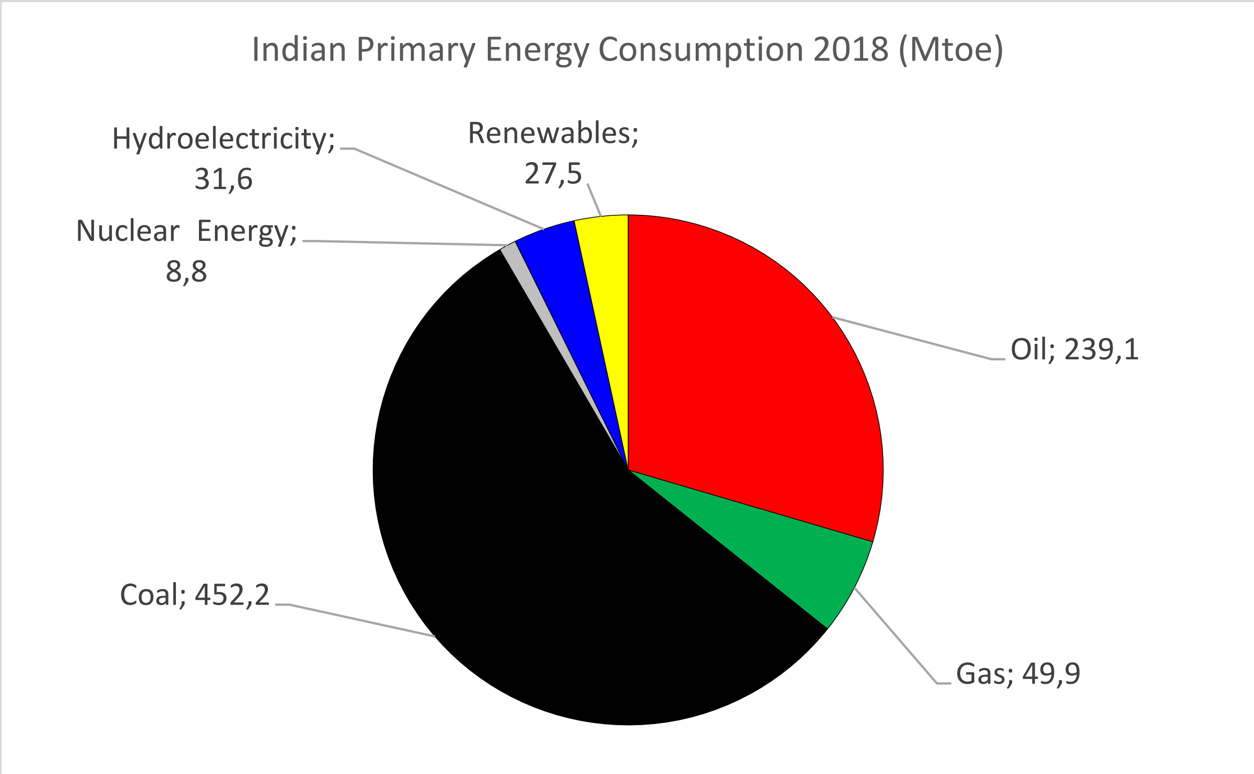


Figure L16. Indian primary energy consumption by raw material source
(Source: BP Statistical Review of World Energy 2019 & Appendix A)

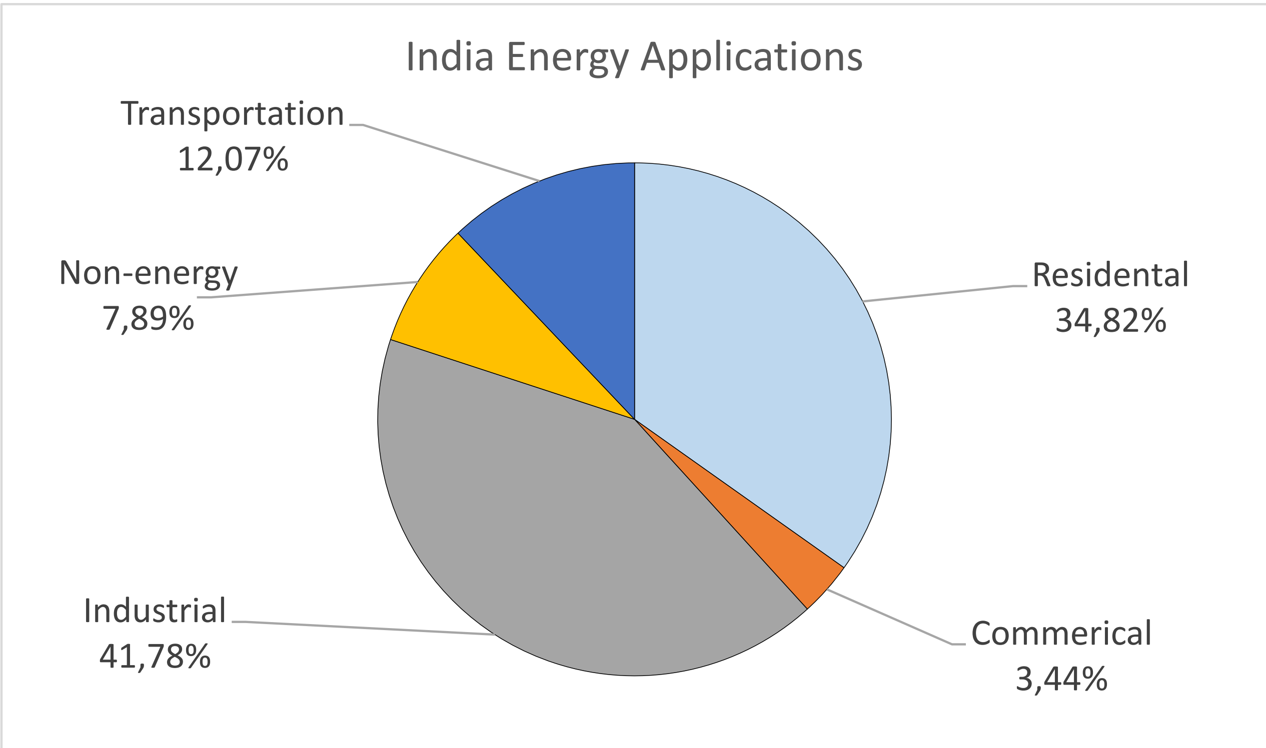


Figure L17. Indian energy applications
(Source: Lawrence Livermore National Laboratory 2017, EIA 2017)

41.5 Industrial Production States

These nation states produce the majority of the goods and services, or have the potential to do so. If our industrial grid was to transform to renewable power only, these economies would have to transition while continuing to produce industrial products.

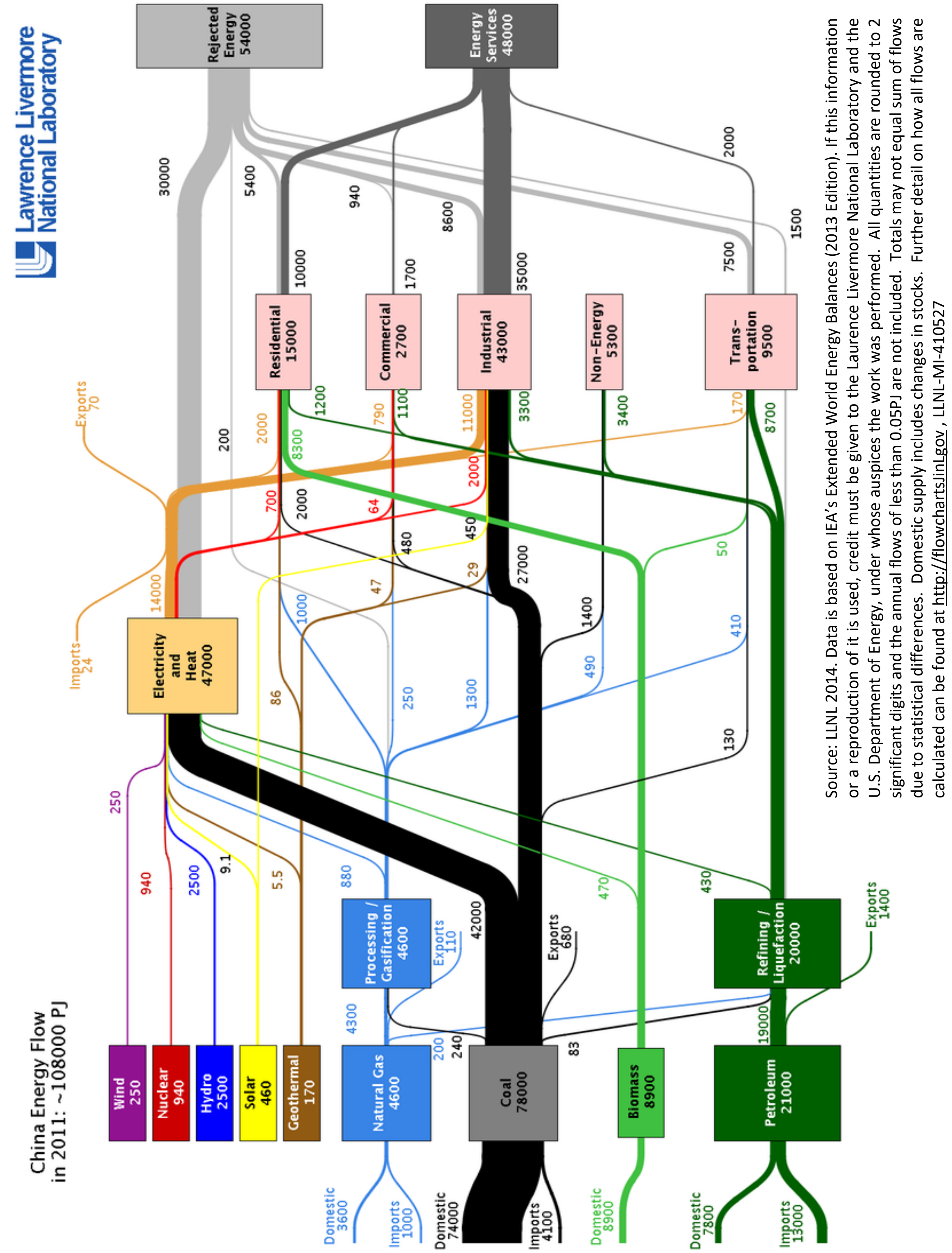


Figure L18. China energy flow between energy source and application
(Source: Lawrence Livermore National Laboratory Energy Flow Charts) (Copyright License: https://creativecommons.org/licenses/by-nc-sa/4.0/)

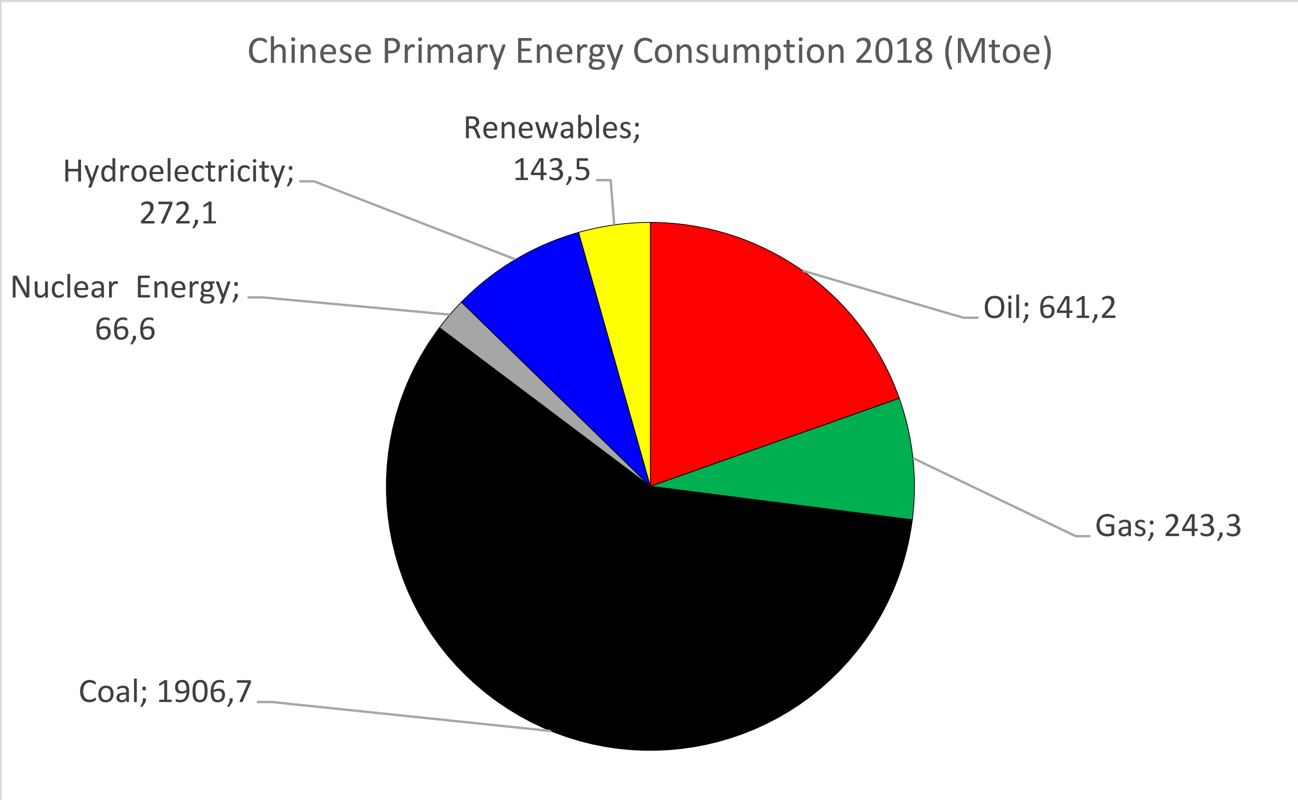


Figure L19. Chinese primary energy consumption by raw material source
(Source: BP Statistical Review of World Energy 2019 & Appendix A)

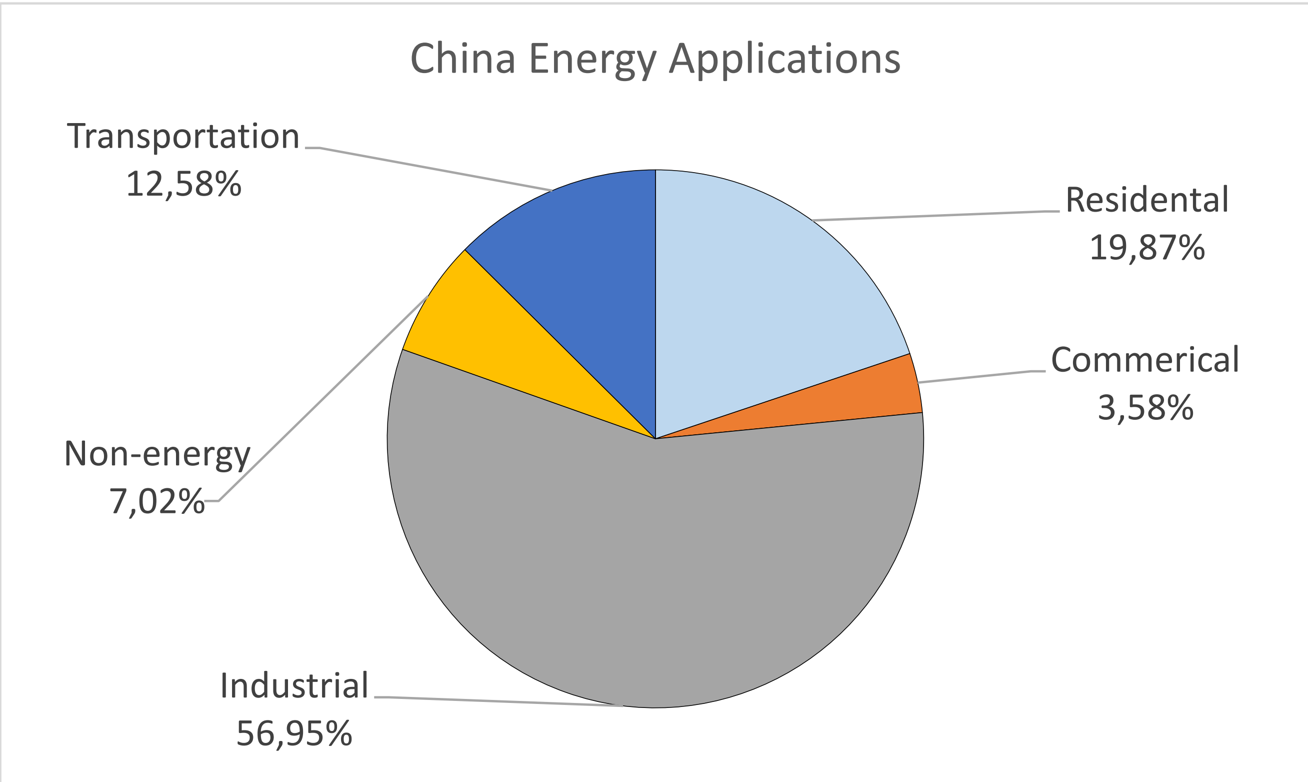


Figure L20. Chinese energy applications
(Source: Lawrence Livermore National Laboratory 2017, EIA 2017)

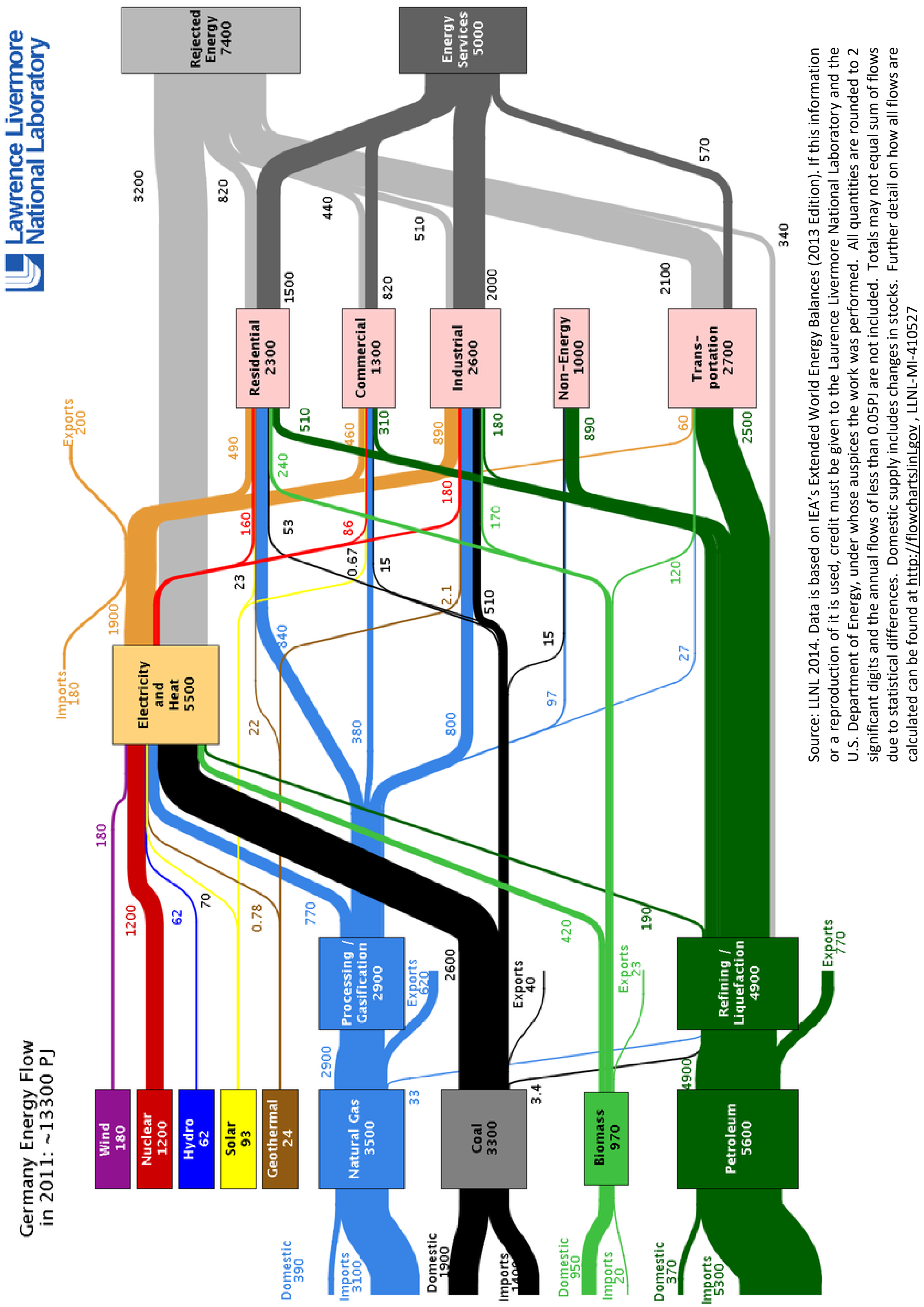


Figure L21. Germany energy flow between energy source and application (Source: Lawrence Livermore National Laboratory Energy Flow Charts) (Copyright License: https://creativecommons.org/licenses/by-nc-sa/4.0/)

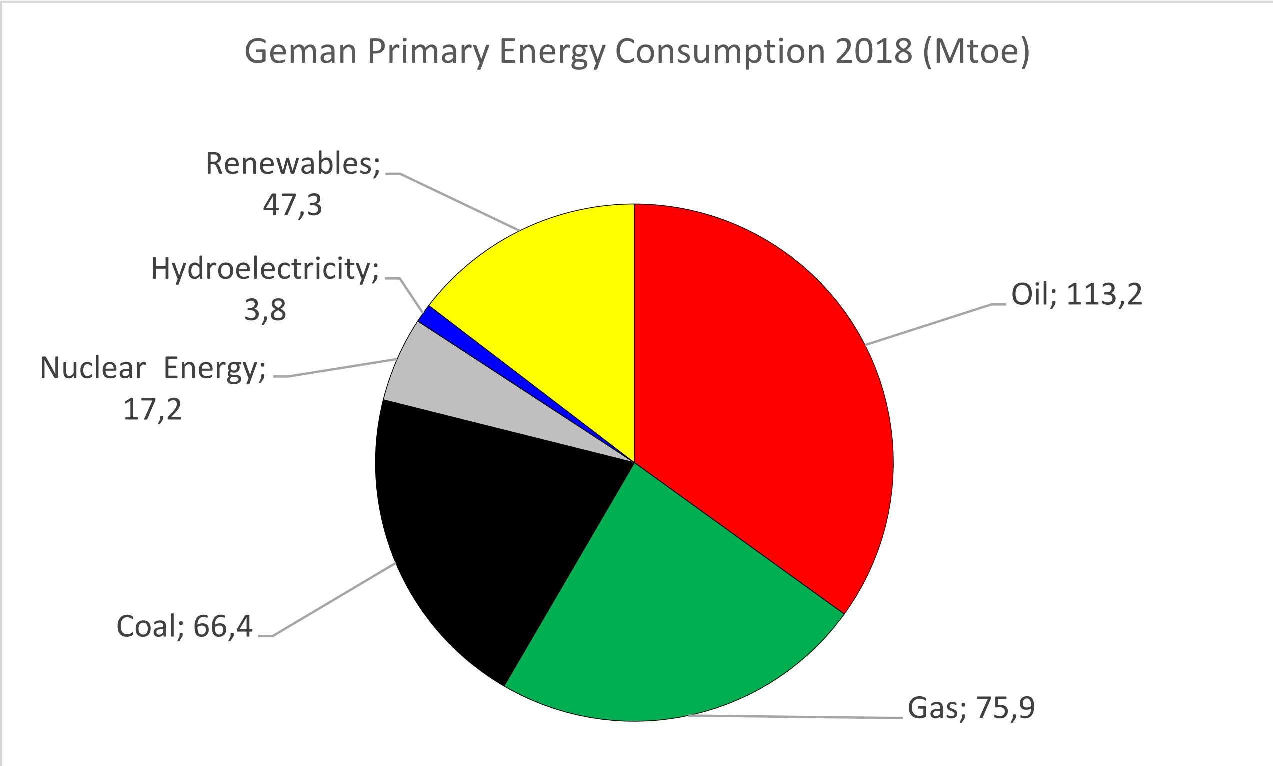


Figure L22. German primary energy consumption by raw material source
(Source: BP Statistical Review of World Energy 2019 & Appendix A)

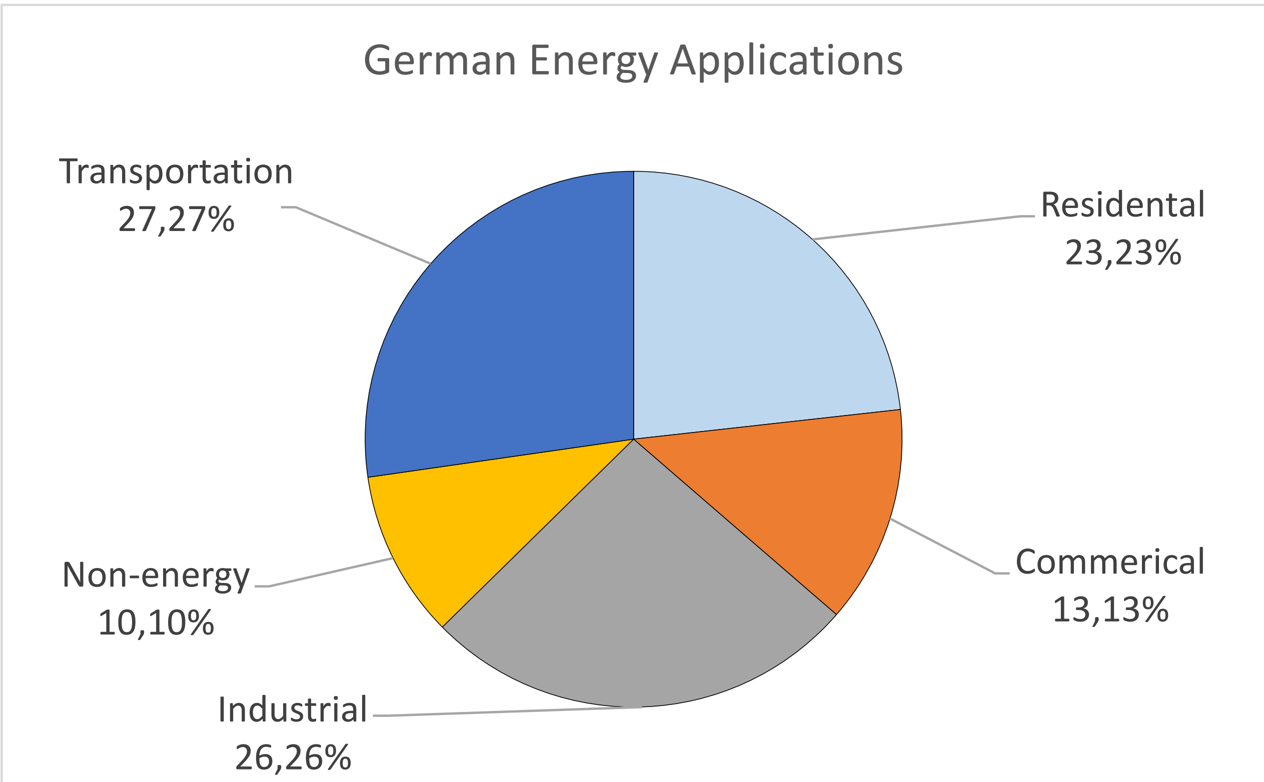


Figure L23. German energy applications
(Source: Lawrence Livermore National Laboratory 2017, EIA 2017)

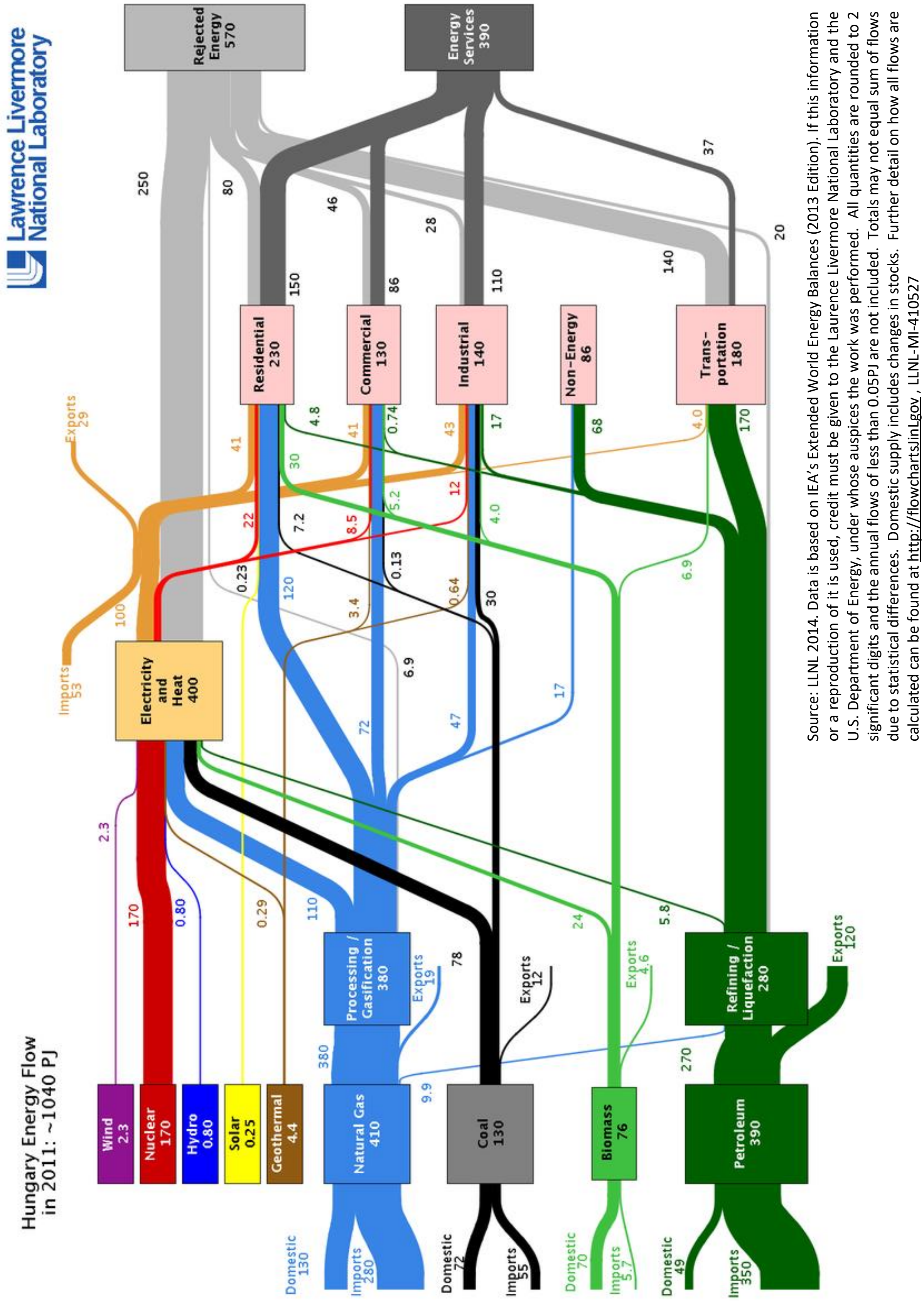


Figure L24. Hungary energy flow between energy source and application (Source: Lawrence Livermore National Laboratory Energy Flow Charts) (Copyright License: https://creativecommons.org/licenses/by-nc-sa/4.0/)

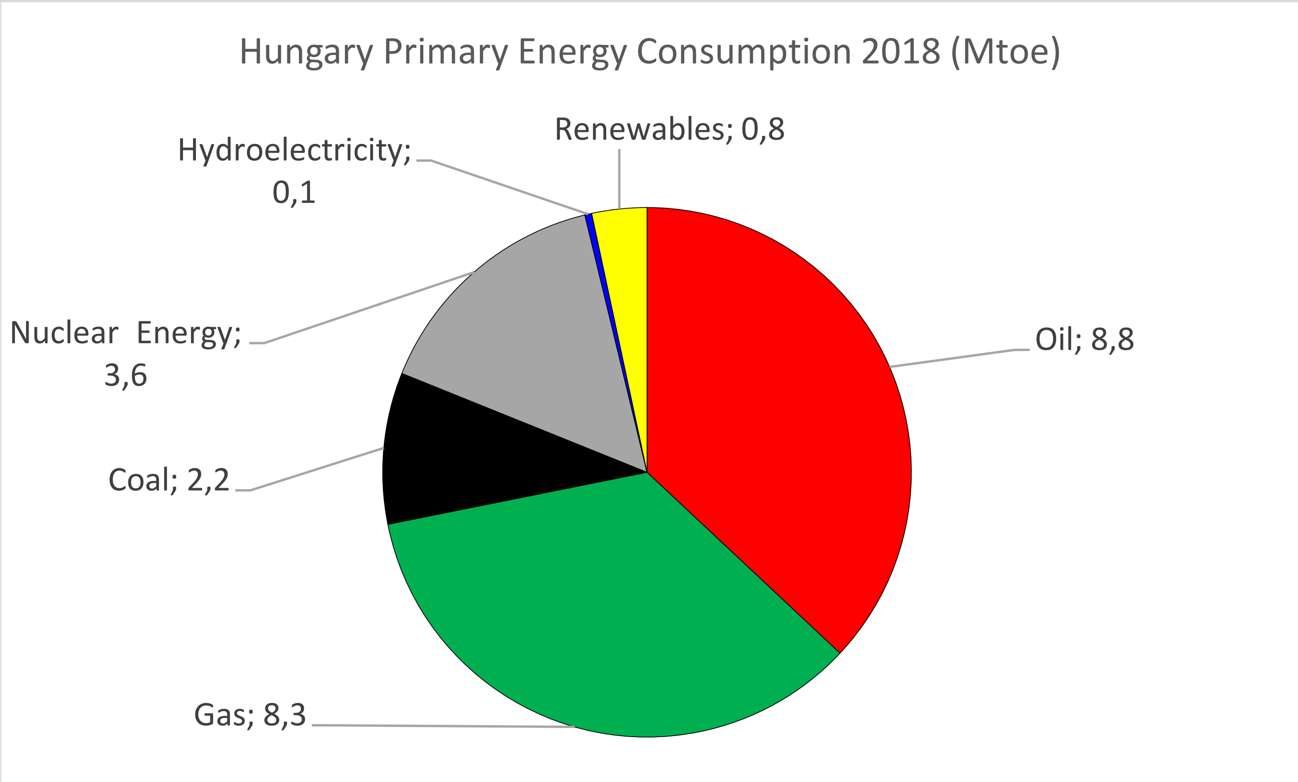


Figure L25. Hungary primary energy consumption by raw material source
(Source: BP Statistical Review of World Energy 2019 & Appendix A)

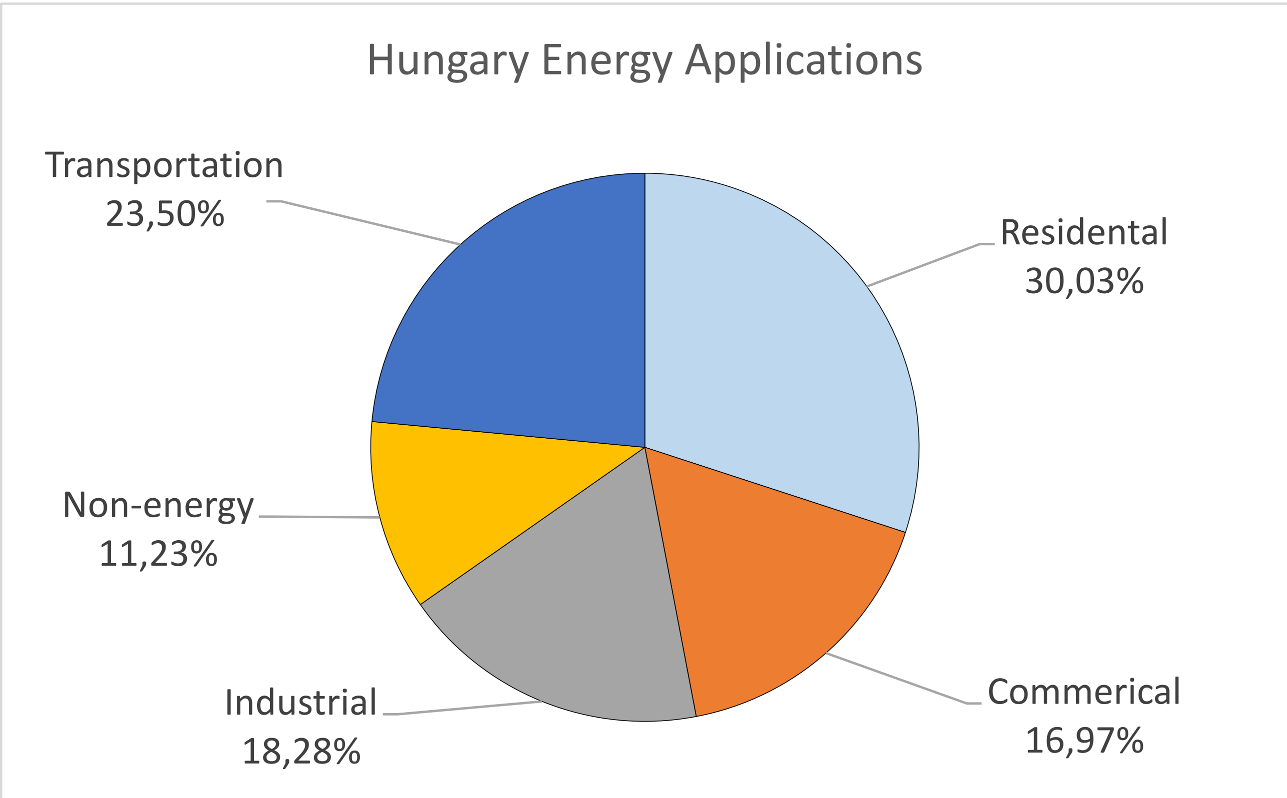


Figure L26. Hungary energy applications
(Source: Lawrence Livermore National Laboratory 2017, EIA 2017)

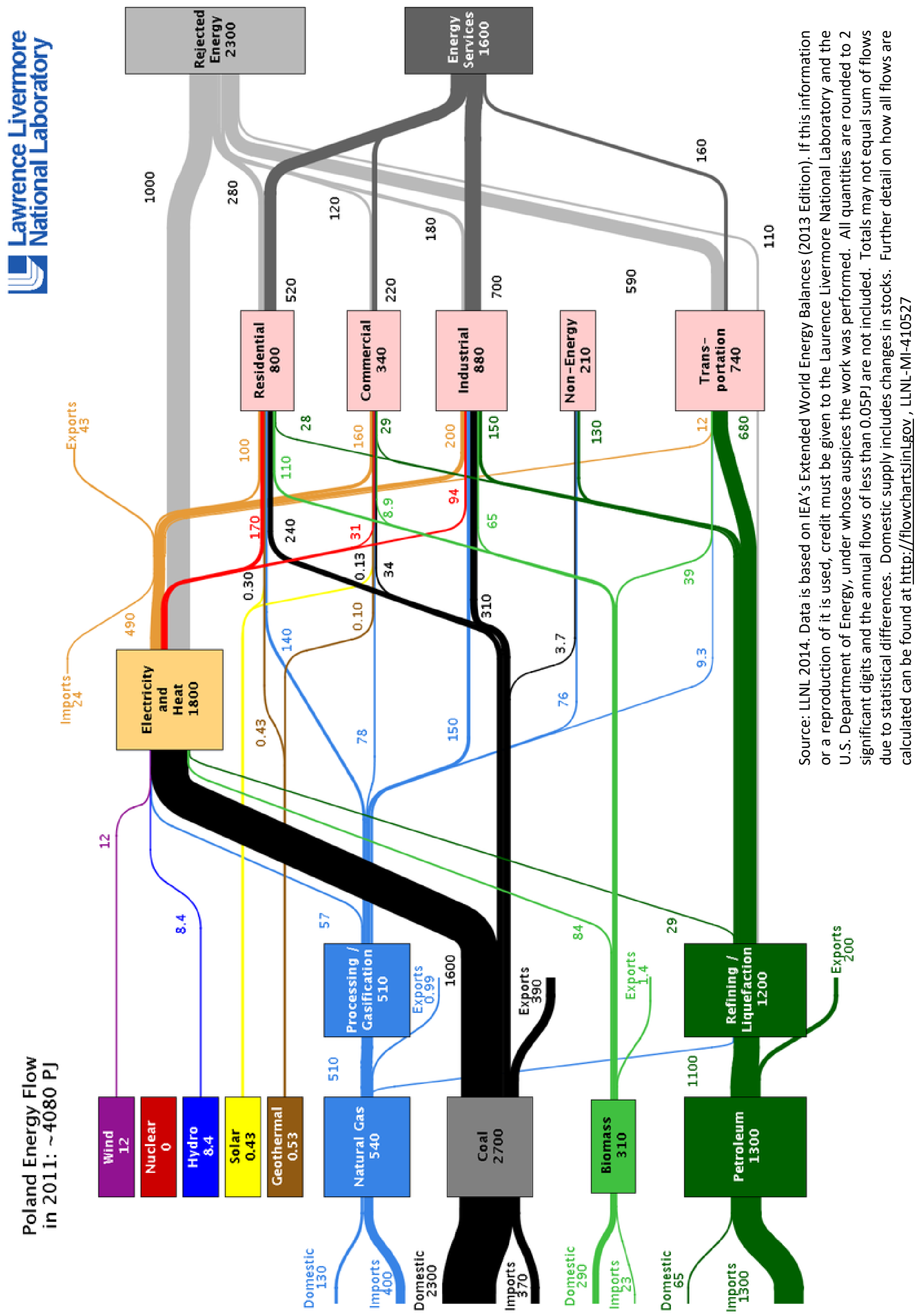


Figure L27. Poland energy flow between energy source and application
(Source: Lawrence Livermore National Laboratory Energy Flow Charts)

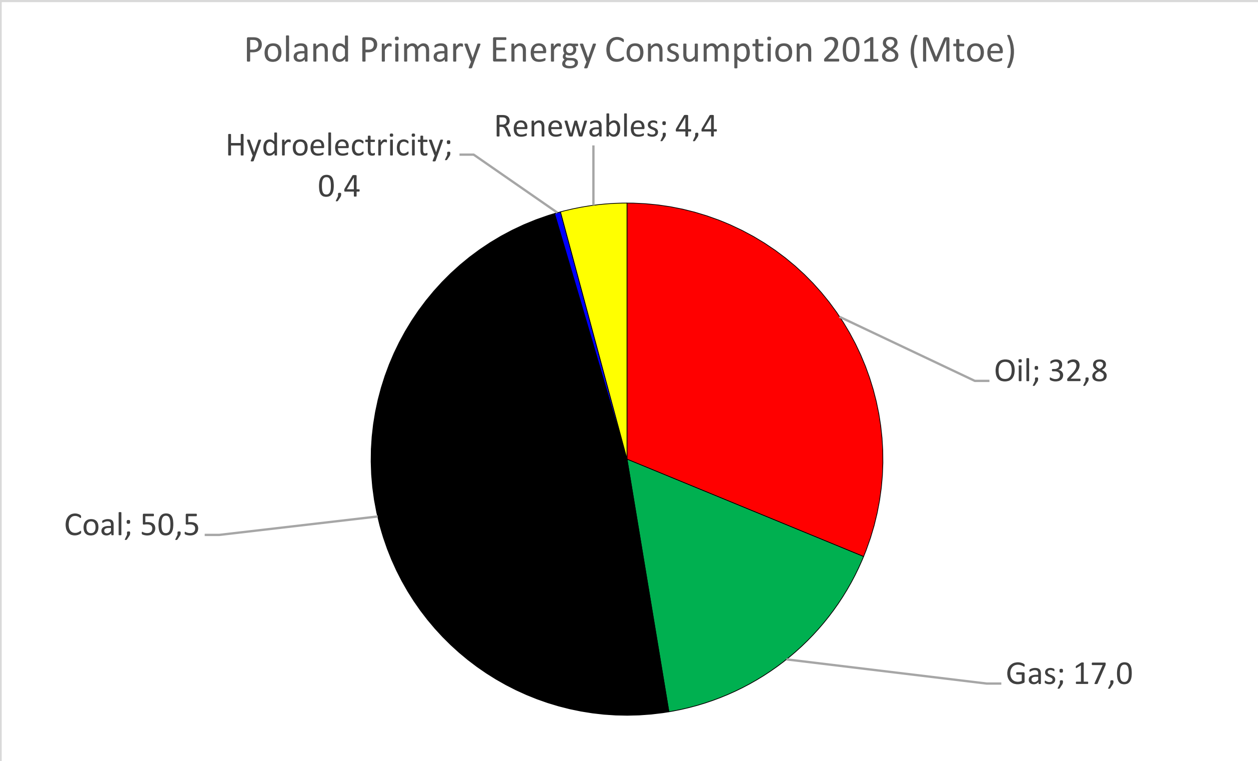


Figure L28. Poland primary energy consumption by raw material source
(Source: BP Statistical Review of World Energy 2019 & Appendix A)

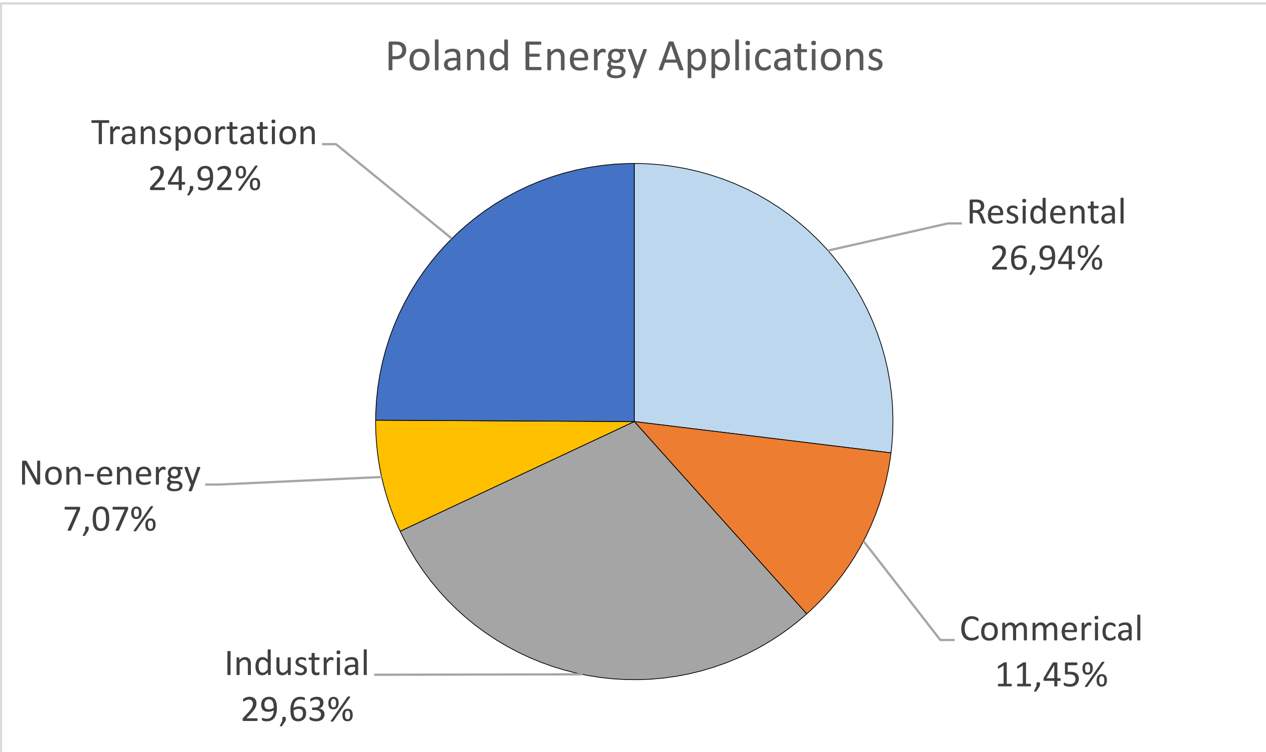


Figure L29. Poland energy applications
(Source: Lawrence Livermore National Laboratory 2017, EIA 2017)

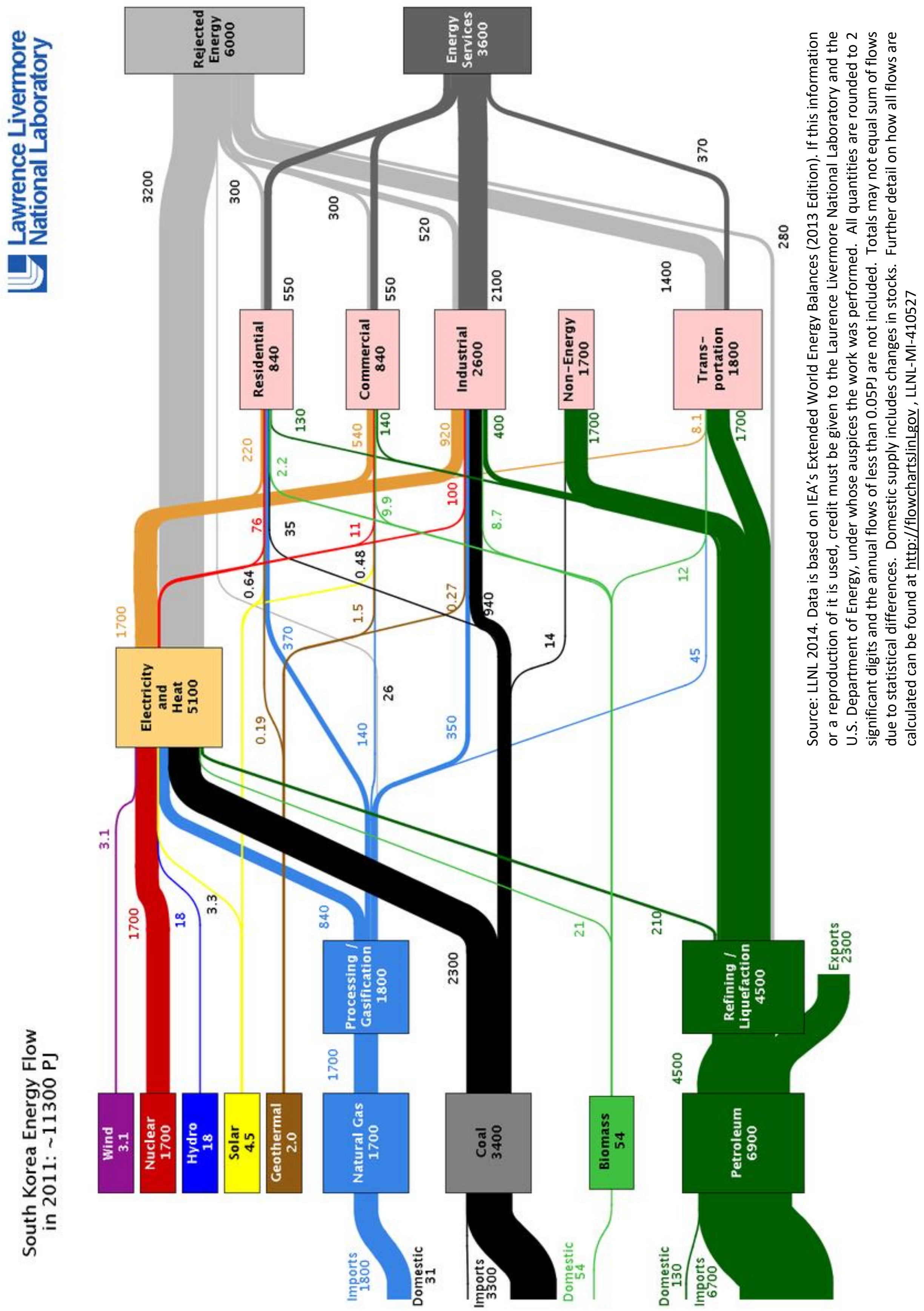


Figure L30. South Korea energy flow between energy source and application
(Source: Lawrence Livermore National Laboratory Energy Flow Charts)

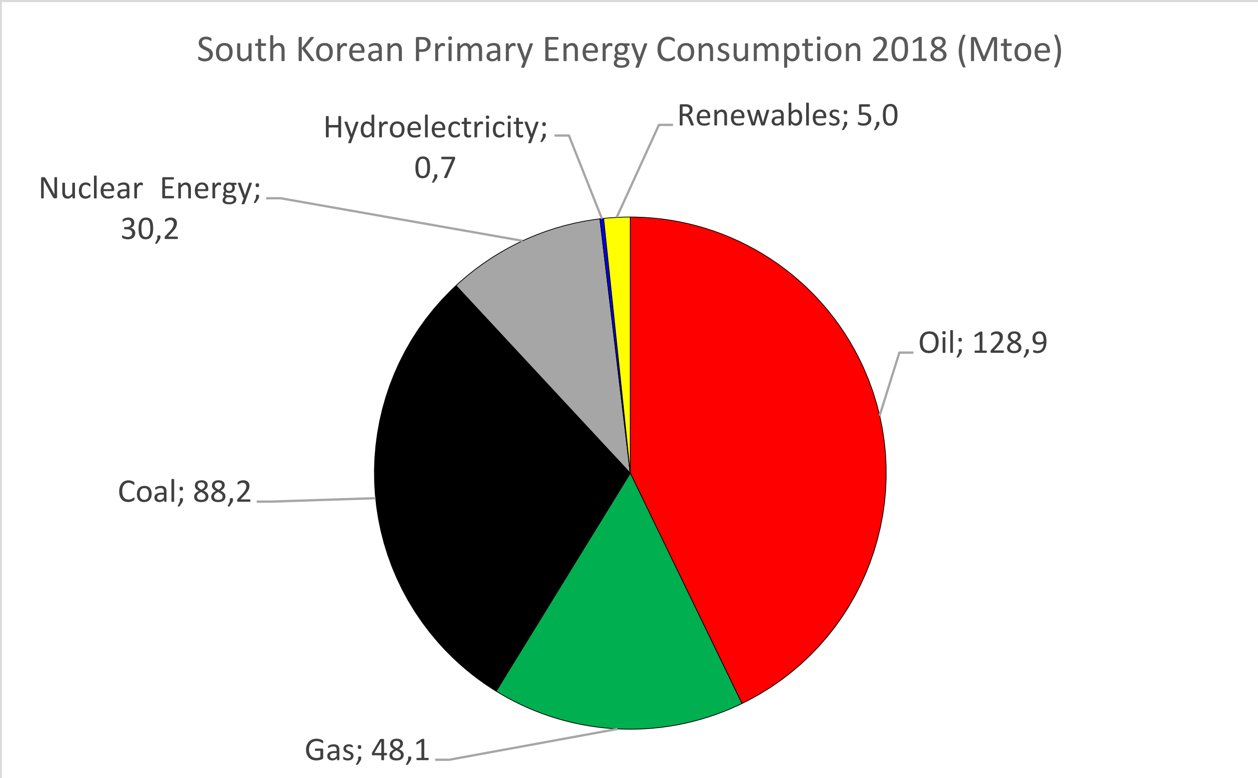


Figure L31. South Korean primary energy consumption by raw material source
(Source: BP Statistical Review of World Energy 2019 & Appendix A)

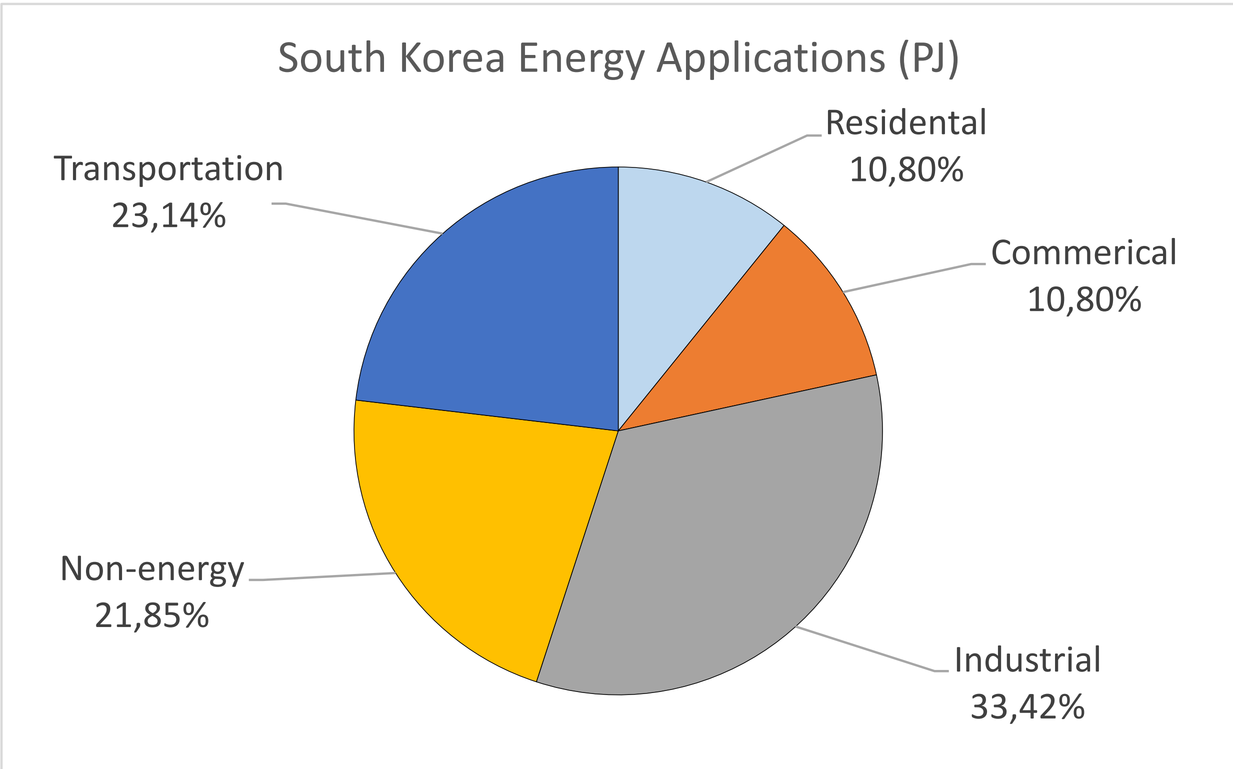


Figure L32. South Korean energy applications
(Source: Lawrence Livermore National Laboratory 2017, EIA 2017)

41.6 Nation States that Produce Energy Raw Materials

The current energy system is heavily dependent on fossil fuels oil, gas and coal. These are the producing nations.

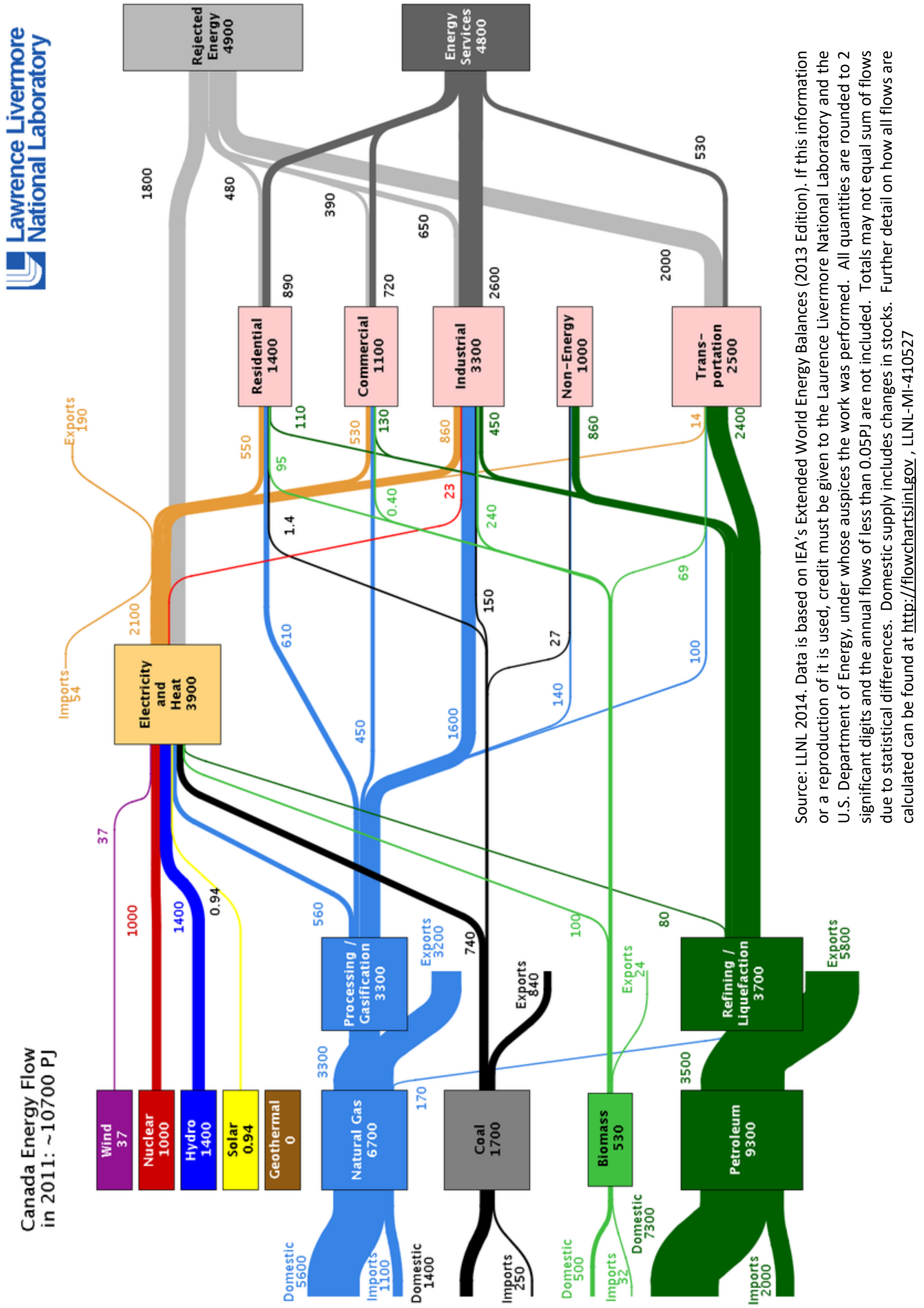


Figure L33. Canada energy flow between energy source and application
(Source: Lawrence Livermore National Laboratory Energy Flow Charts)

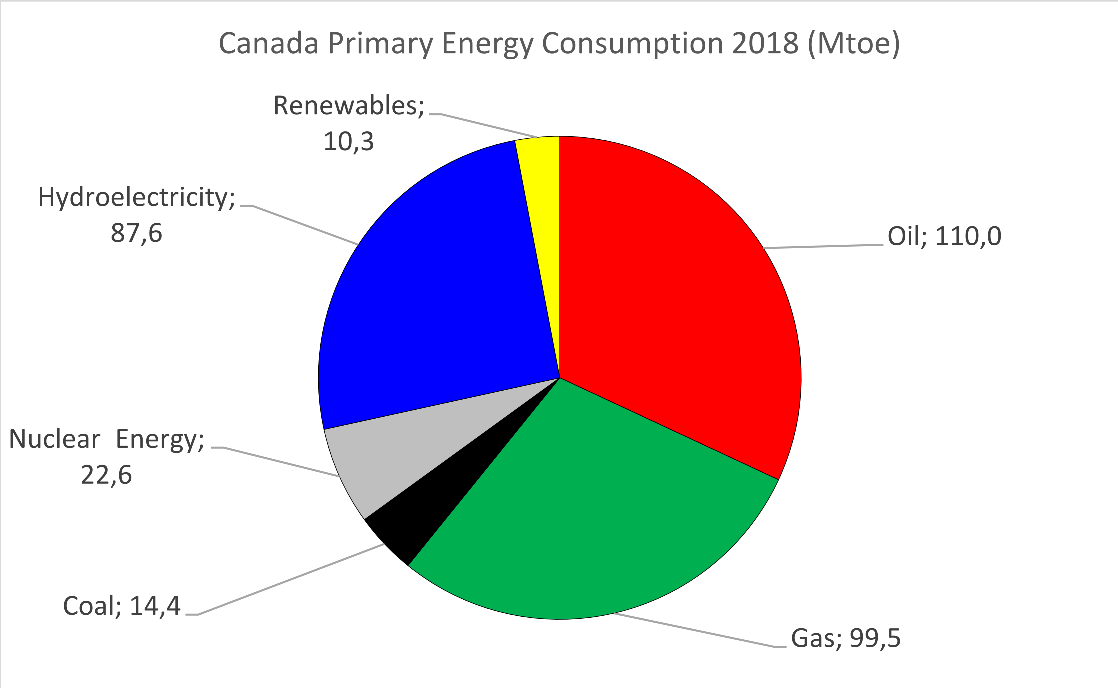


Figure L34. Canada primary energy consumption by raw material source
(Source: BP Statistical Review of World Energy 2019 & Appendix A)

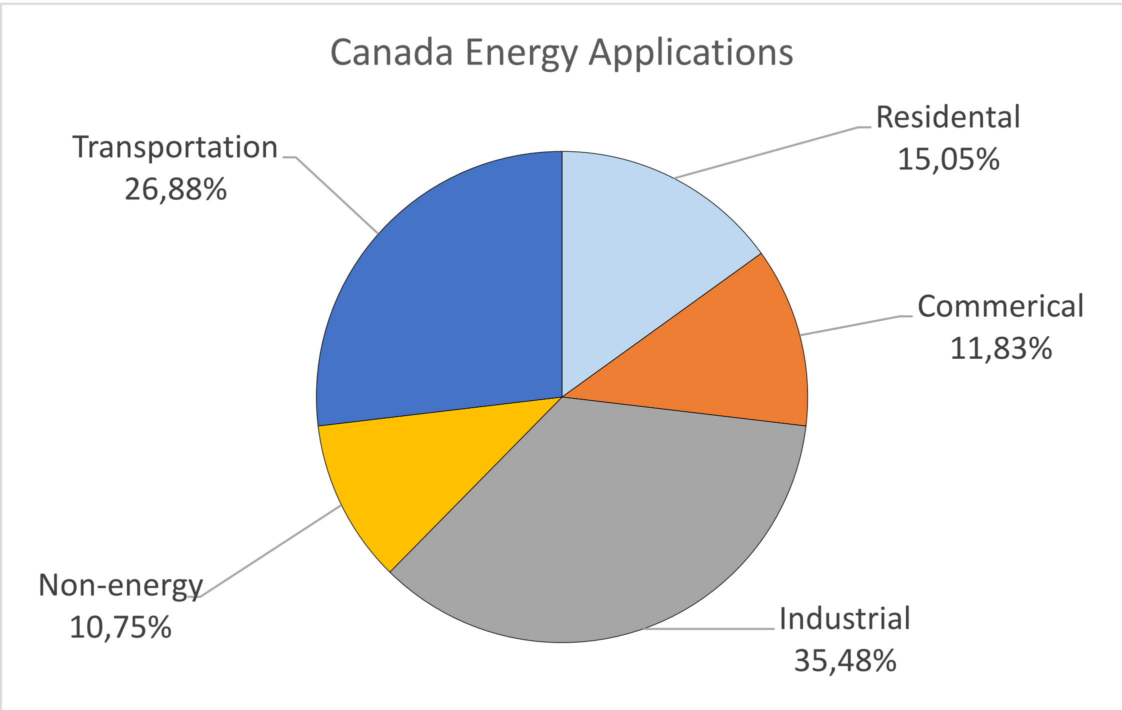


Figure L35. Canada energy applications
(Source: Lawrence Livermore National Laboratory 2017, EIA 2017)

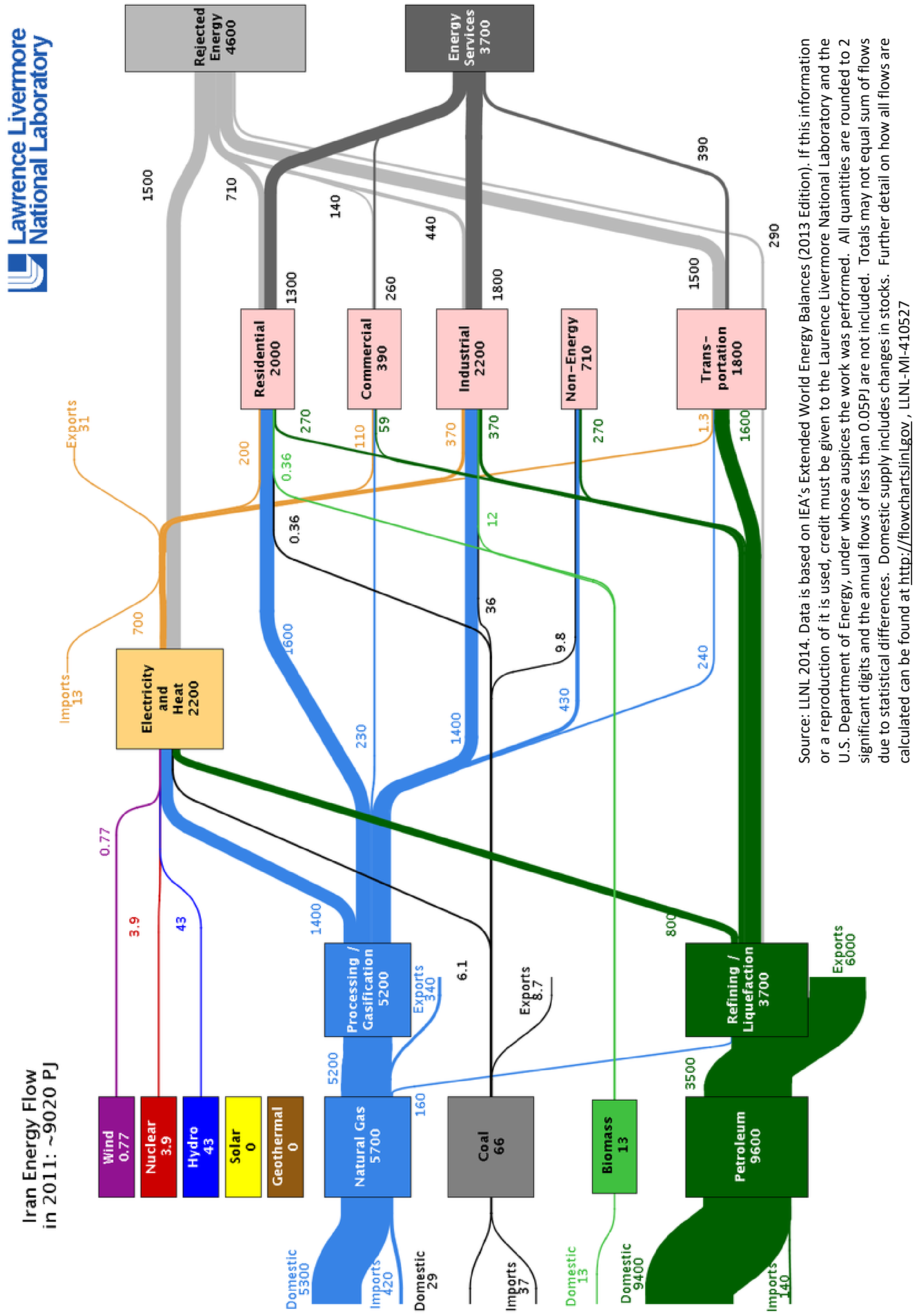


Figure L36. Iran energy flow between energy source and application
(Source: Lawrence Livermore National Laboratory Energy Flow Charts)

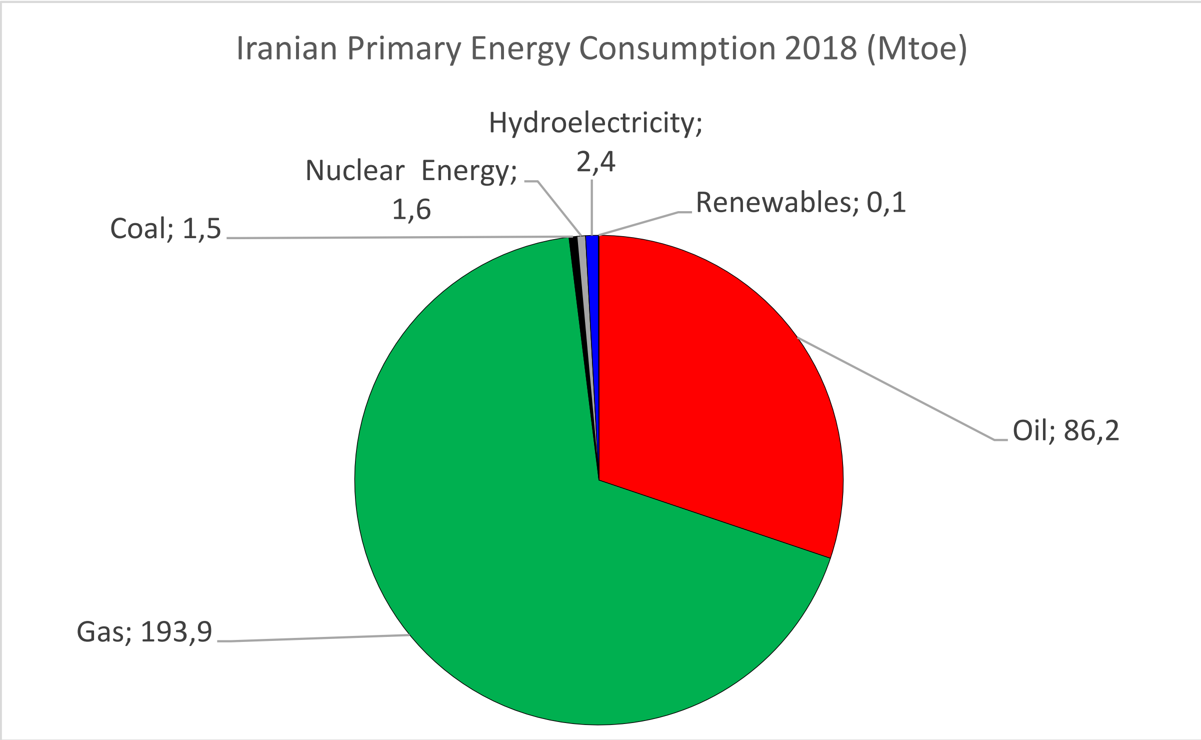


Figure L37. Iranian primary energy consumption by raw material source
(Source: BP Statistical Review of World Energy 2019 & Appendix A)

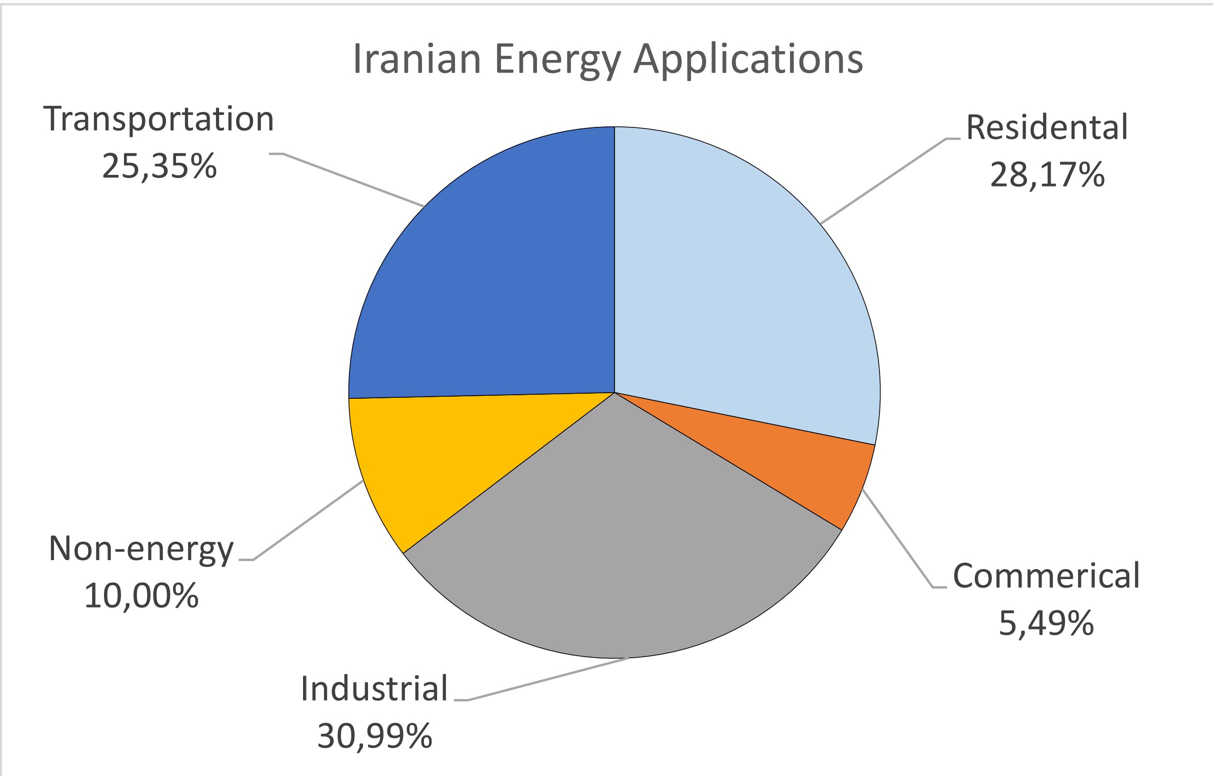


Figure L38. Iranian energy applications
(Source: Lawrence Livermore National Laboratory 2017, EIA 2017)

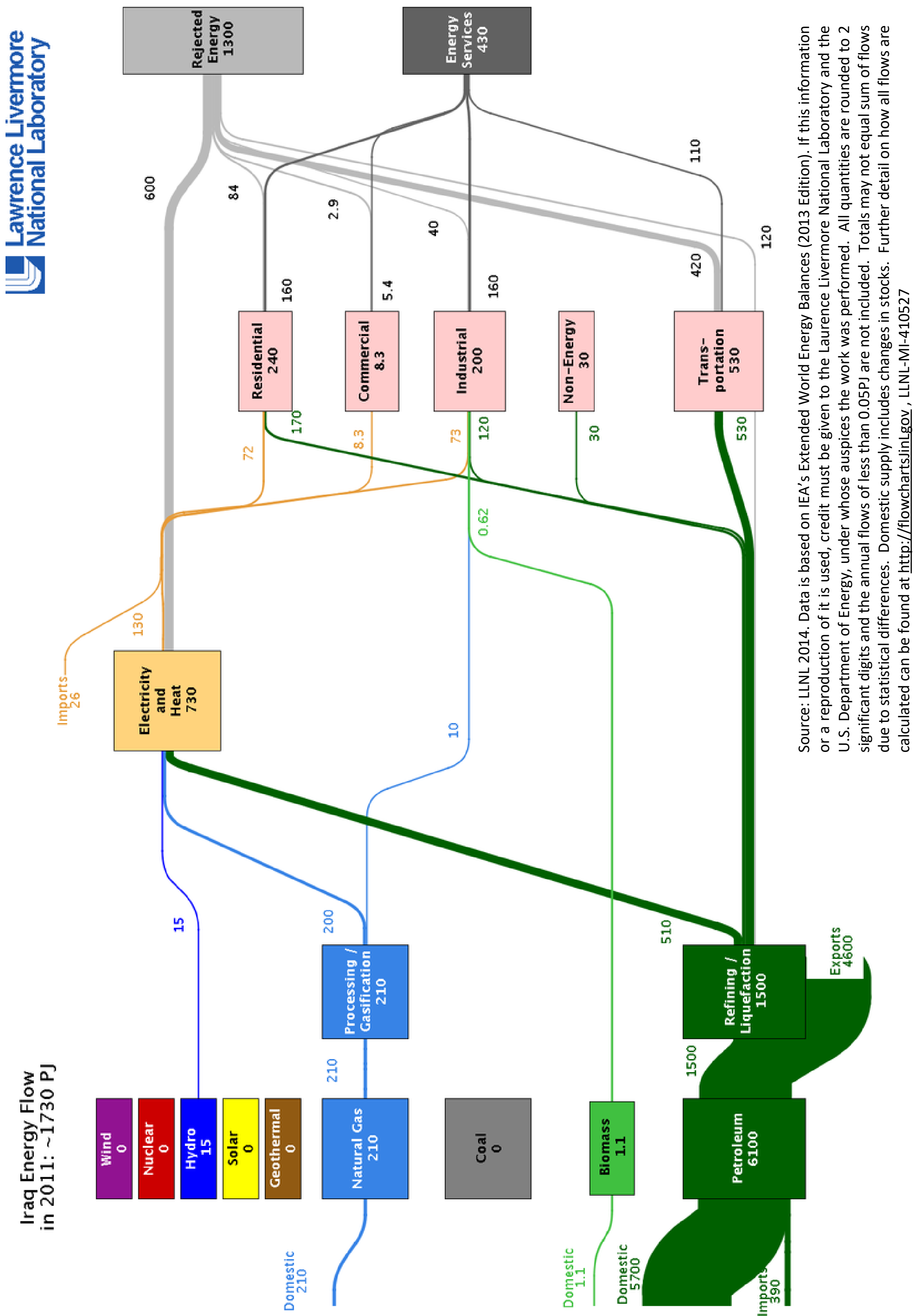


Figure L39. Iraq energy flow between energy source and application (Source: Lawrence Livermore National Laboratory Energy Flow Charts) (Copyright License: https://creativecommons.org/licenses/by-nc-sa/4.0/)

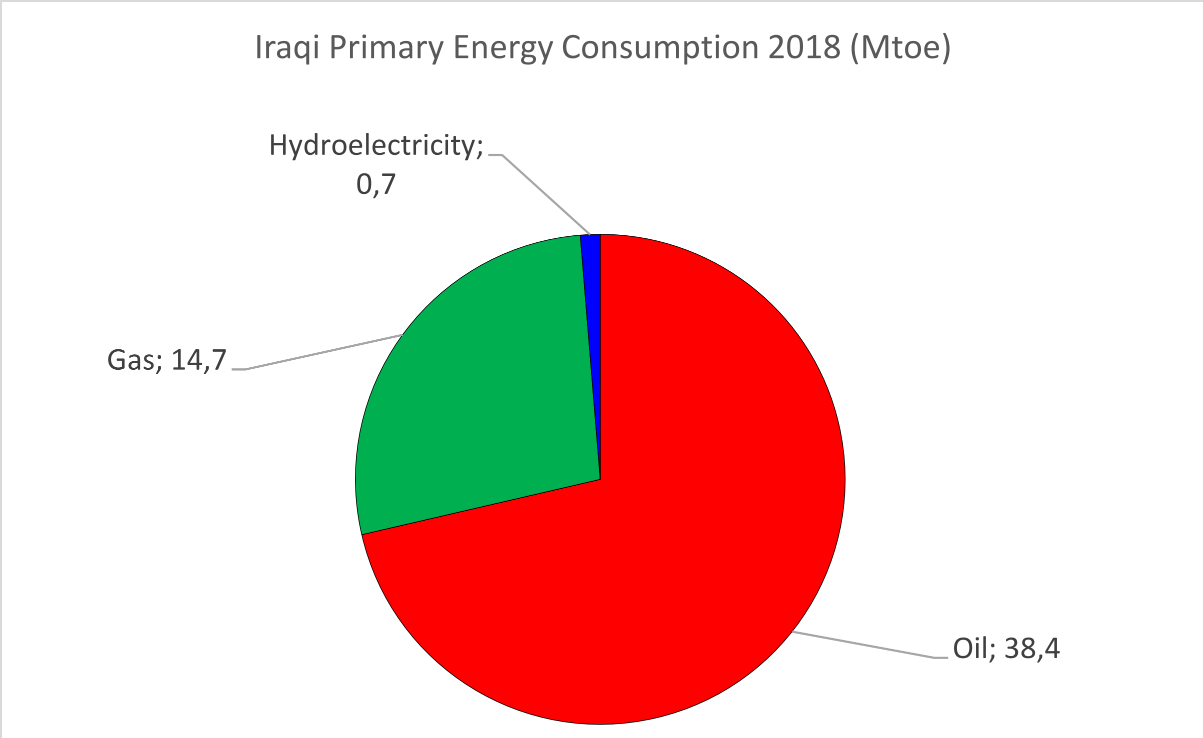


Figure L40. Iraqi primary energy consumption by raw material source
(Source: BP Statistical Review of World Energy 2019 & Appendix A)

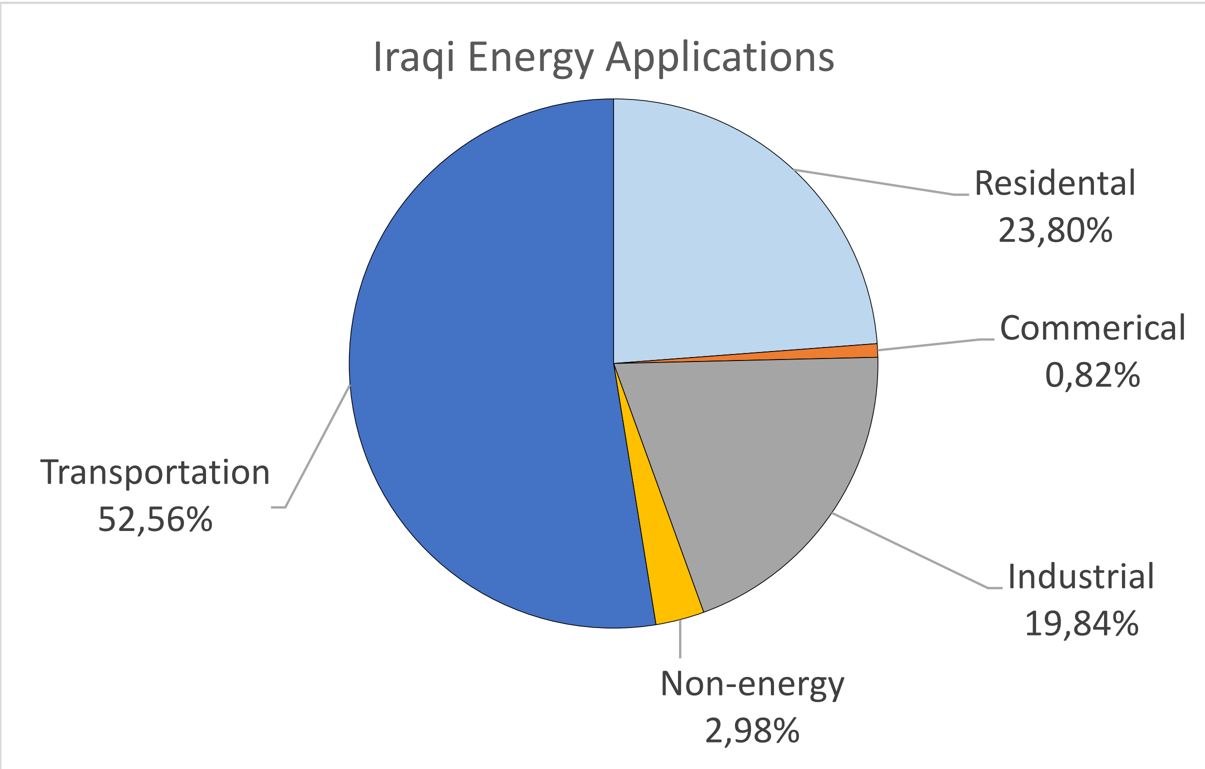


Figure L41. Iraqi energy applications
(Source: Lawrence Livermore National Laboratory 2017, EIA 2017)

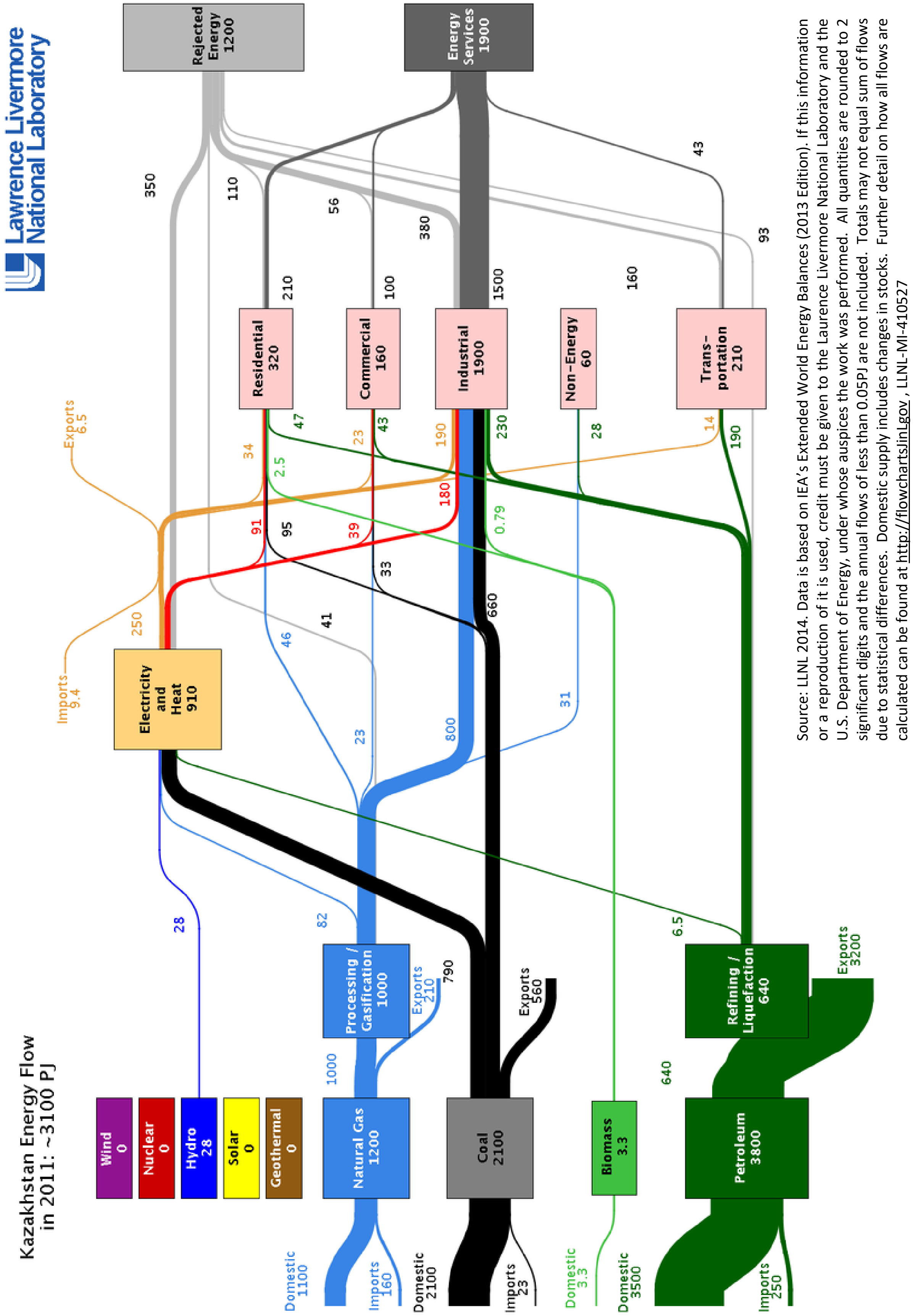


Figure L42. Kazakhstan energy flow between energy source and application
(Source: Lawrence Livermore National Laboratory Energy Flow Charts)

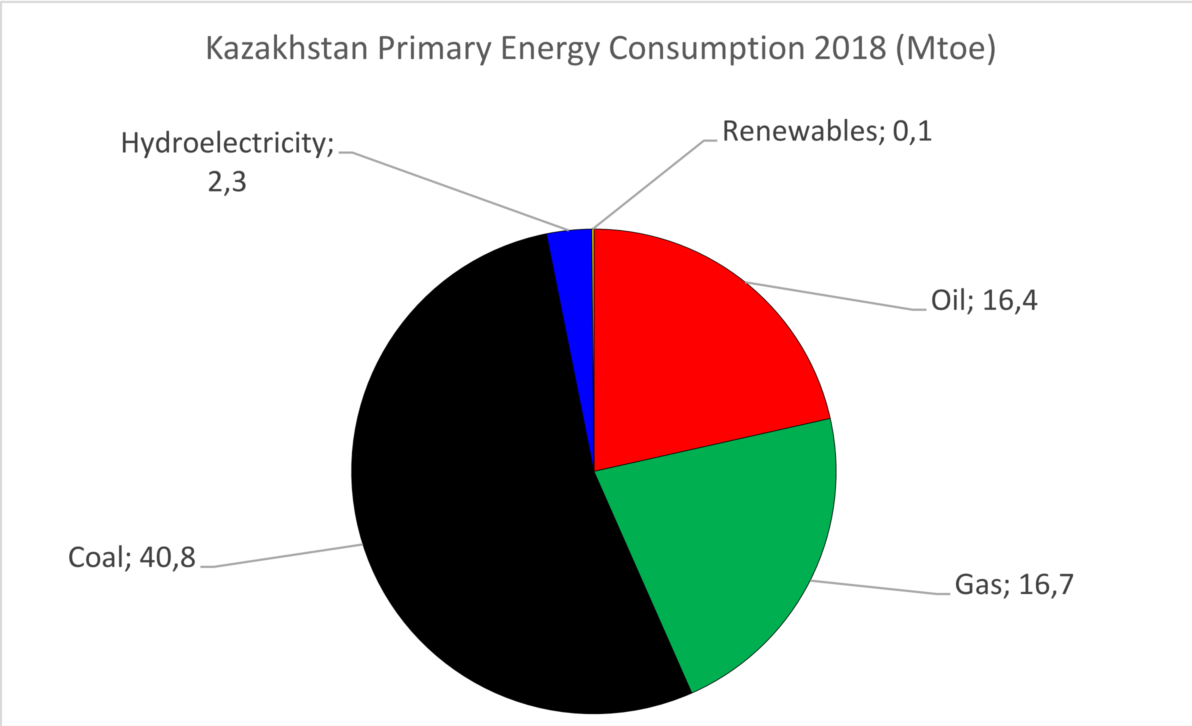


Figure L43. Kazakhstan primary energy consumption by raw material source
(Source: BP Statistical Review of World Energy 2019 & Appendix A)

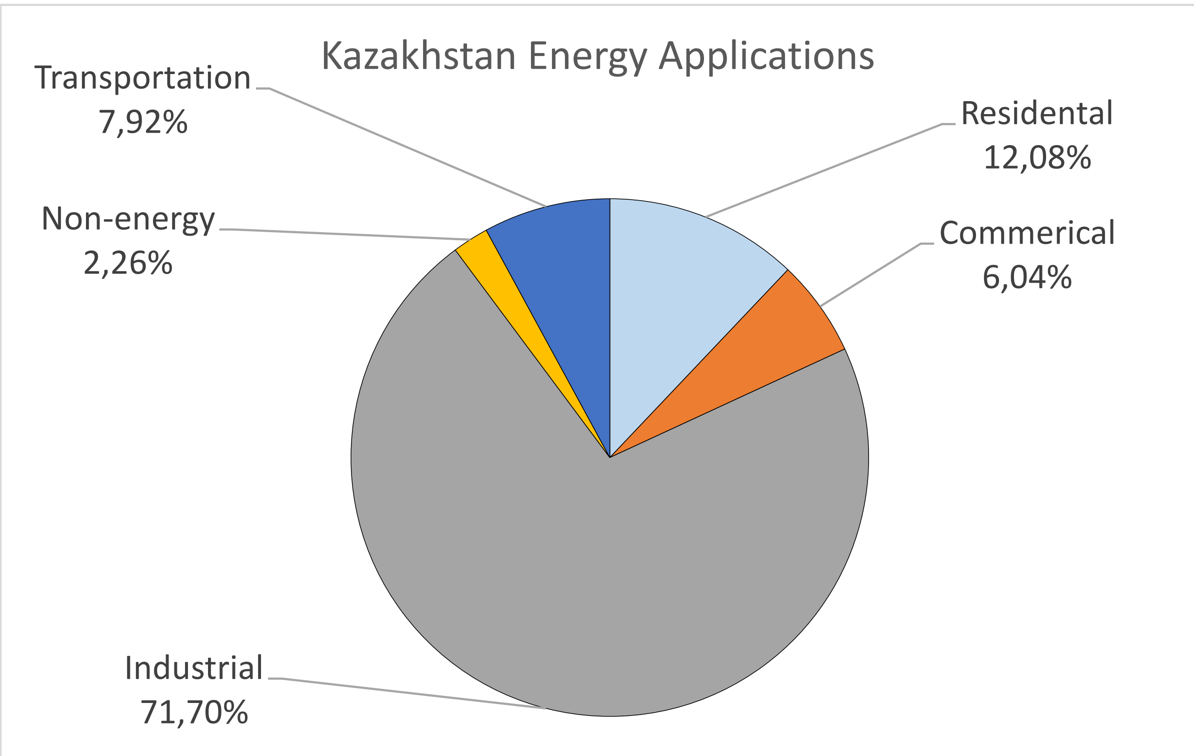


Figure L44. Kazakhstan energy applications
(Source: Lawrence Livermore National Laboratory 2017, EIA 2017)

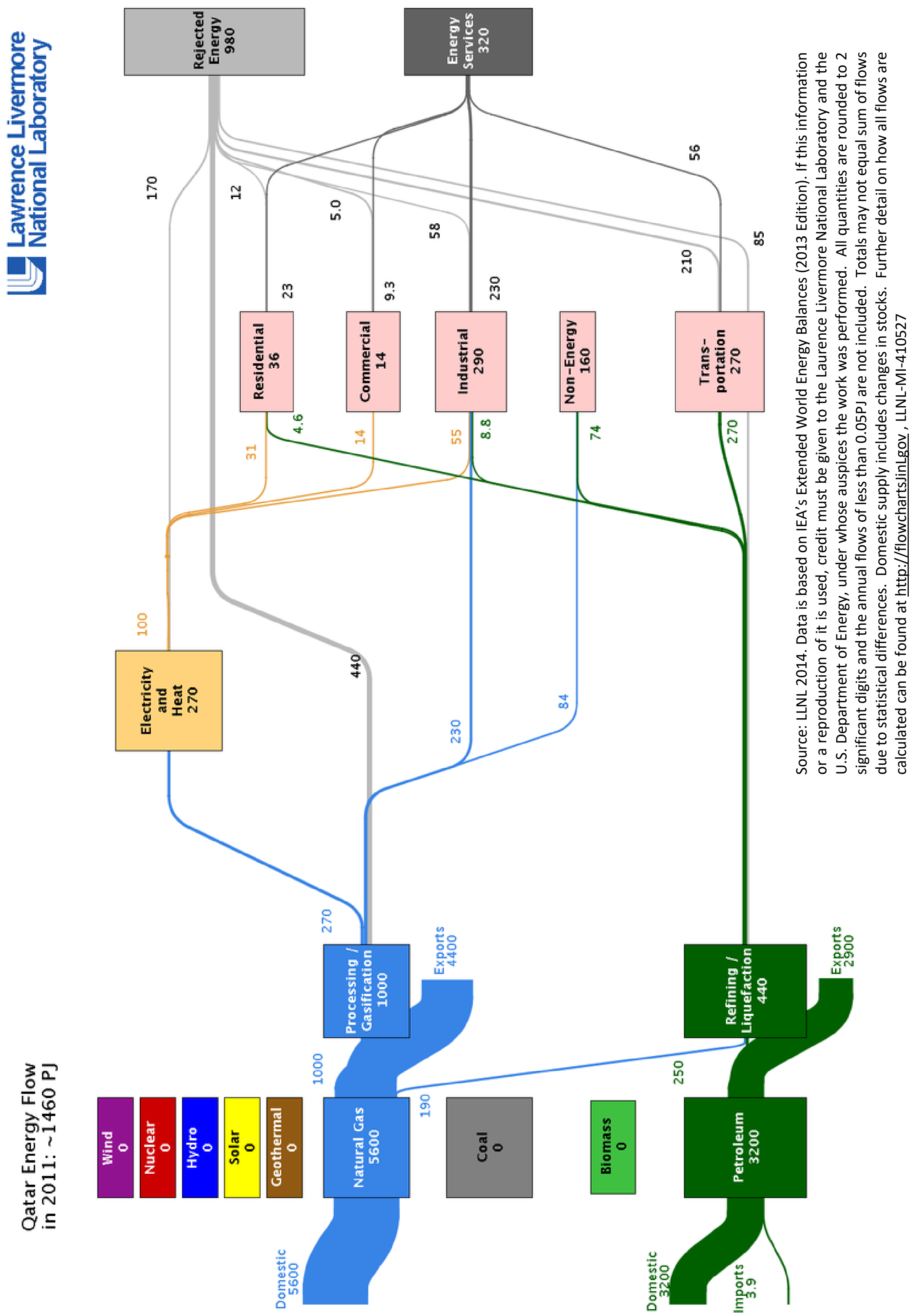


Figure L45. Qatar energy flow between energy source and application
(Source: Lawrence Livermore National Laboratory Energy Flow Charts)

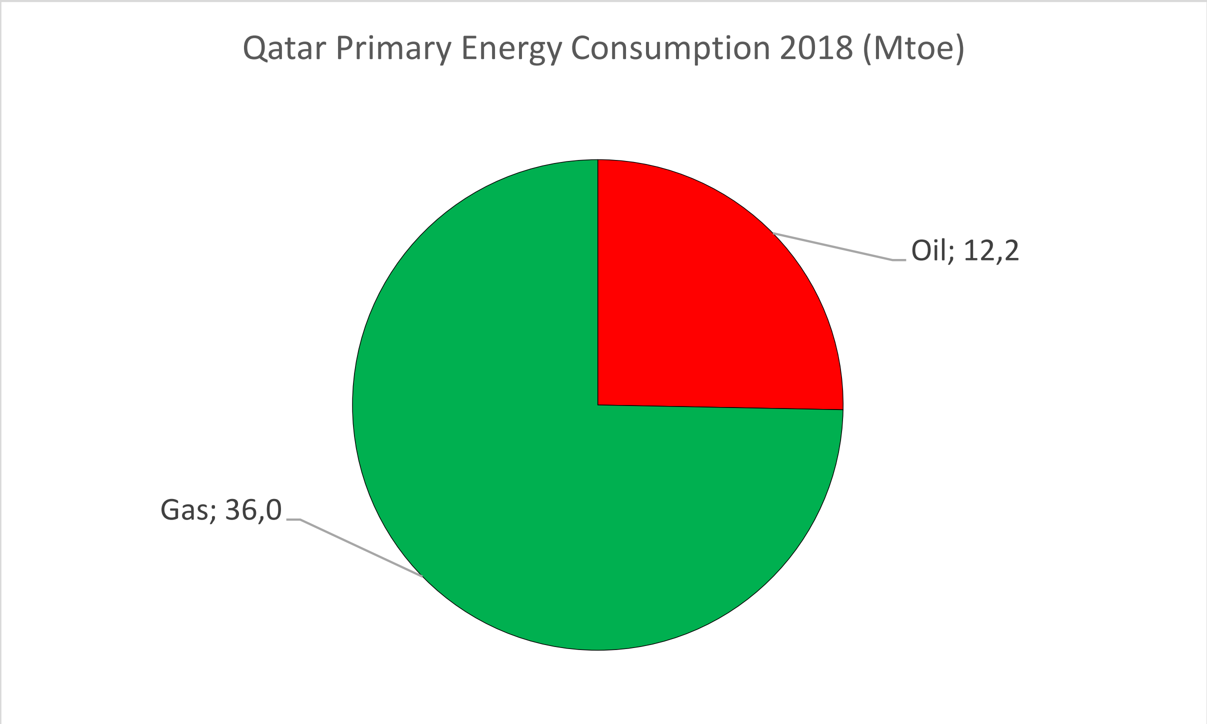


Figure L46. Qatar primary energy consumption by raw material source
(Source: BP Statistical Review of World Energy 2019 & Appendix A)

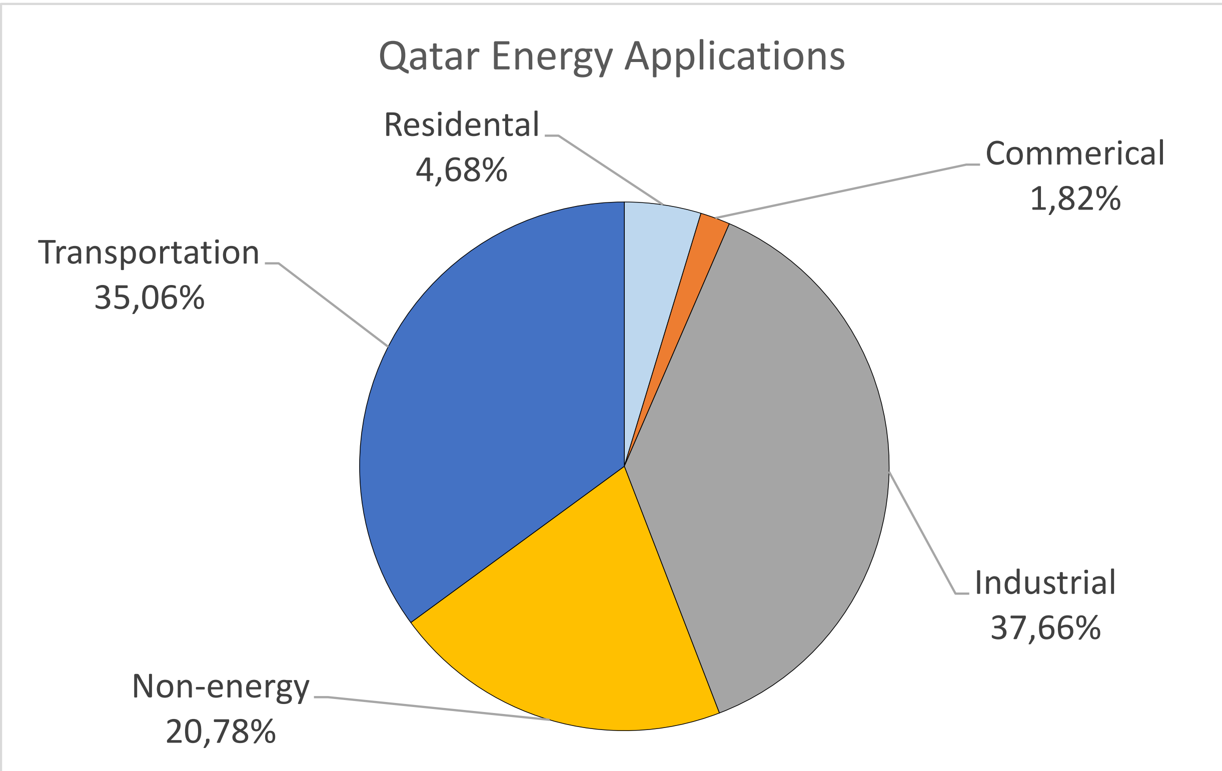


Figure L47. Qatar energy applications
(Source: Lawrence Livermore National Laboratory 2017, EIA 2017)

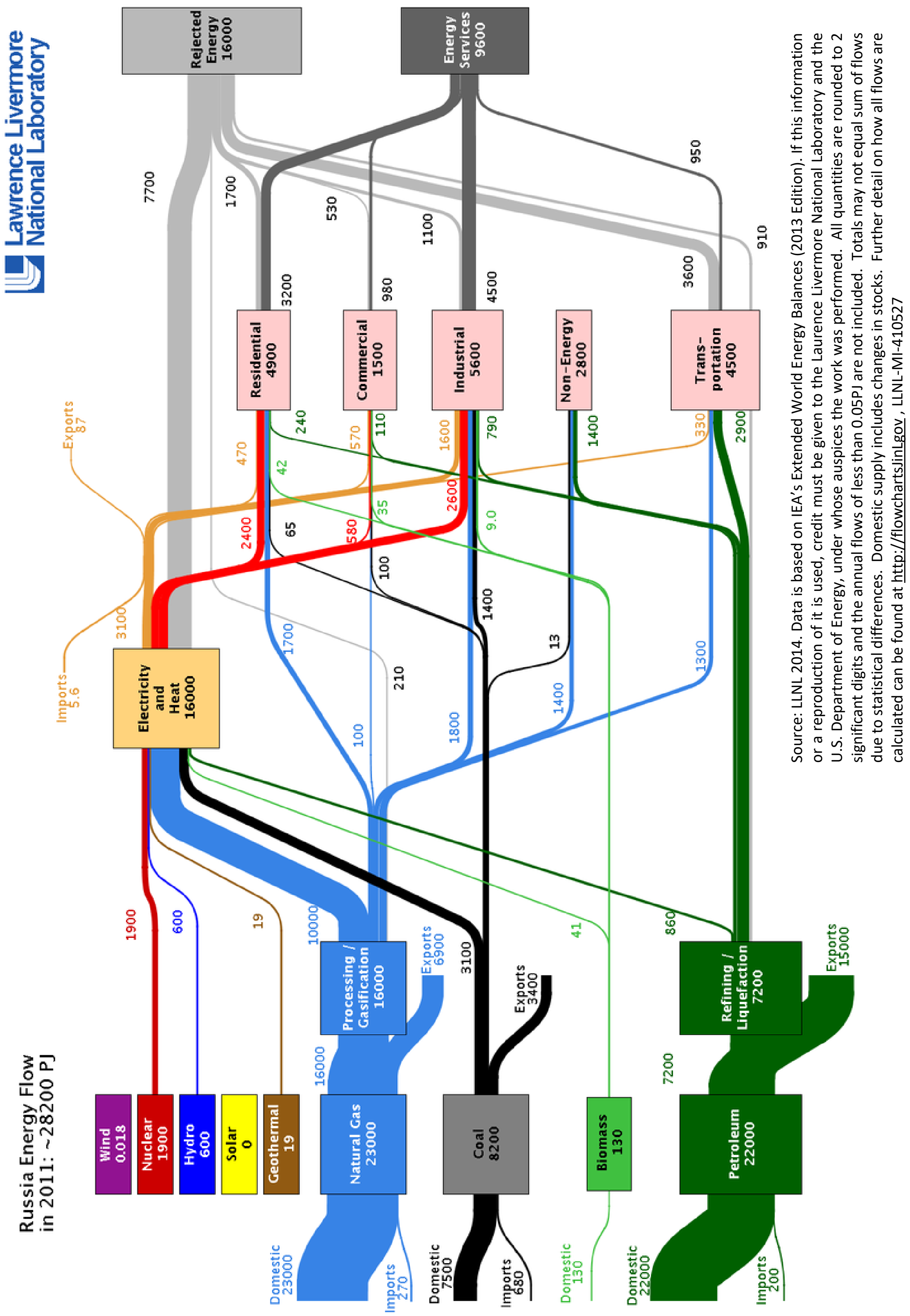


Figure L48. Russia energy flow between energy source and application
(Source: Lawrence Livermore National Laboratory Energy Flow Charts)

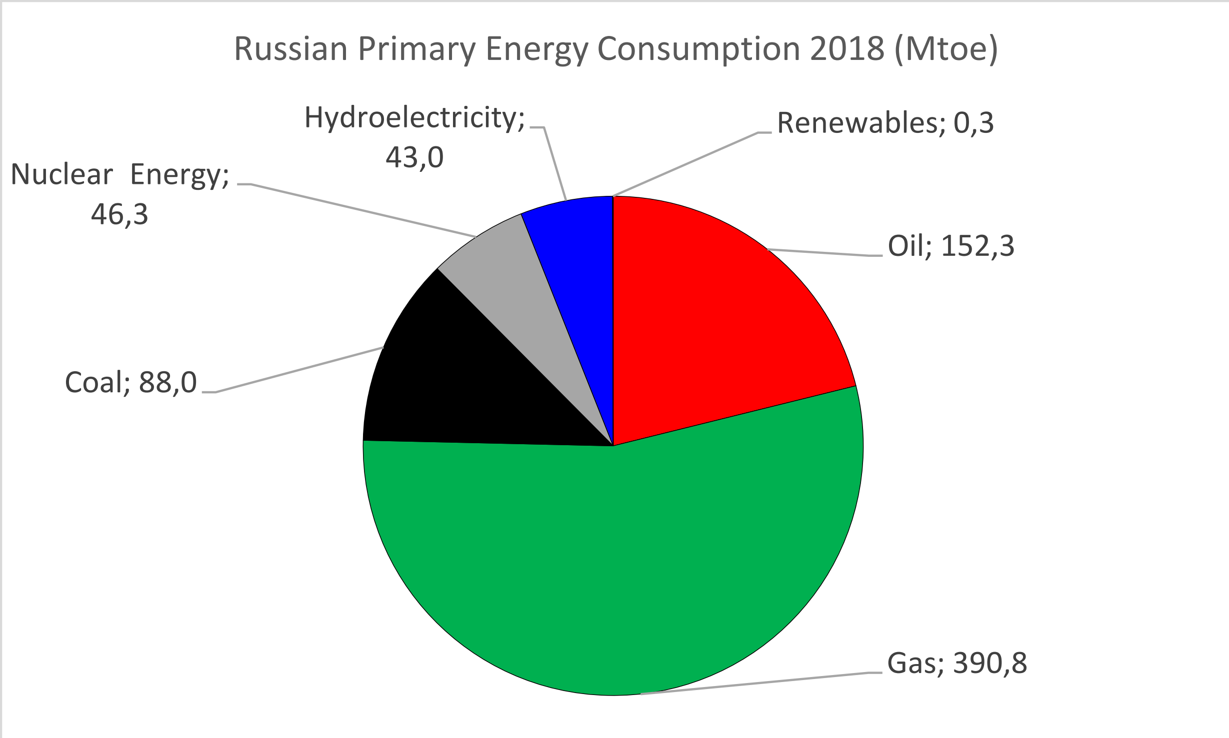


Figure L49. Russian primary energy consumption by raw material source
(Source: BP Statistical Review of World Energy 2019 & Appendix A)

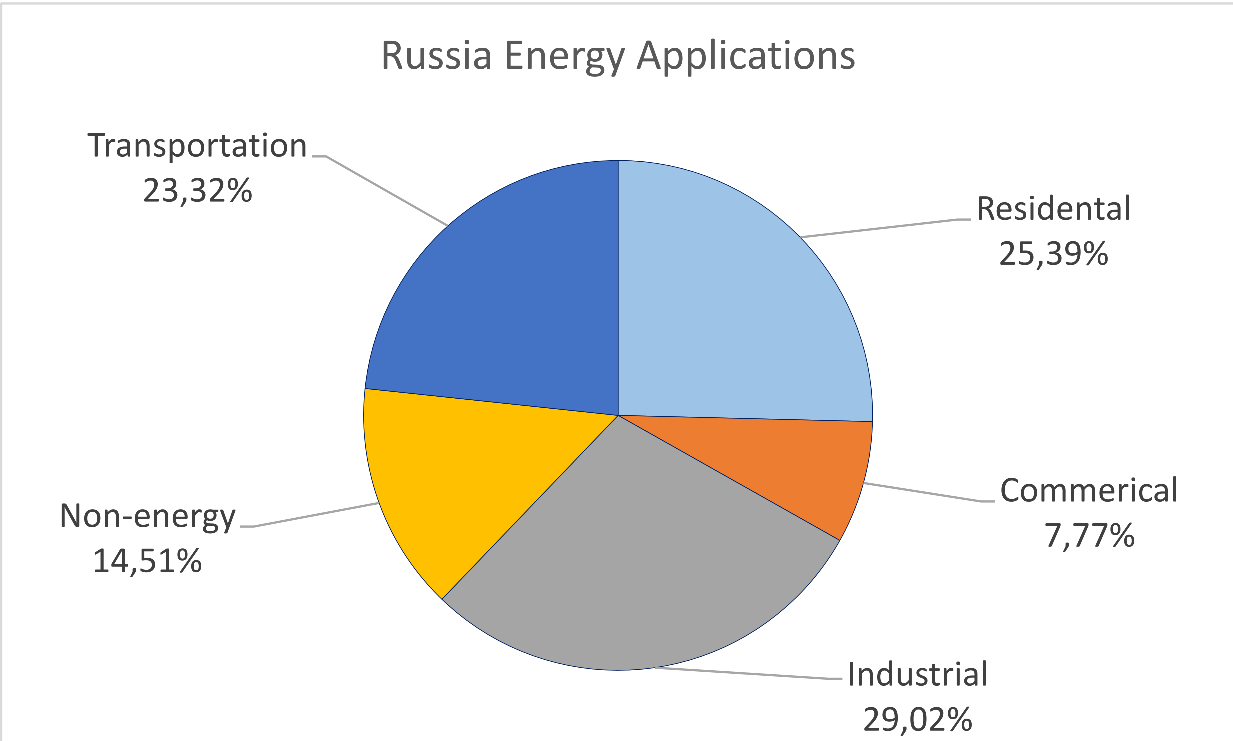


Figure L50. Russian energy applications
(Source: Lawrence Livermore National Laboratory 2017, EIA 2017)

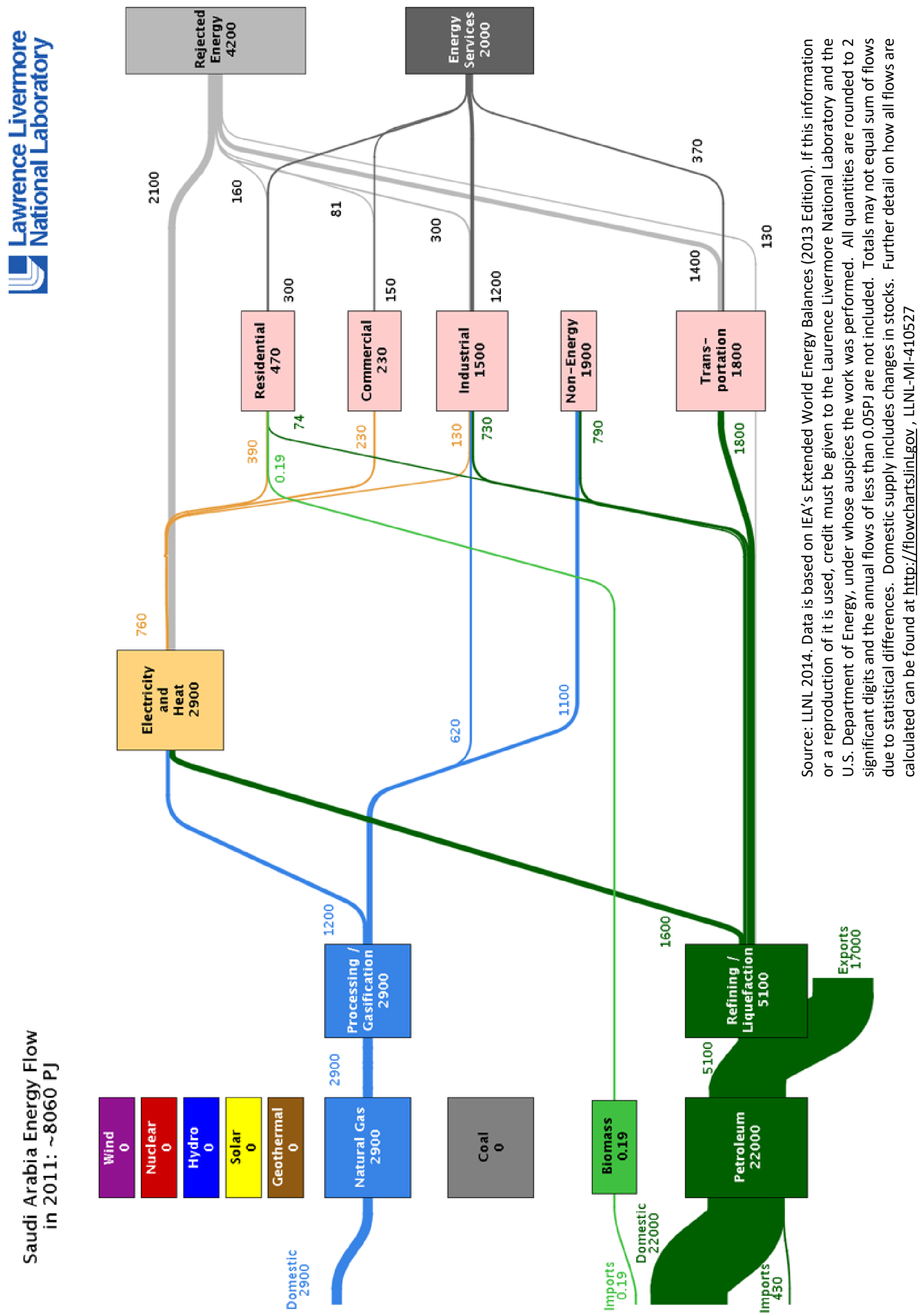


Figure L51. Saudi Arabia energy flow between energy source and application
(Source: Lawrence Livermore National Laboratory Energy Flow Charts)

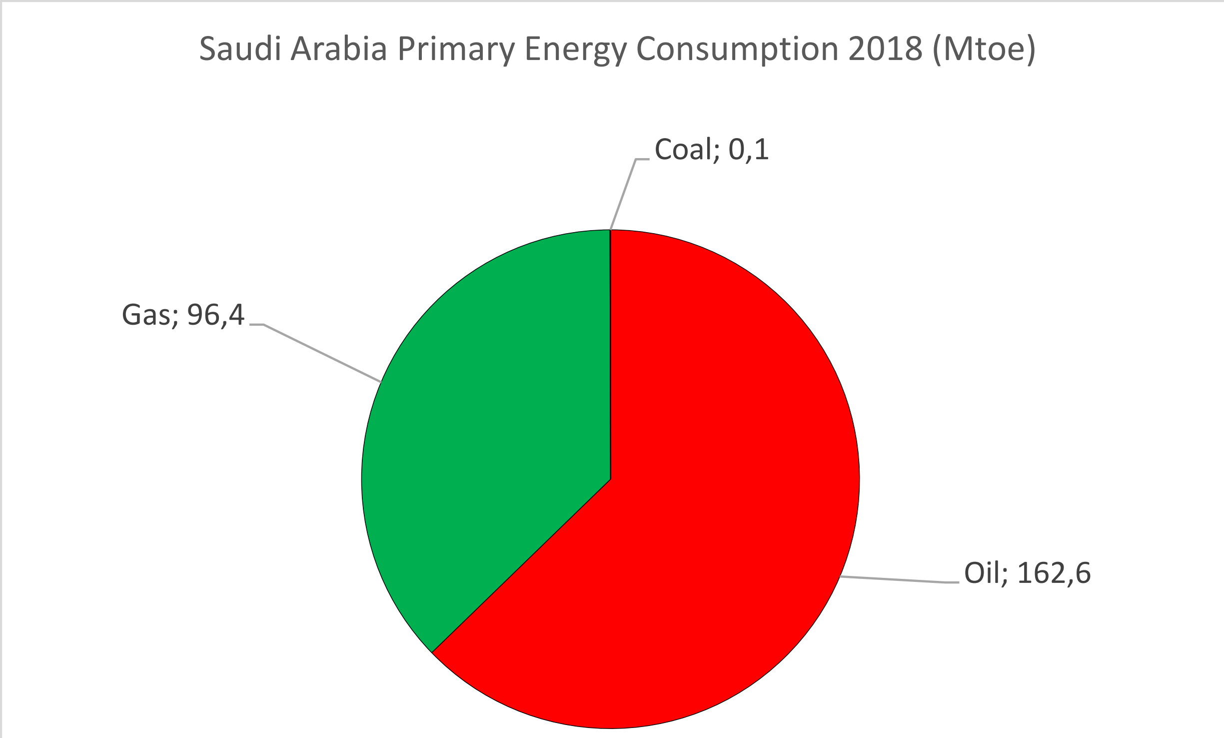


Figure L52. Saudi Arabia primary energy consumption by raw material source
(Source: BP Statistical Review of World Energy 2019 & Appendix A)

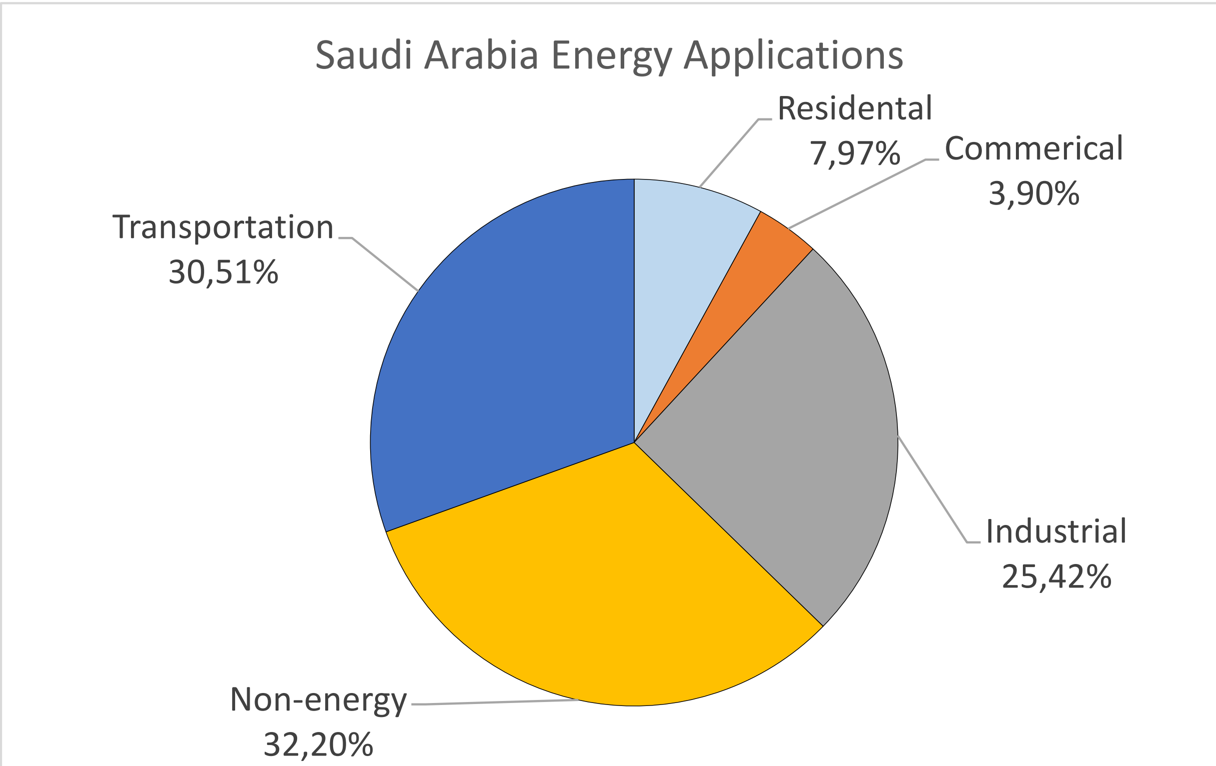


Figure L53. Saudi Arabia energy applications
(Source: Lawrence Livermore National Laboratory 2017, EIA 2017)

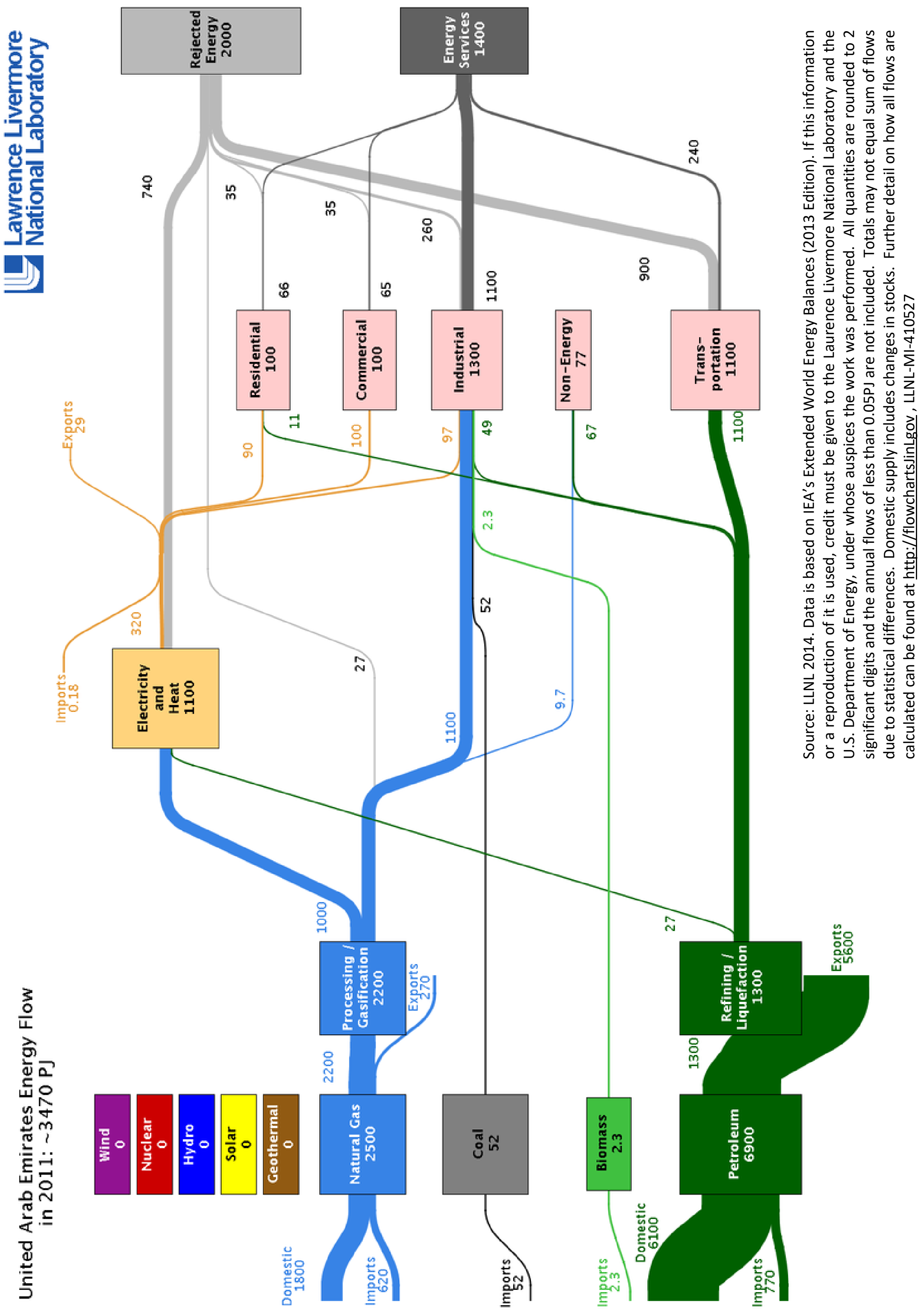


Figure L54. United Arab Emirates energy flow between energy source and application
(Source: Lawrence Livermore National Laboratory Energy Flow Charts)

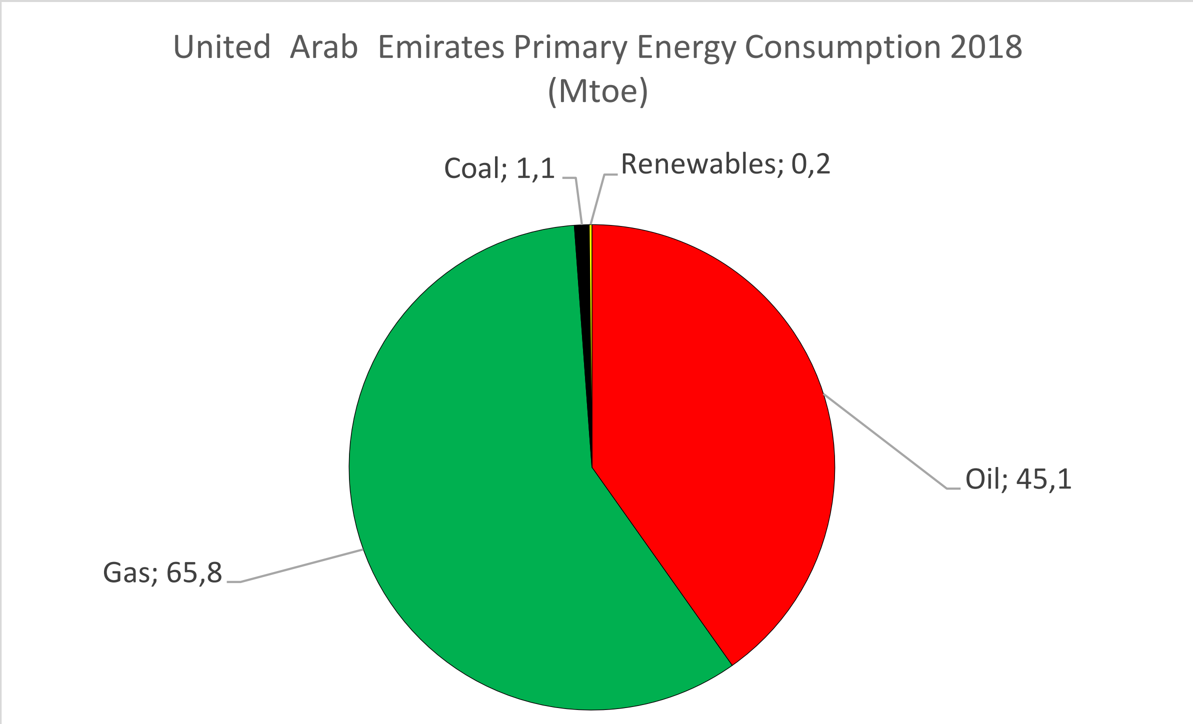


Figure L55. United Arab Emirates primary energy consumption by raw material source
(Source: BP Statistical Review of World Energy 2019 & Appendix A)

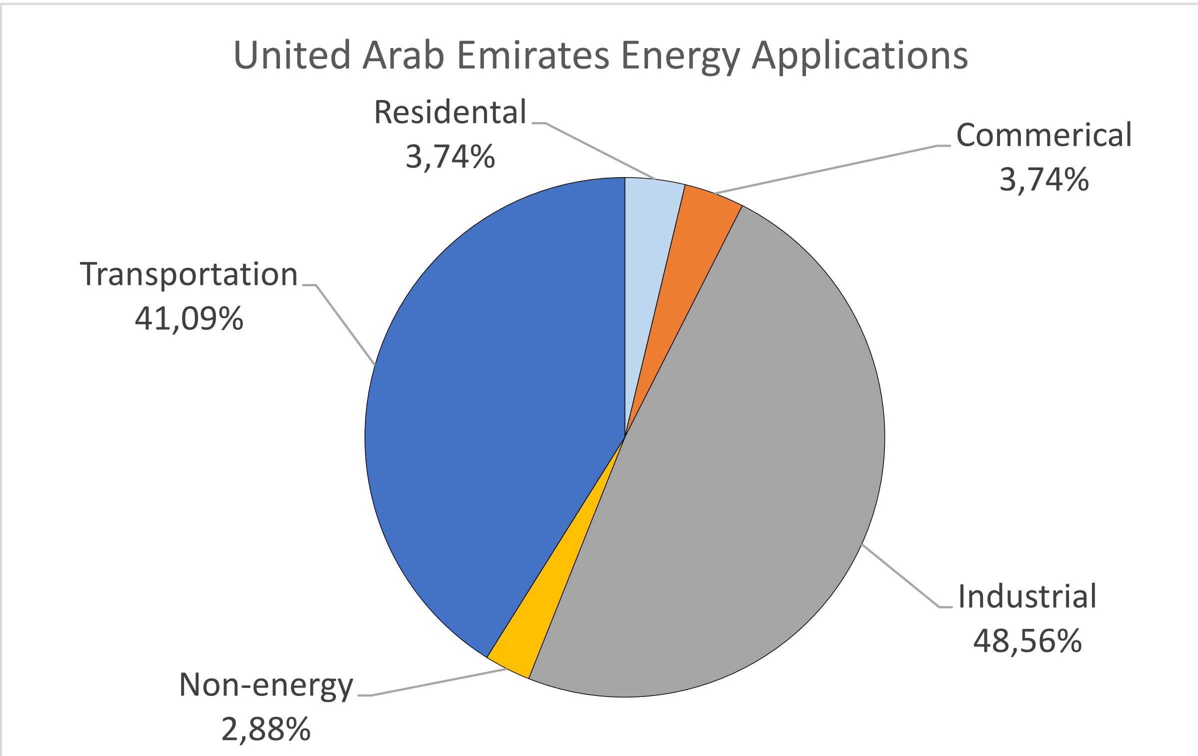


Figure L56. United Arab Emirates energy applications
(Source: Lawrence Livermore National Laboratory 2017, EIA 2017)

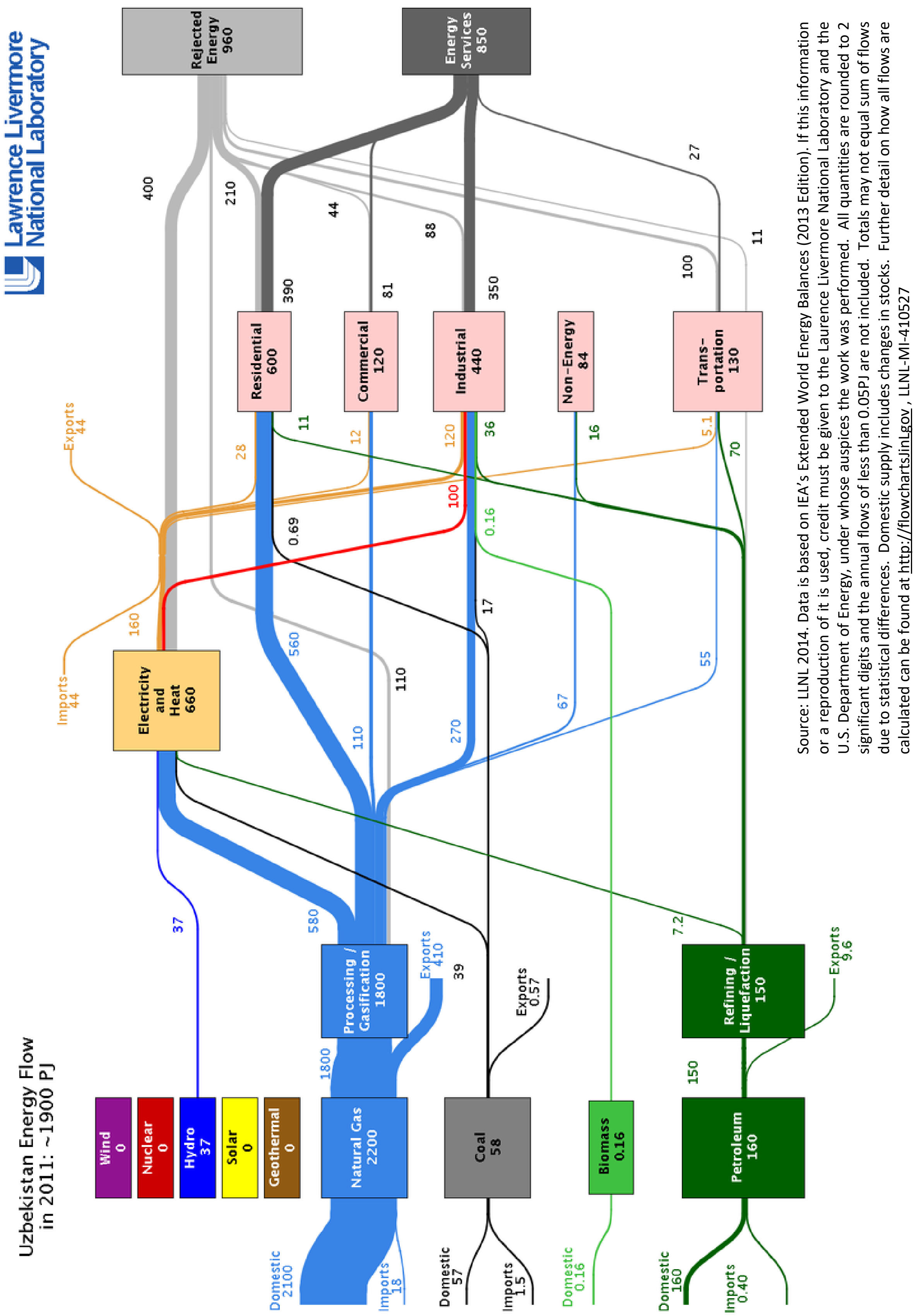


Figure L57. Uzbekistan energy flow between energy source and application
(Source: Lawrence Livermore National Laboratory Energy Flow Charts)

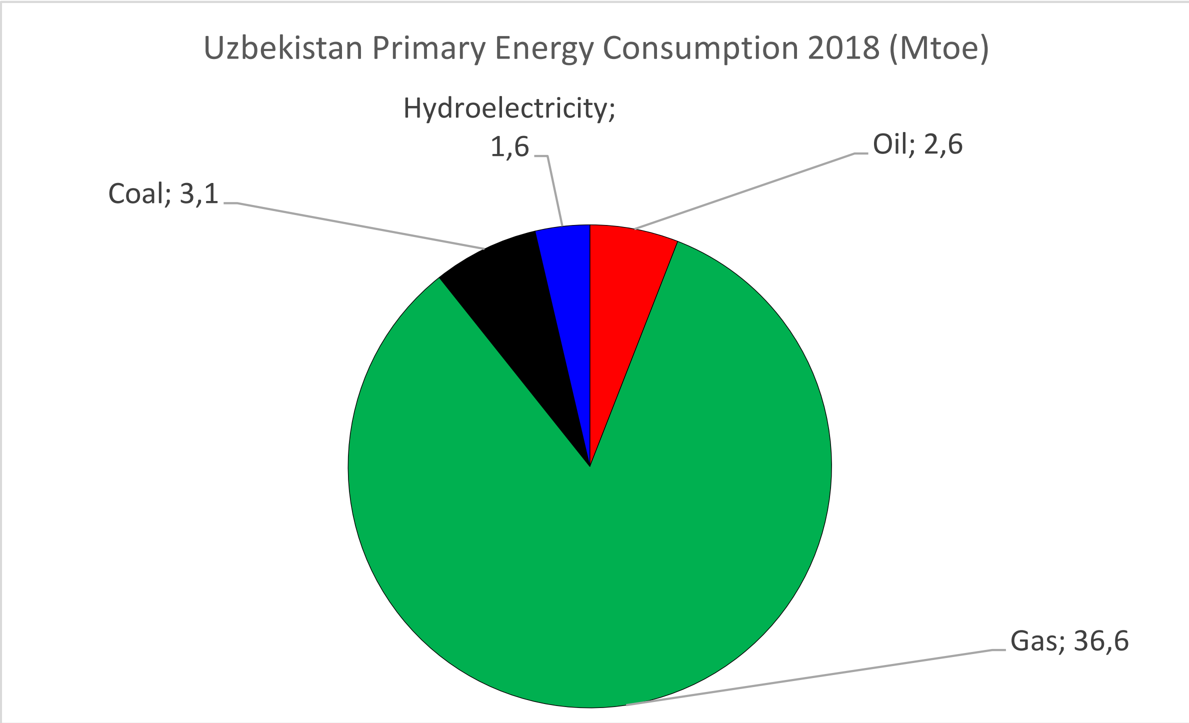


Figure L58. Uzbekistan primary energy consumption by raw material source
(Source: BP Statistical Review of World Energy 2019 & Appendix A)

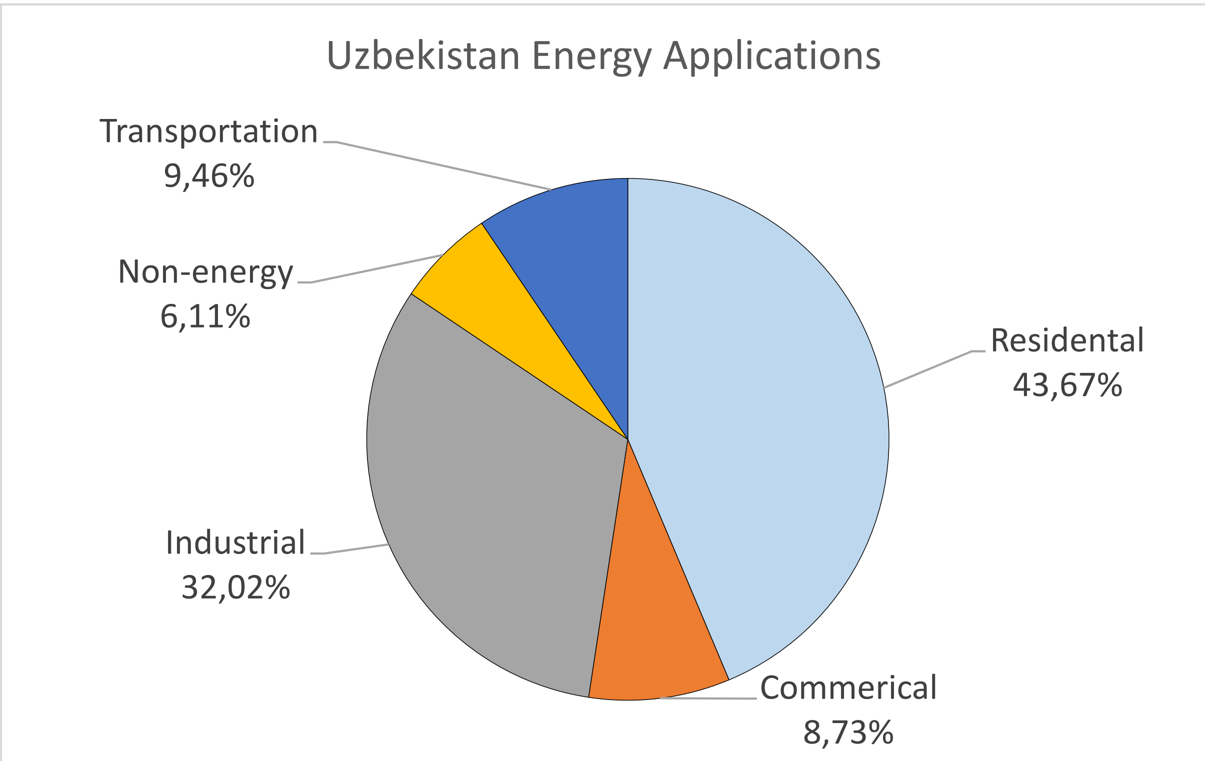


Figure L59. Uzbekistan energy applications
(Source: Lawrence Livermore National Laboratory 2017, EIA 2017)

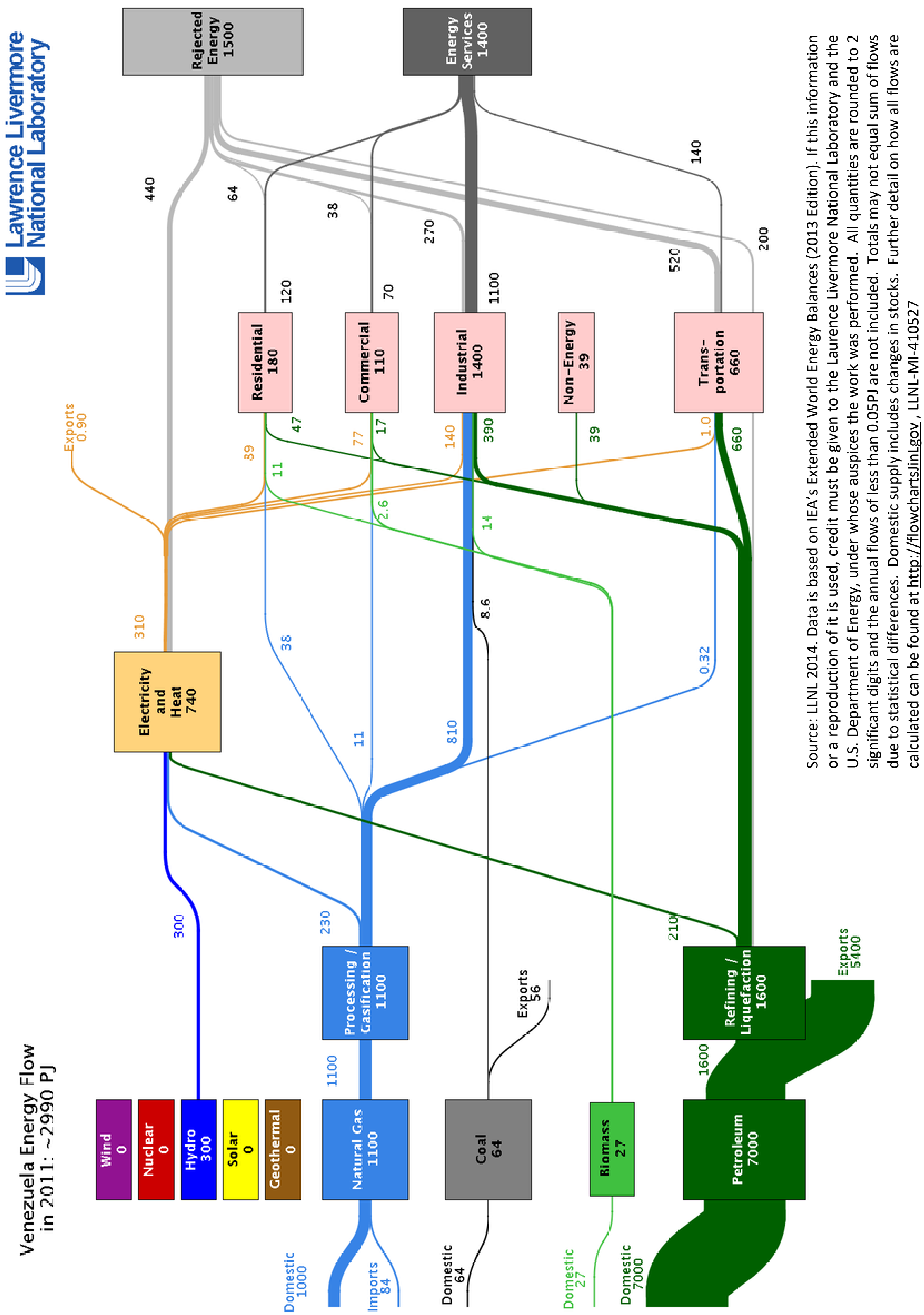


Figure L60. Venezuela energy flow between energy source and application
(Source: Lawrence Livermore National Laboratory Energy Flow Charts)

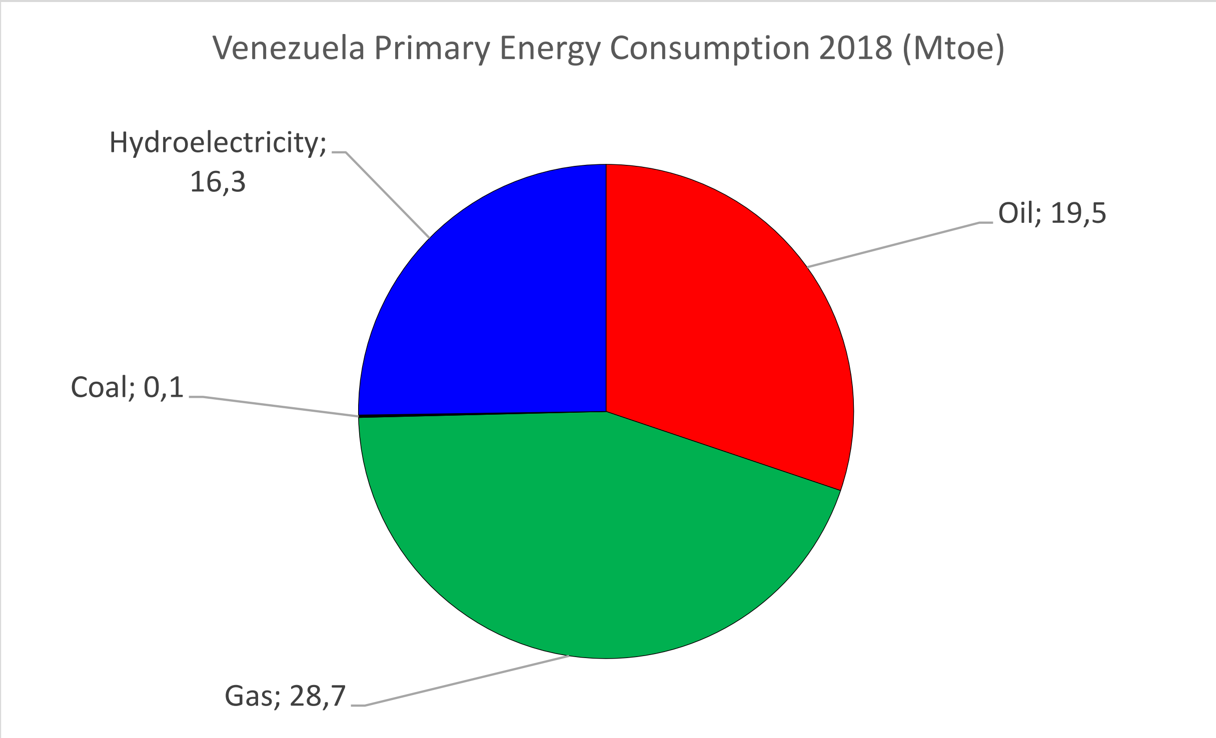


Figure L61. Venezuela primary energy consumption by raw material source
(Source: BP Statistical Review of World Energy 2019 & Appendix A)

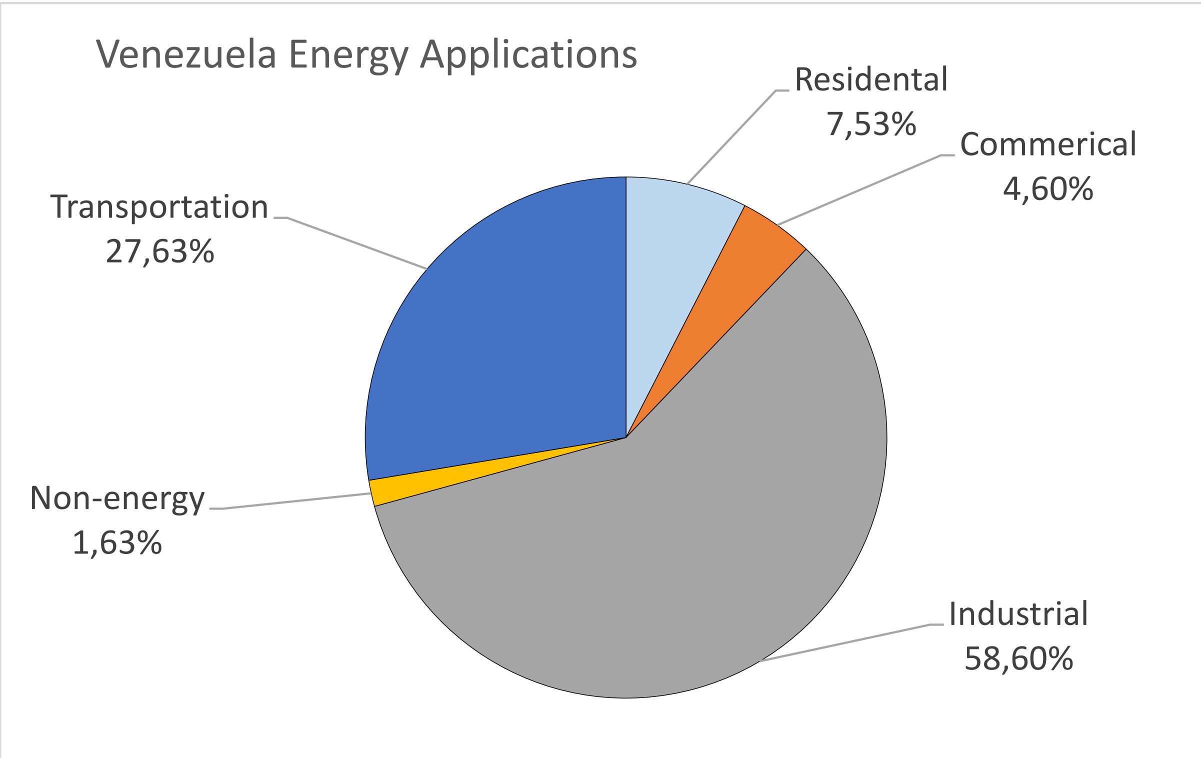


Figure L62. Venezuela energy applications
(Source: Lawrence Livermore National Laboratory 2017, EIA 2017)

41.7 Nation States that Produce Raw Materials

These nation states produce mineral resources and agricultural products. They are a vital part of the industrial ecosystem.

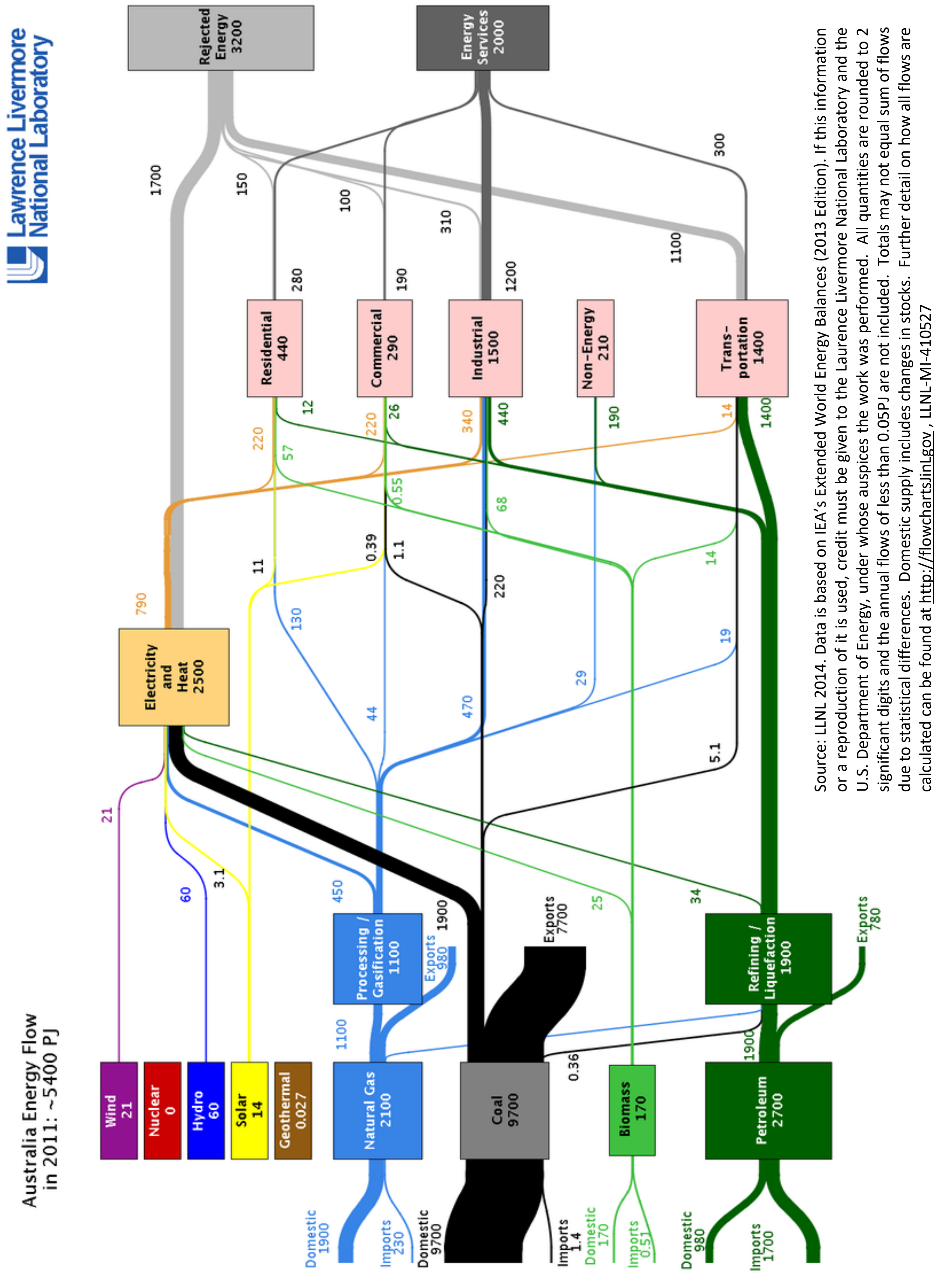


Figure L63. Australia energy flow between energy source and application
(Source: Lawrence Livermore National Laboratory Energy Flow Charts)

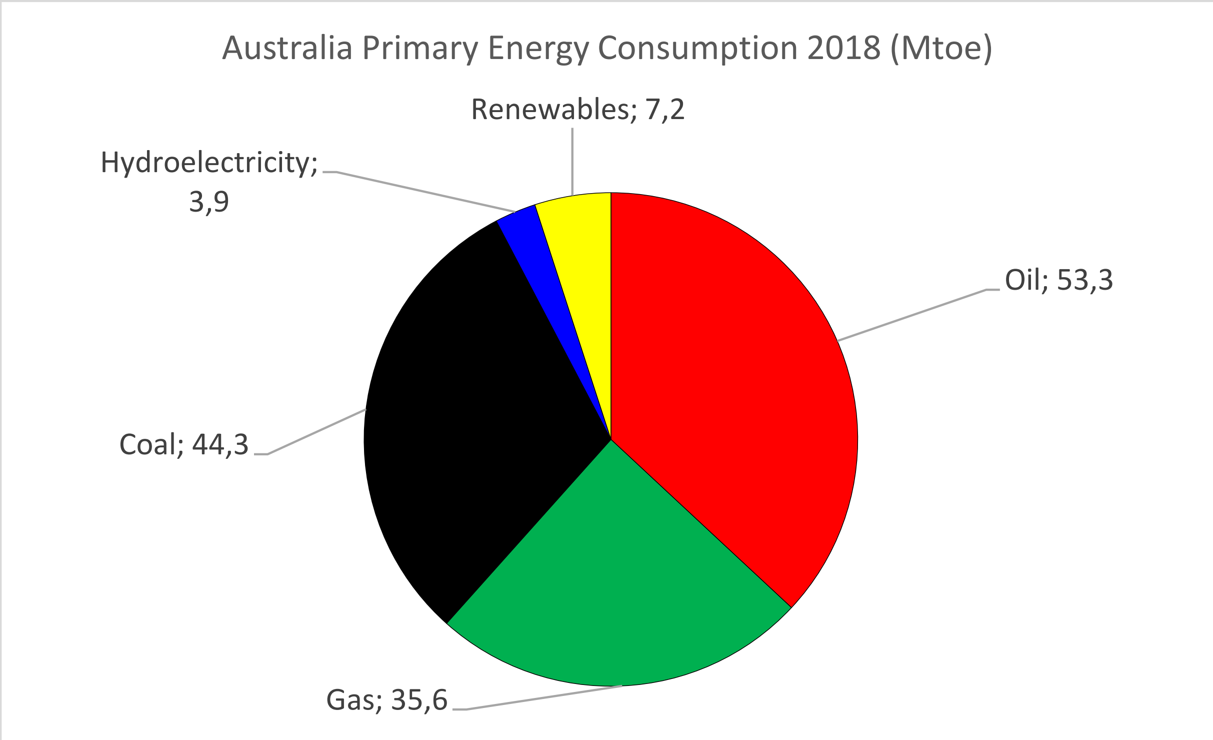


Figure L64. Australia primary energy consumption by raw material source
(Source: BP Statistical Review of World Energy 2019 & Appendix A)

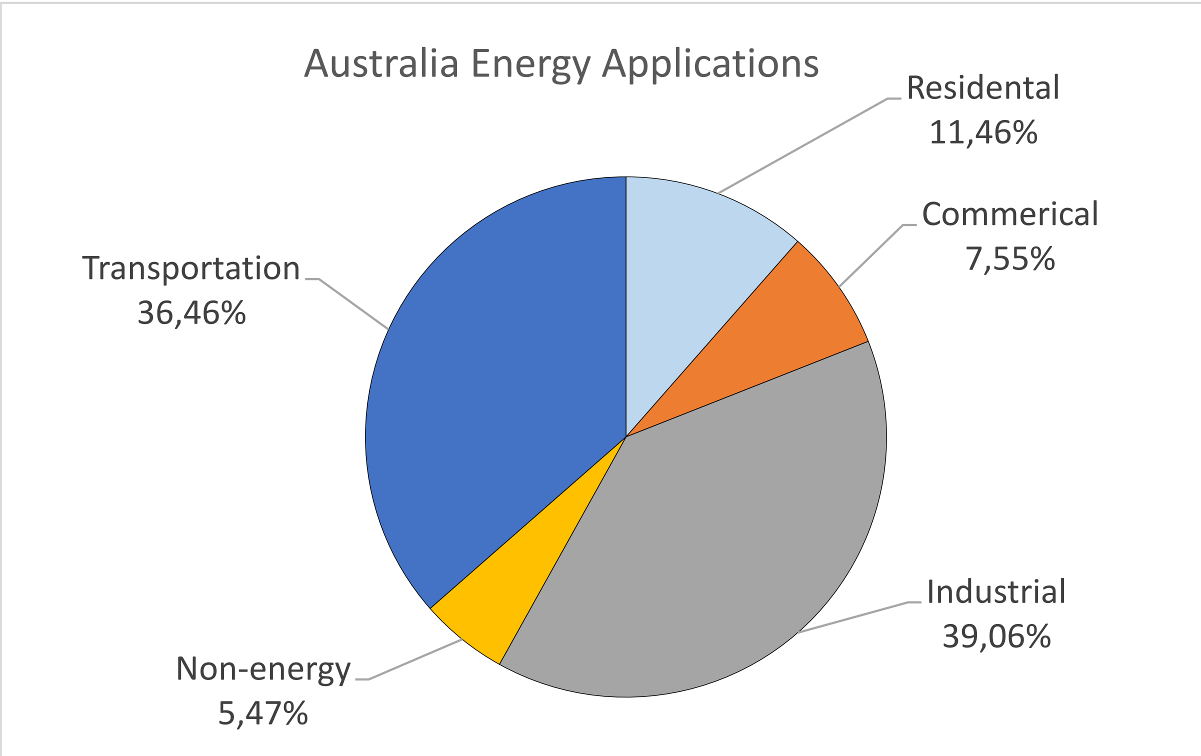


Figure L65. Australia energy applications
(Source: Lawrence Livermore National Laboratory 2017, EIA 2017)

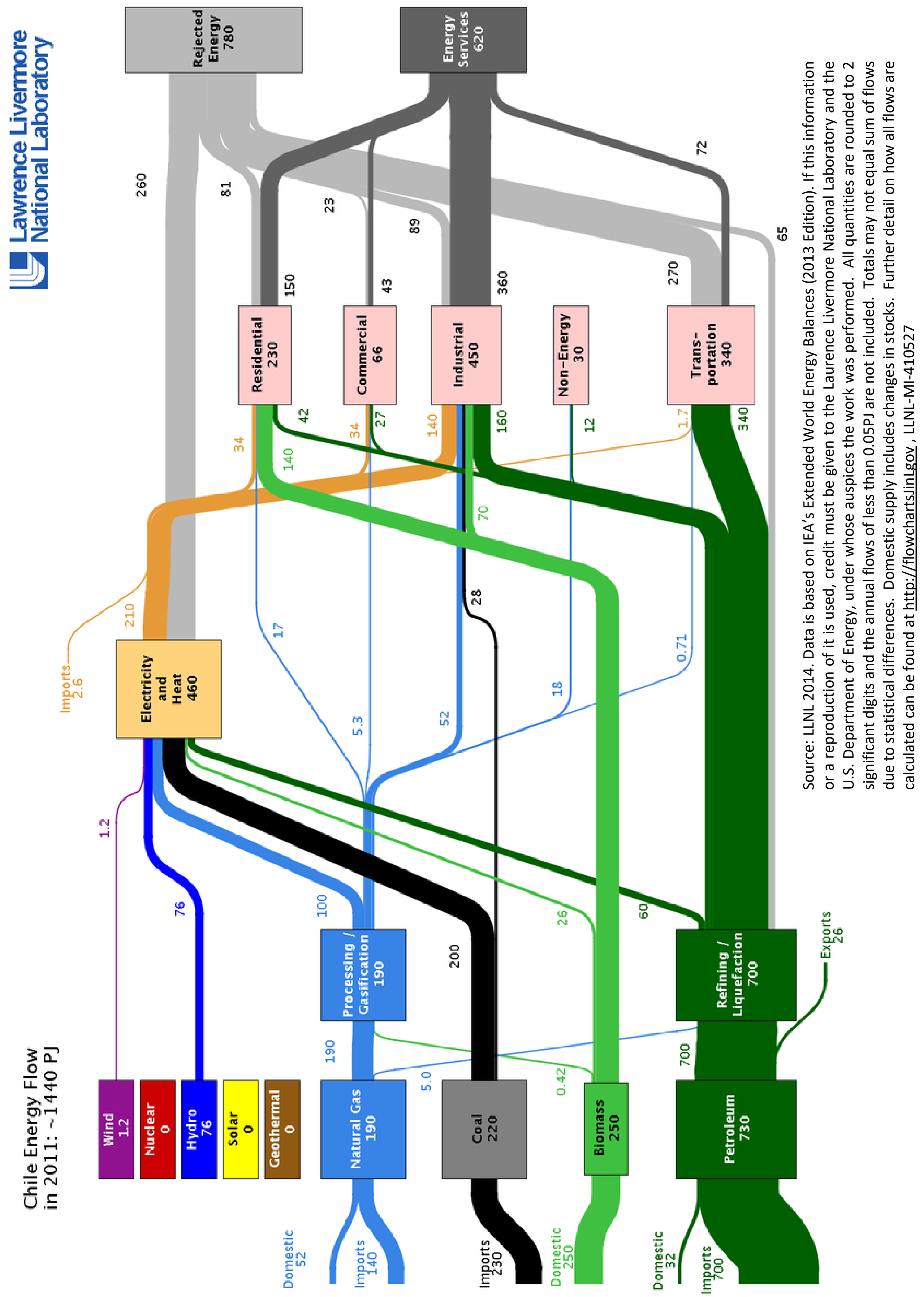


Figure L66. Chile energy flow between energy source and application
(Source: Lawrence Livermore National Laboratory Energy Flow Charts)
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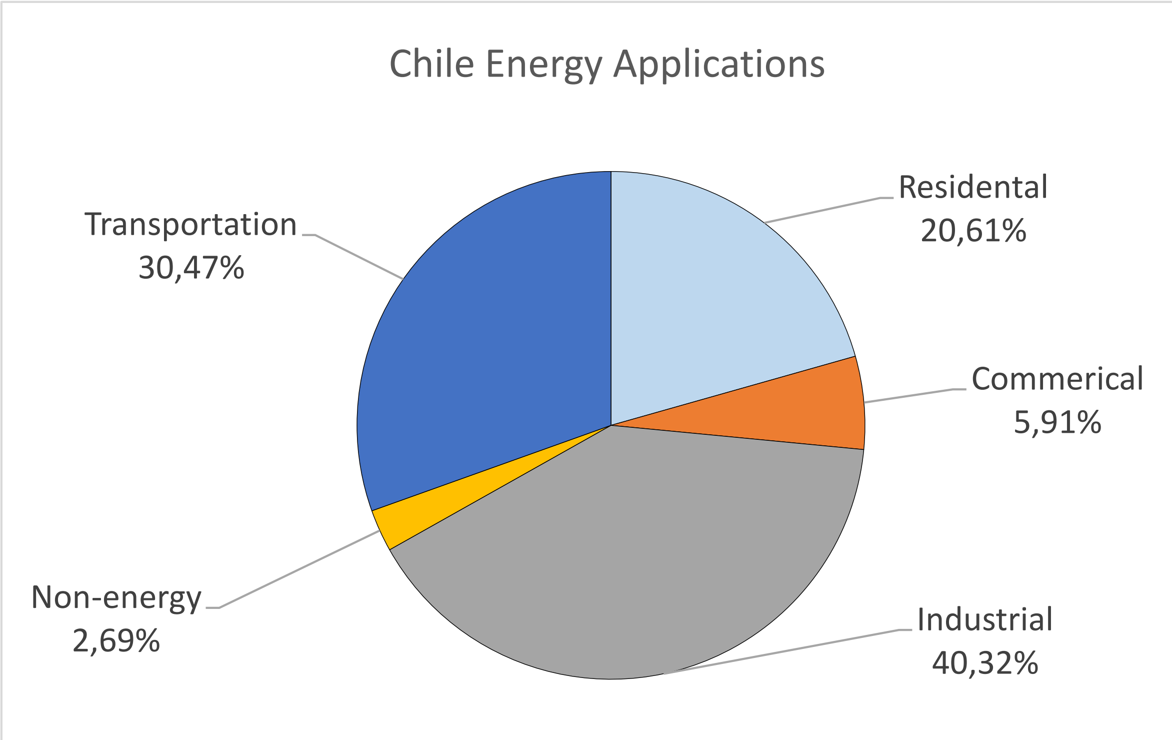

Figure L67. Chile primary energy consumption by raw material source
(Source: BP Statistical Review of World Energy 2019 & Appendix A)

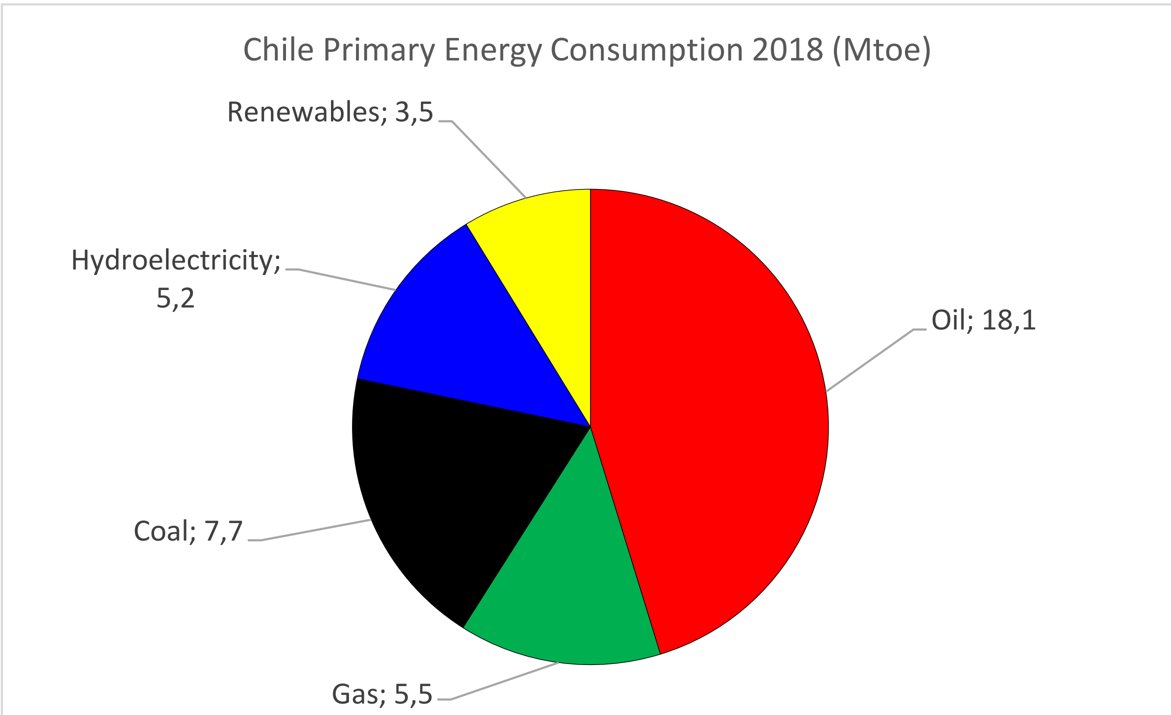

Figure L68. Chile energy applications
(Source: Lawrence Livermore National Laboratory 2017, EIA 2017)

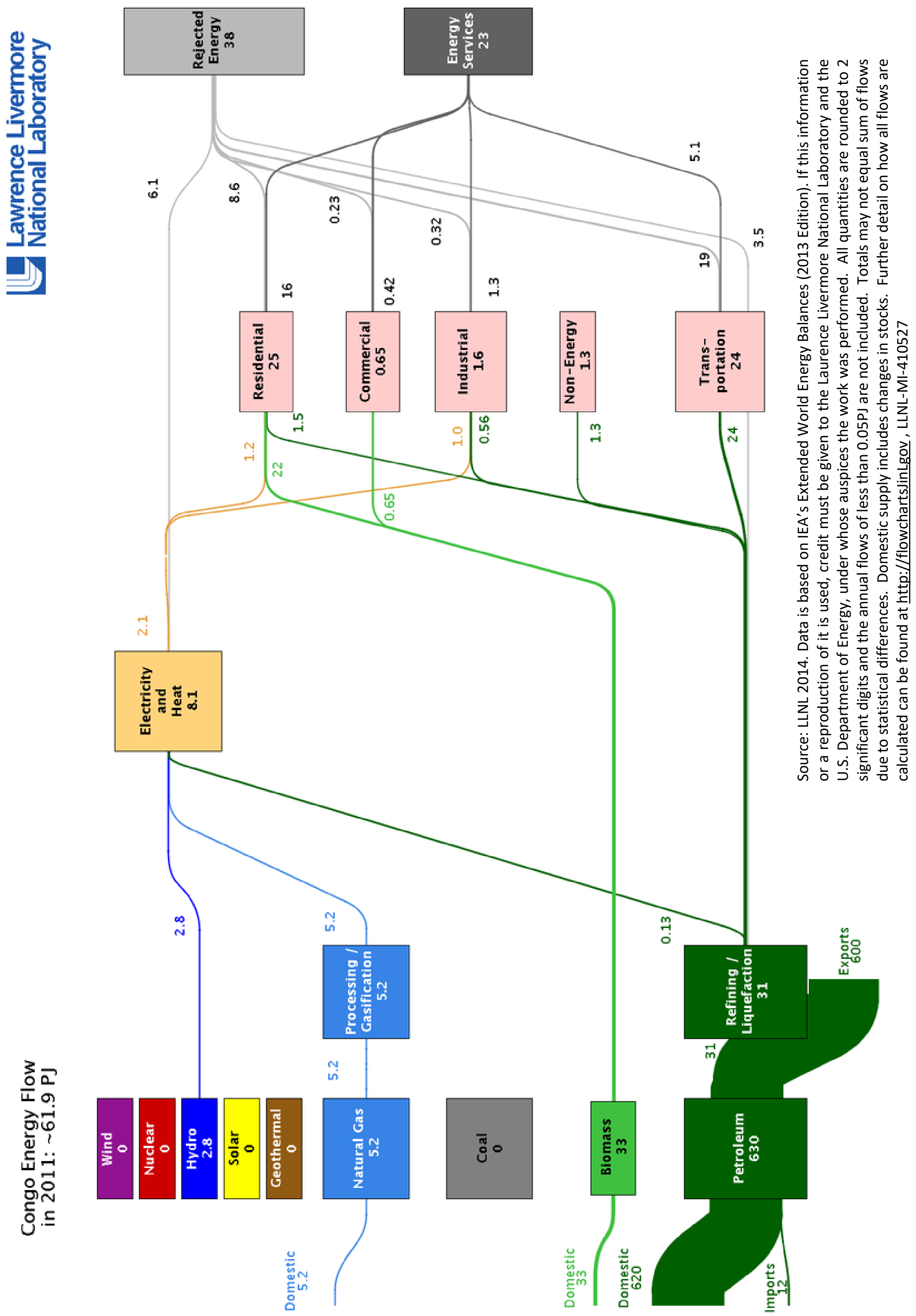

Figure L69. Congo energy flow between energy source and application
(Source: Lawrence Livermore National Laboratory Energy Flow Charts)
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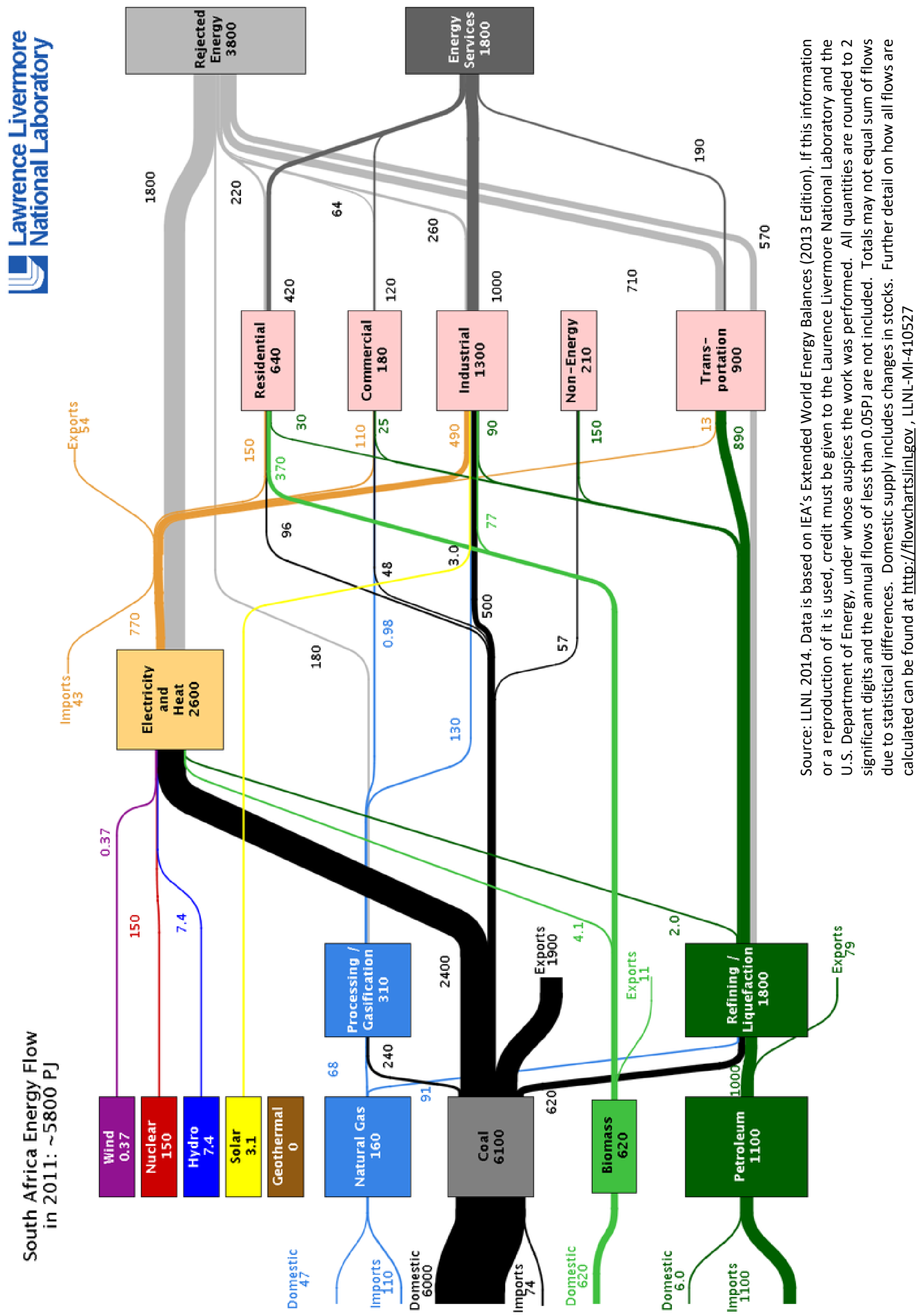

Figure L70. South Africa energy flow between energy source and application
(Source: Lawrence Livermore National Laboratory Energy Flow Charts)
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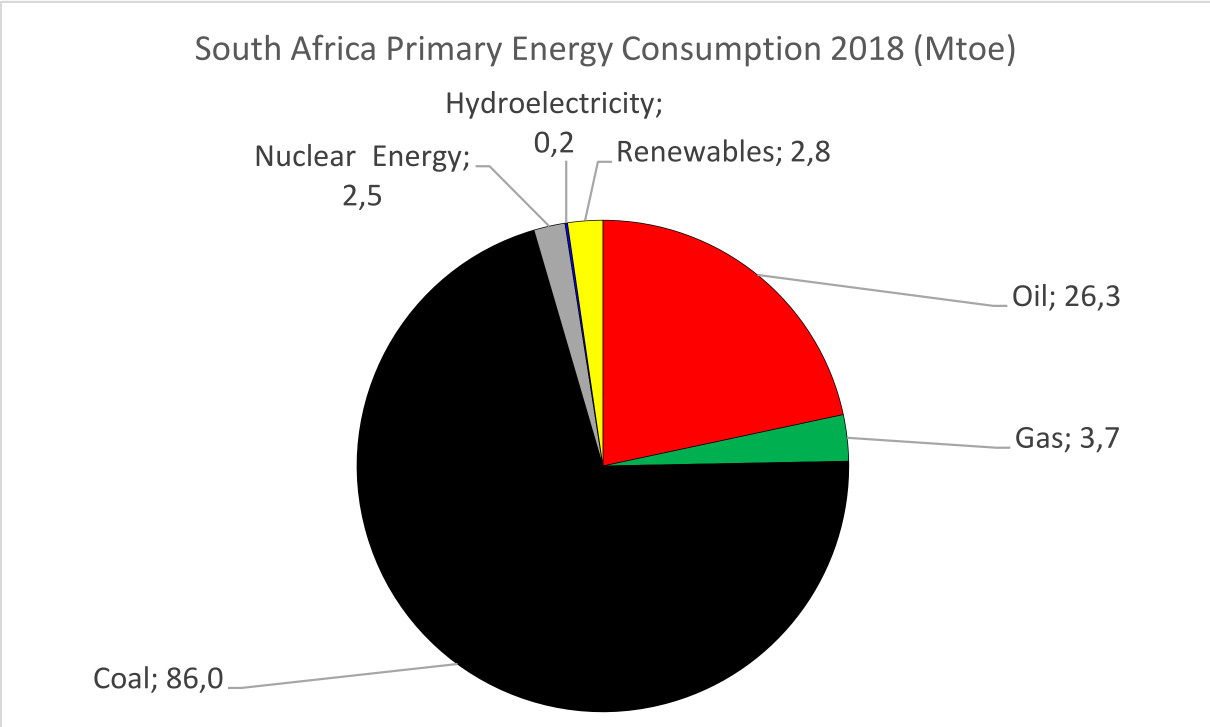

Figure L71. South Africa primary energy consumption by raw material source
(Source: BP Statistical Review of World Energy 2019 & Appendix A)

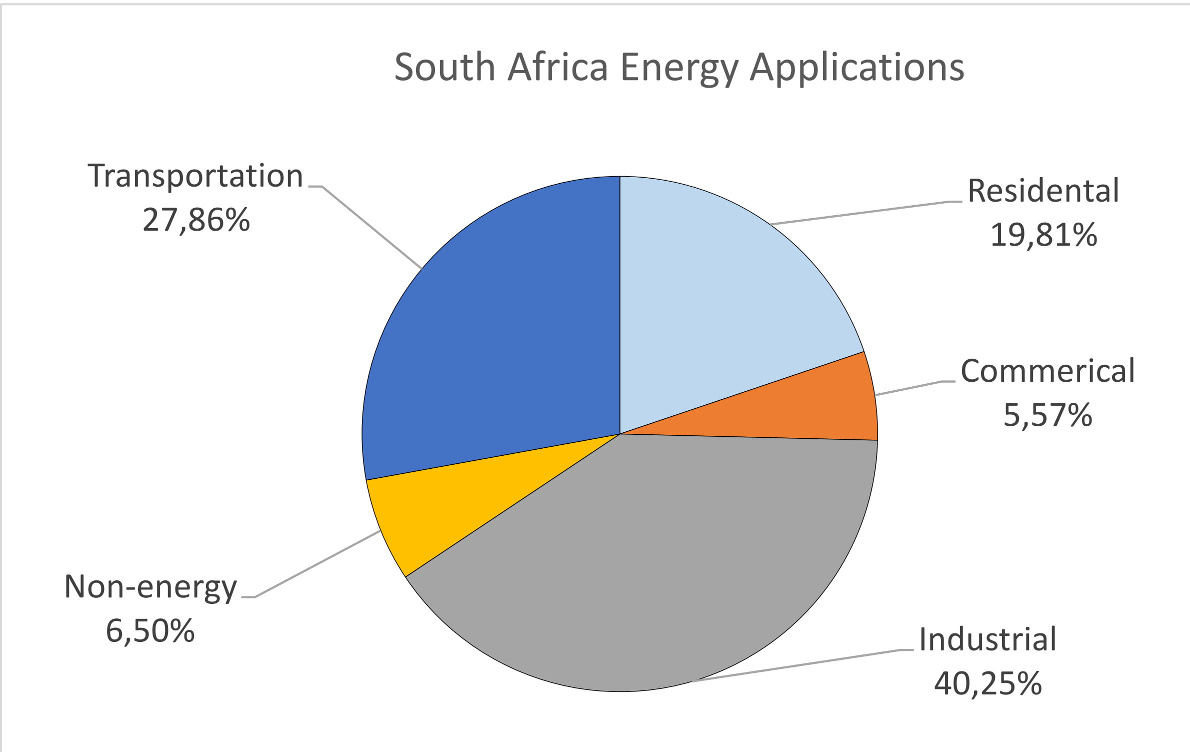

Figure L72. South Africa energy applications
(Source: Lawrence Livermore National Laboratory 2017, EIA 2017)

41.8 Developed Nation States that are Consumers

These nation states are fully developed and complex ‘first world’ economic systems. They do not produce raw materials, they consume them. Some industrial capacity.

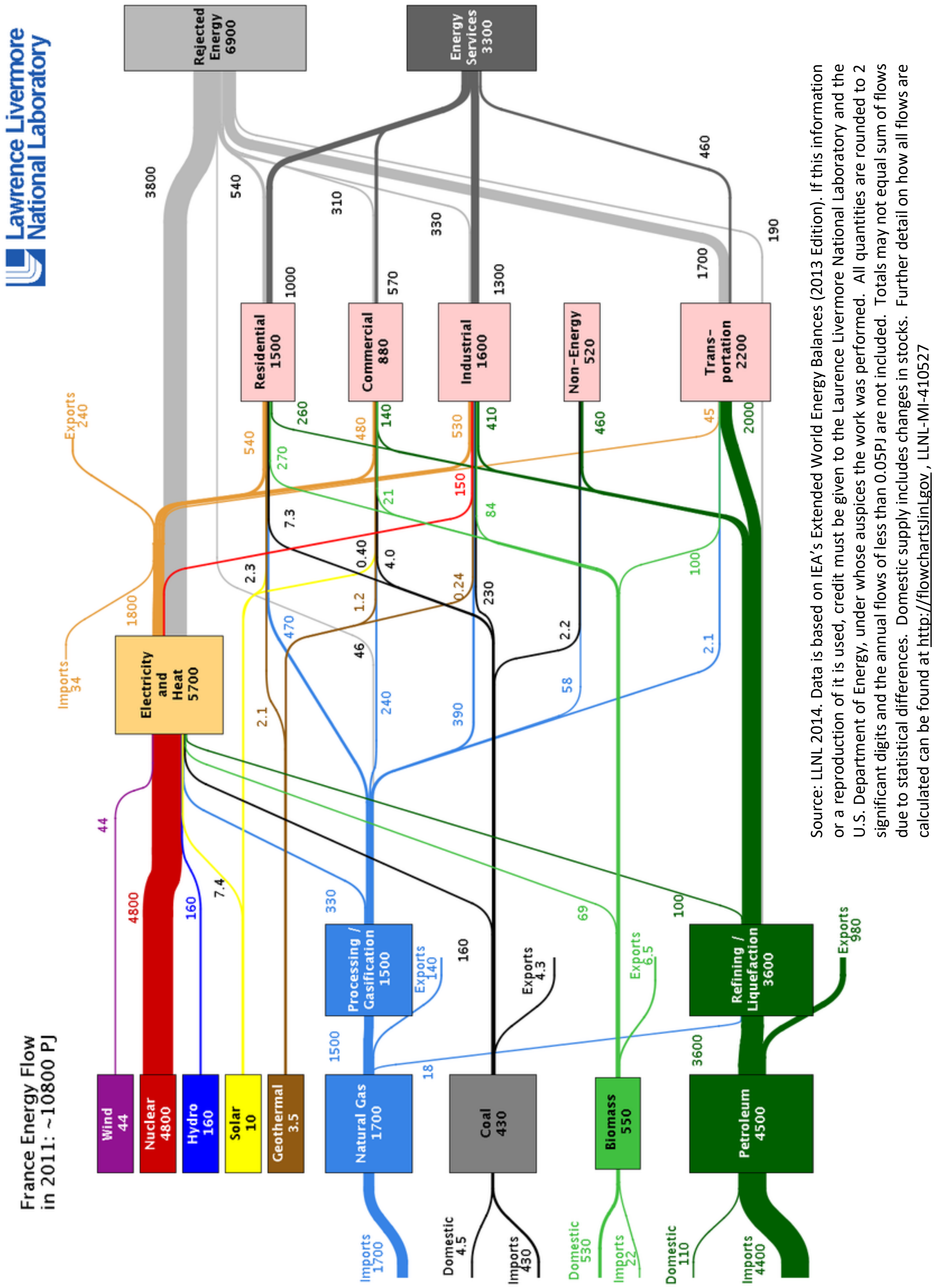

Figure L73. France energy flow between energy source and application
(Source: Lawrence Livermore National Laboratory Energy Flow Charts)

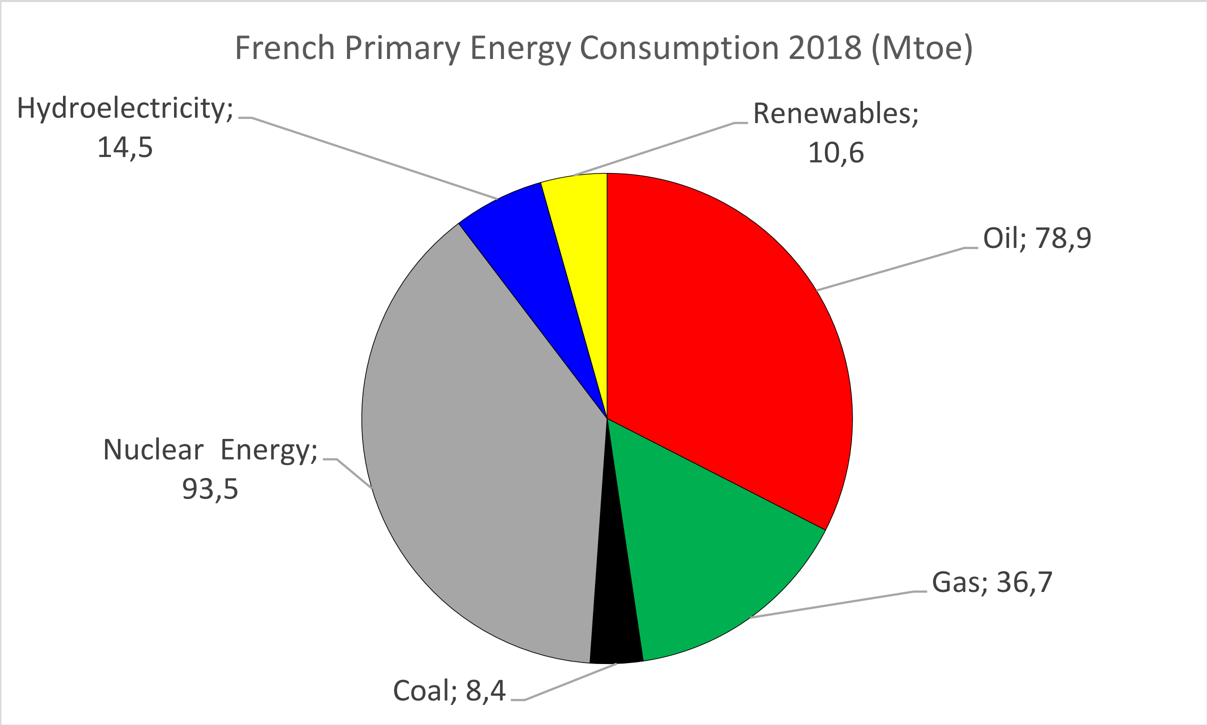

Figure L74. French primary energy consumption by raw material source
(Source: BP Statistical Review of World Energy 2019 & Appendix A)

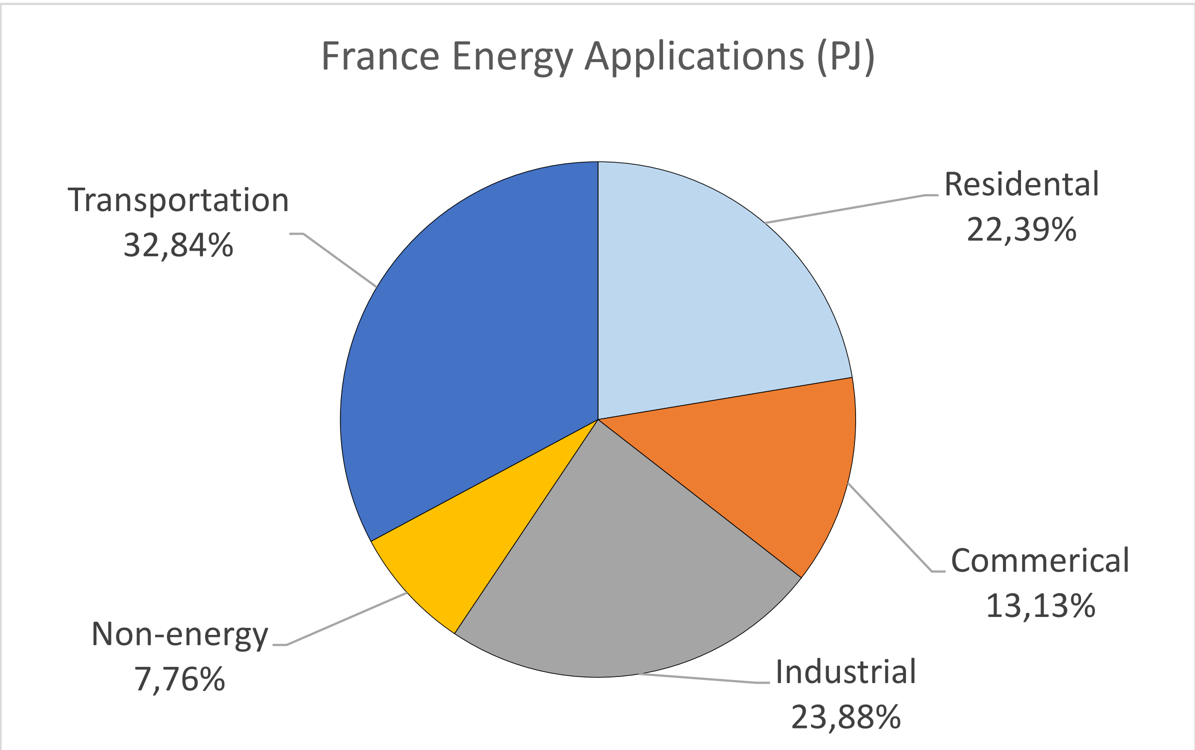

Figure L75. French energy applications
(Source: Lawrence Livermore National Laboratory 2017, EIA 2017)

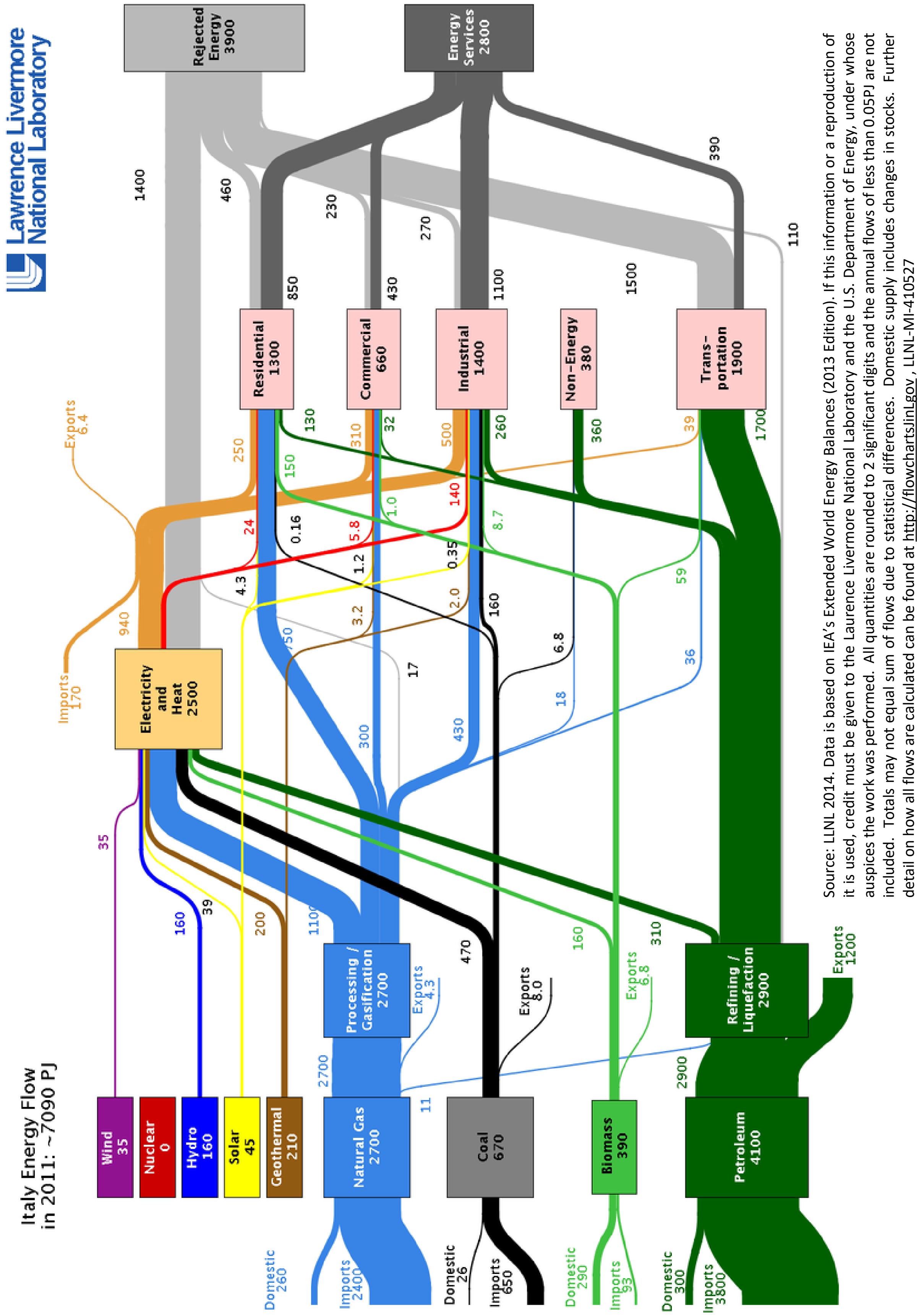

Figure L76. Italy energy flow between energy source and application
(Source: Lawrence Livermore National Laboratory Energy Flow Charts)

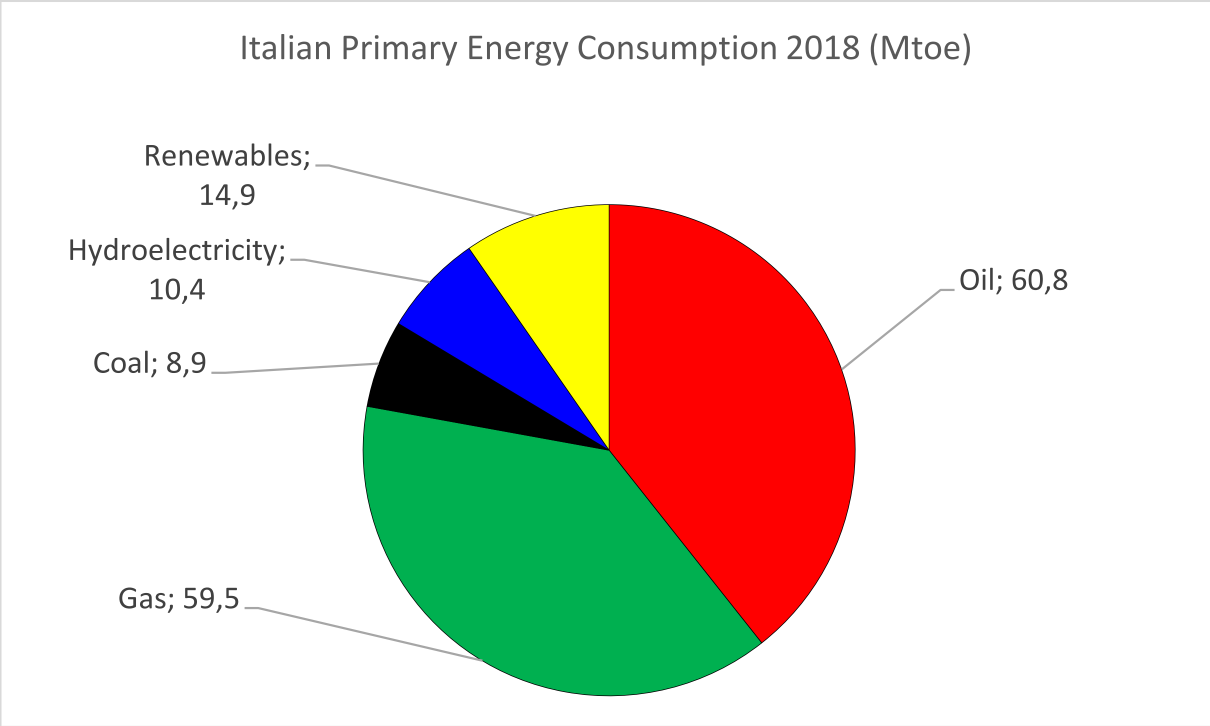

Figure L77. Italian primary energy consumption by raw material source
(Source: BP Statistical Review of World Energy 2019 & Appendix A)

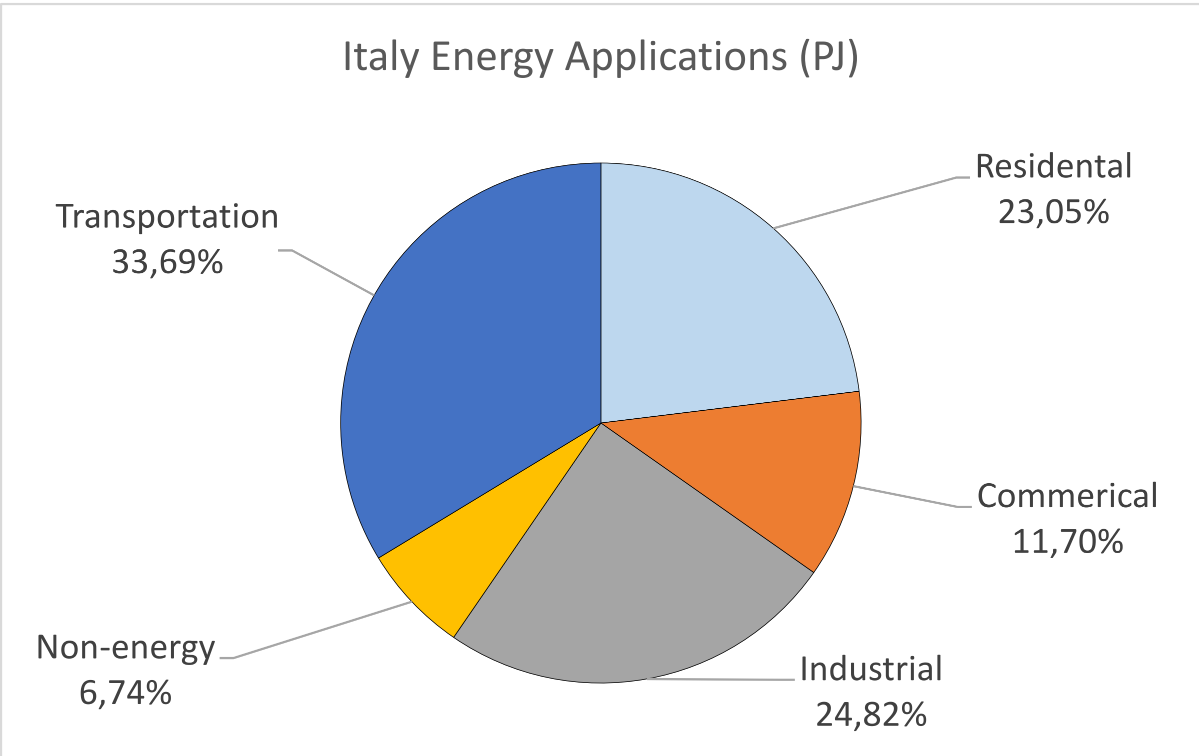

Figure L78. Italian energy applications
(Source: Lawrence Livermore National Laboratory 2017, EIA 2017)

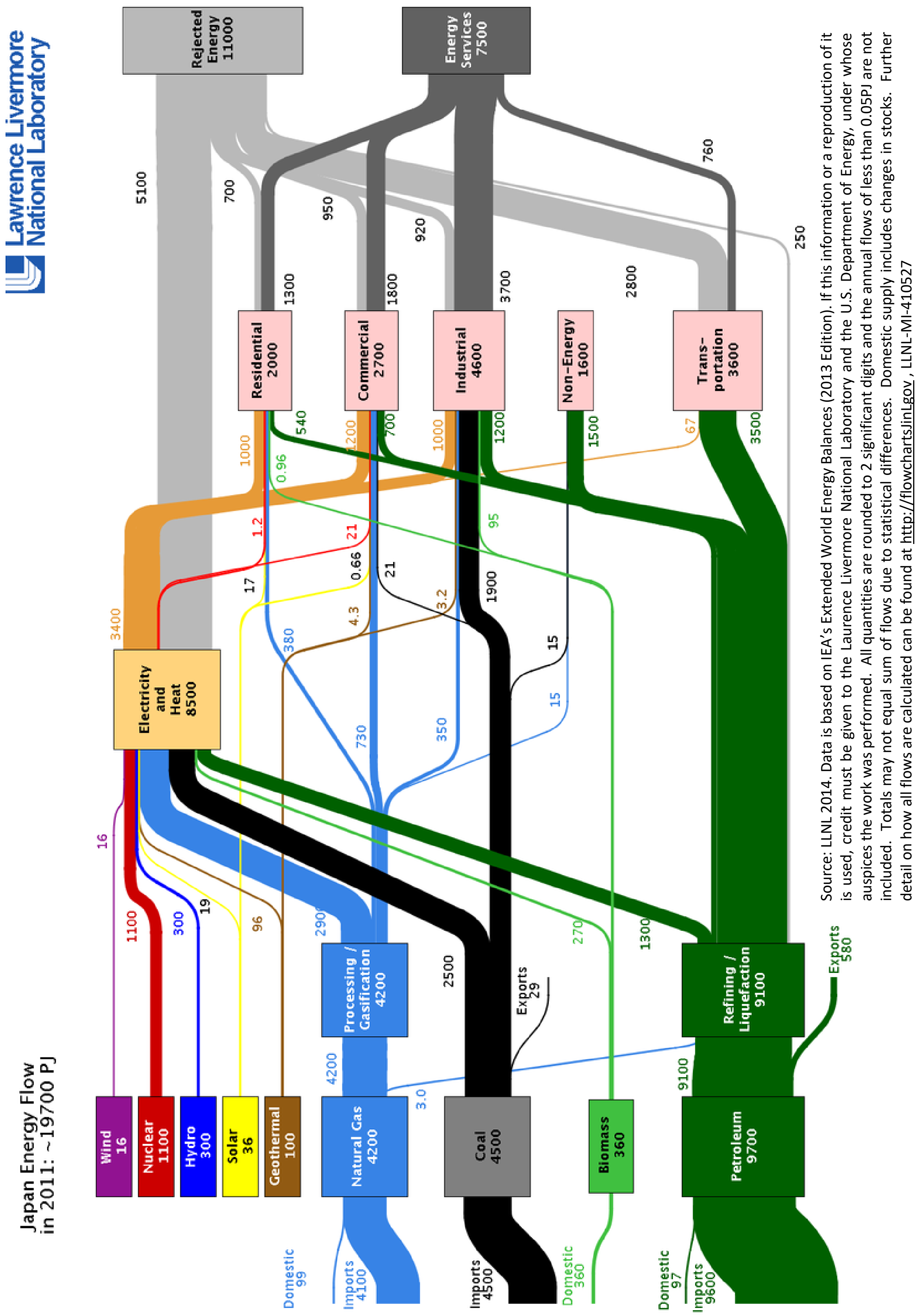

Figure L79. Japanese energy flow between energy source and application
(Source: Lawrence Livermore National Laboratory Energy Flow Charts)

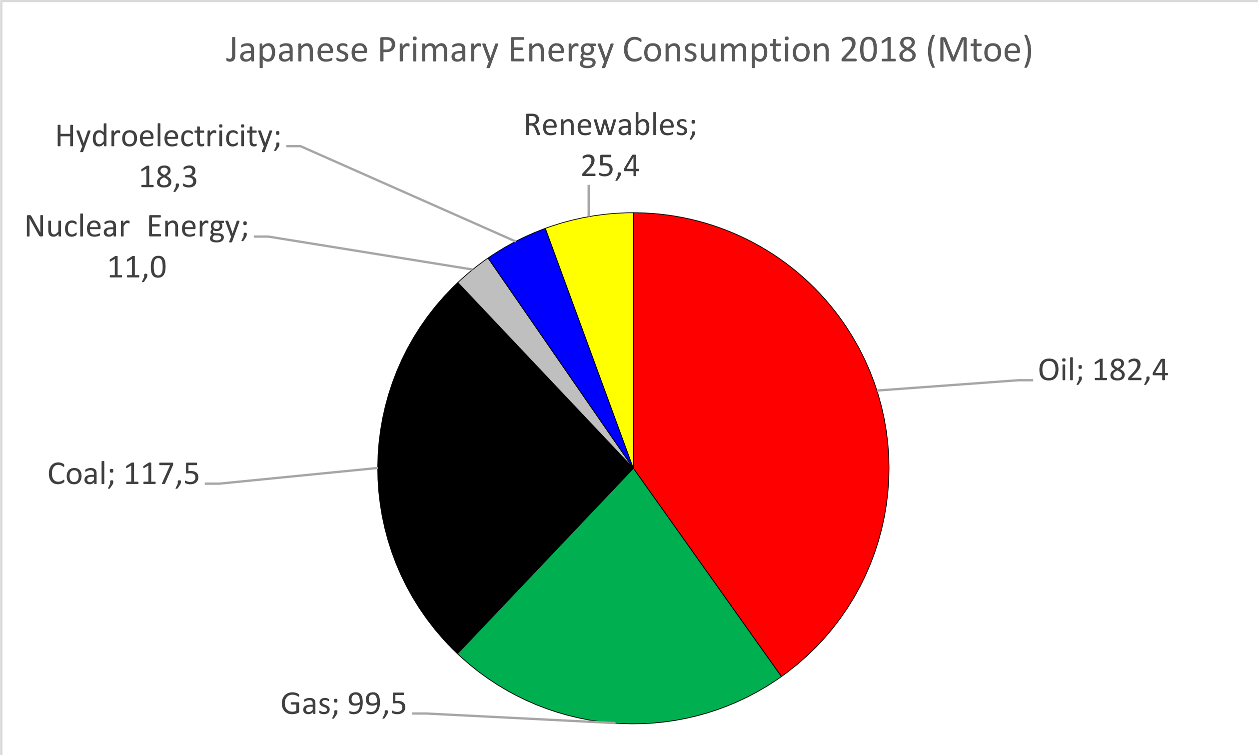

Figure L80. Japanese primary energy consumption by raw material source
(Source: BP Statistical Review of World Energy 2019 & Appendix A)

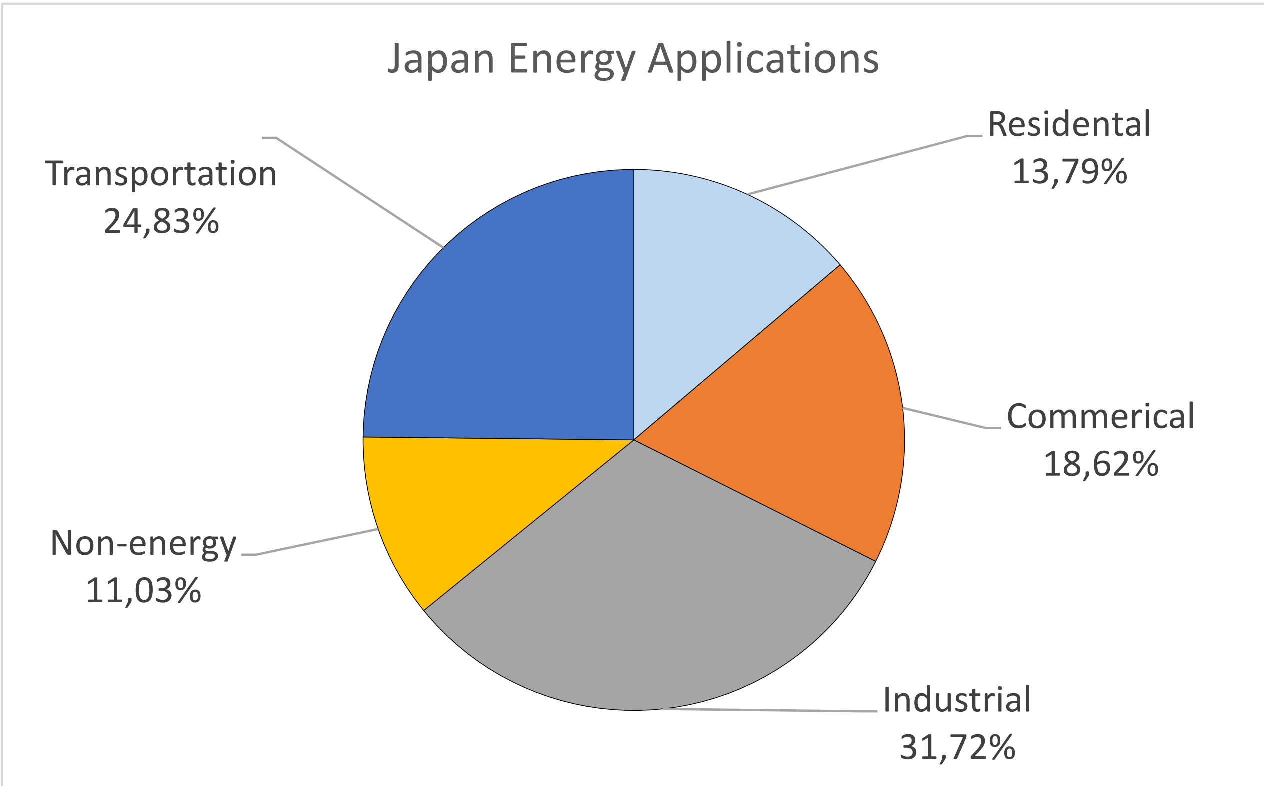

Figure L81. Japanese energy applications
(Source: Lawrence Livermore National Laboratory 2017, EIA 2017)

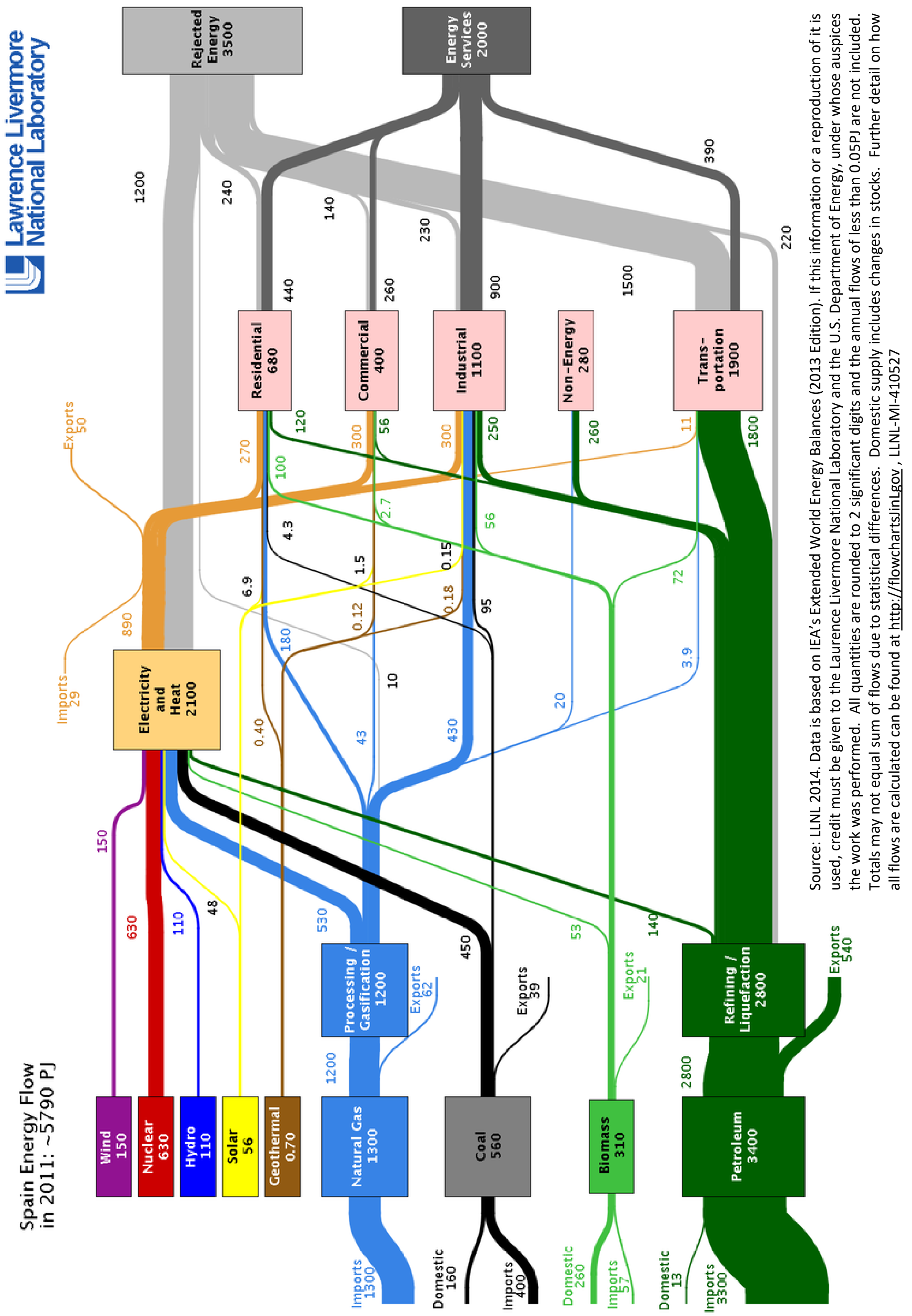

Figure L82. Spanish energy flow between energy source and application
(Source: Lawrence Livermore National Laboratory Energy Flow Charts)

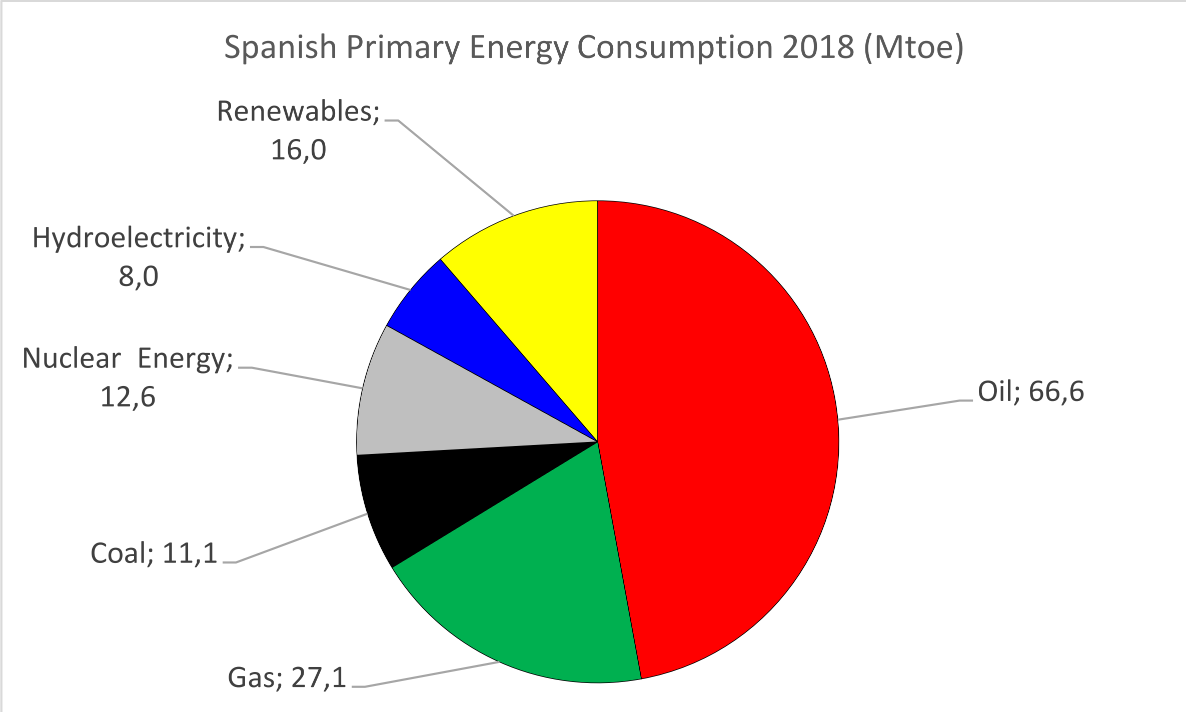

Figure L83. Spanish primary energy consumption by raw material source
(Source: BP Statistical Review of World Energy 2019 & Appendix A)

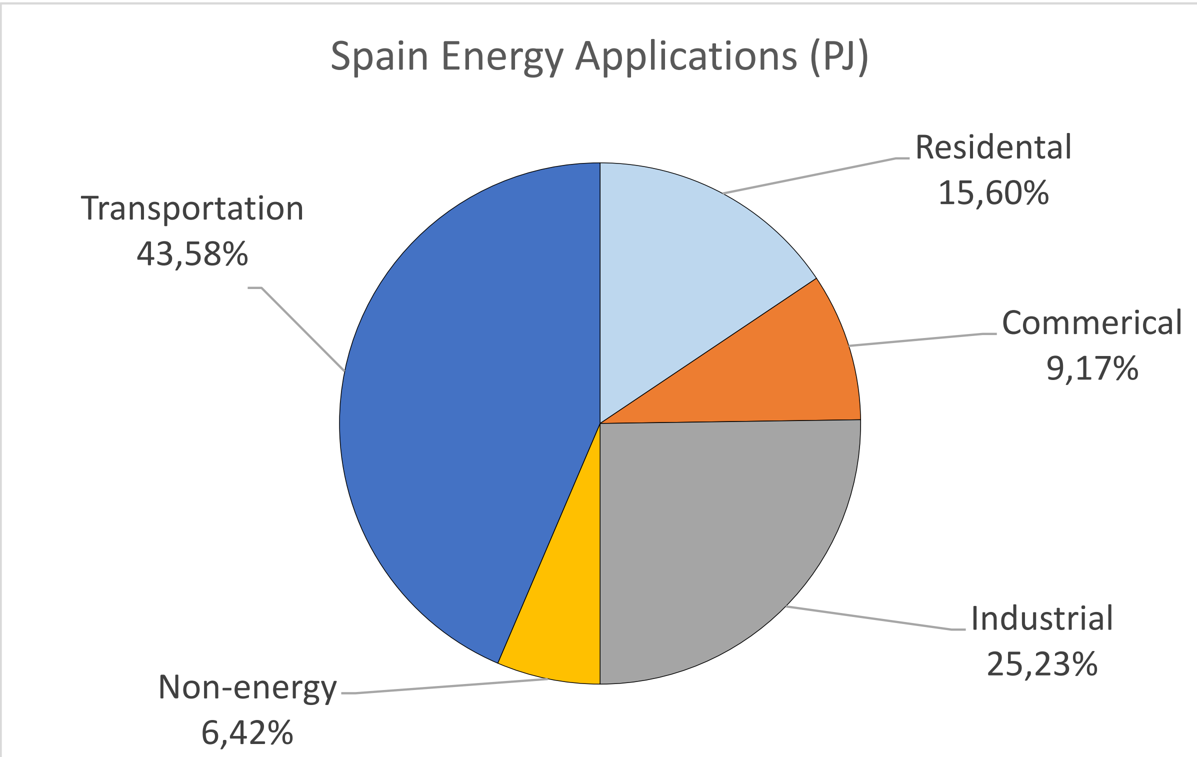

Figure L84. Spanish energy applications
(Source: Lawrence Livermore National Laboratory 2017, EIA 2017)

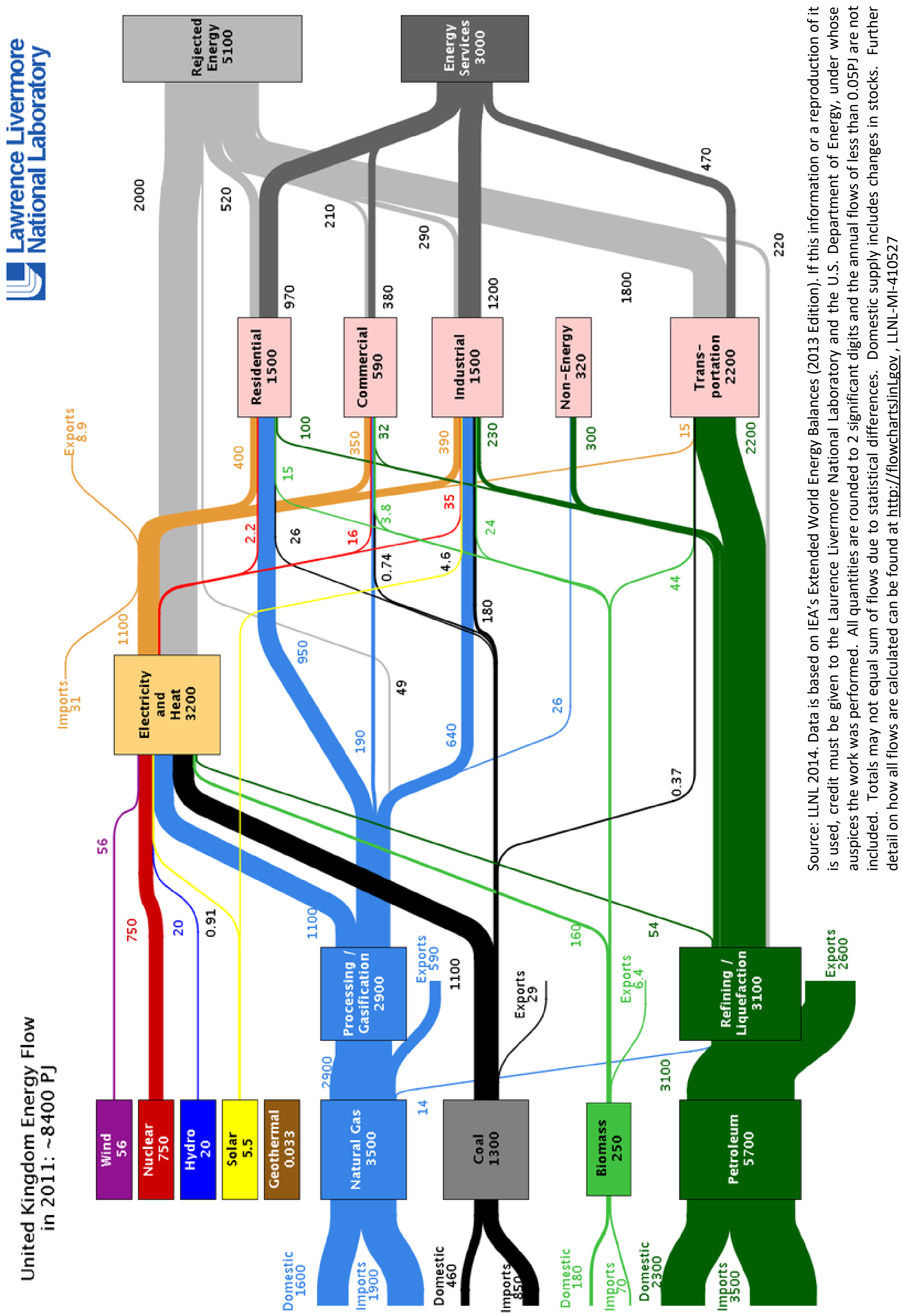

Figure L85. United Kingdom energy flow between energy source and application
(Source: Lawrence Livermore National Laboratory Energy Flow Charts)

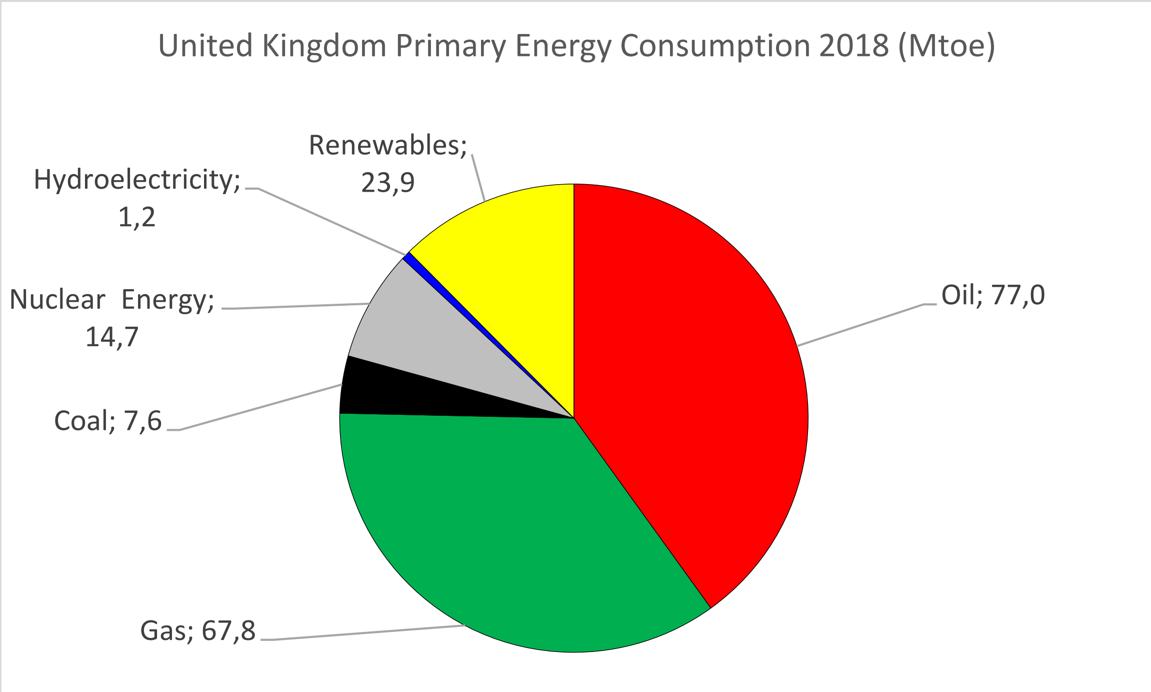

Figure L86. United Kingdom primary energy consumption by raw material source
(Source: BP Statistical Review of World Energy 2019 & Appendix A)

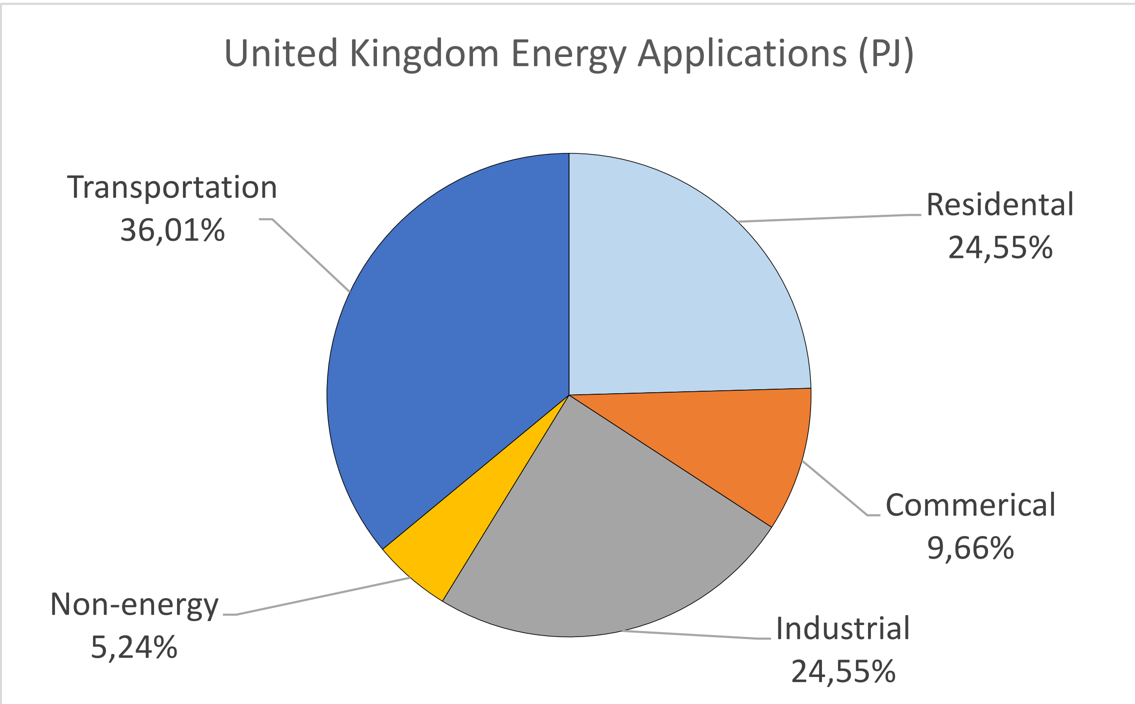

Figure L87. United Kindgom energy applications
(Source: Lawrence Livermore National Laboratory 2017, EIA 2017)

41.9 Nation States Around Finland.

The implications of this reports and others like it suggest that structure of the industrial ecosystem will change in the next 5 to 50 years. The future ecosystem architecture may well be a series of alliances between industrial clusters. These clusters will almost certainly be geographically close. This report was written for the Finnish ecosystem and its neighbors.

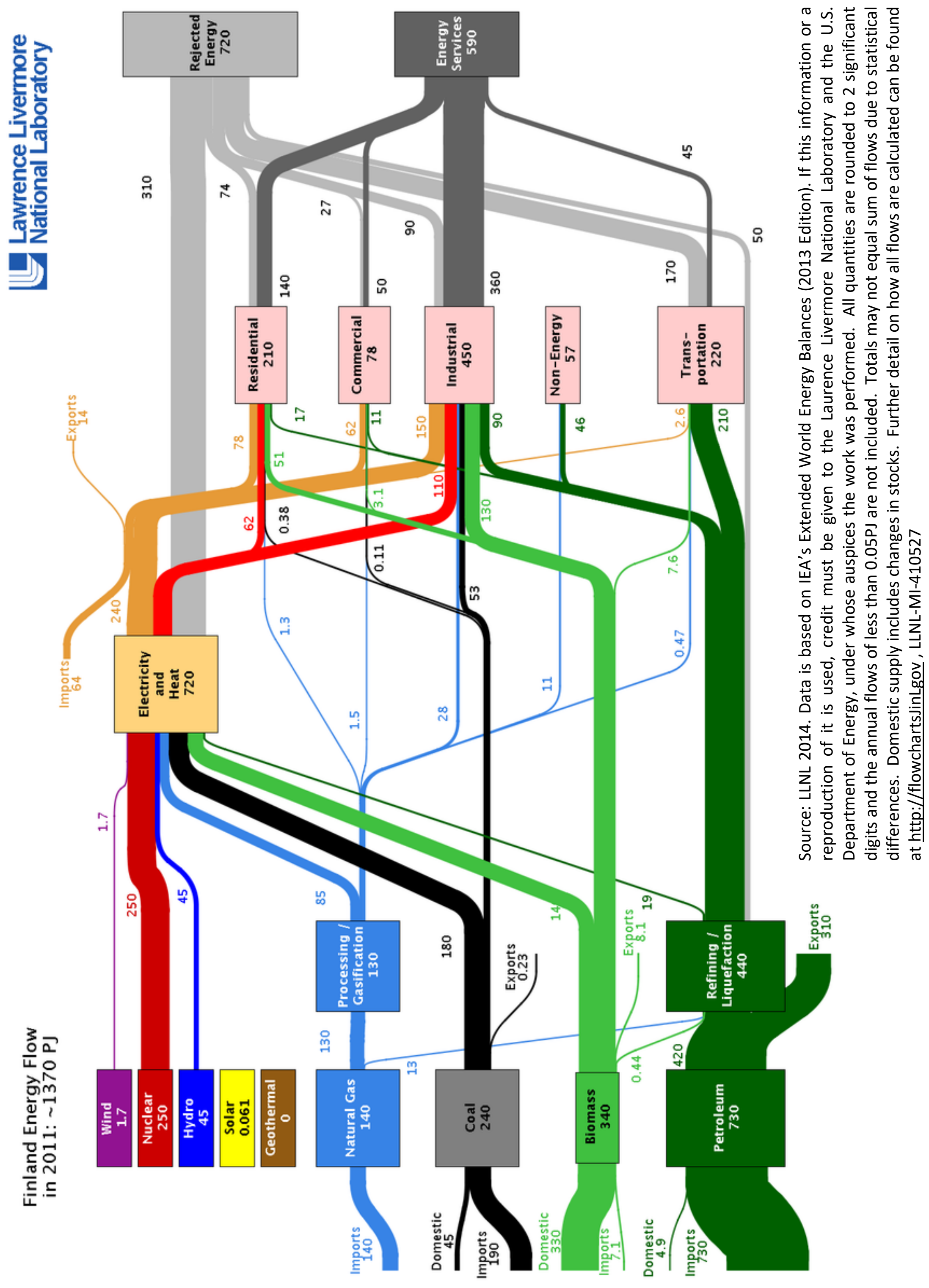

Figure L88. Finnish energy flow between energy source and application
(Source: Lawrence Livermore National Laboratory Energy Flow Charts)

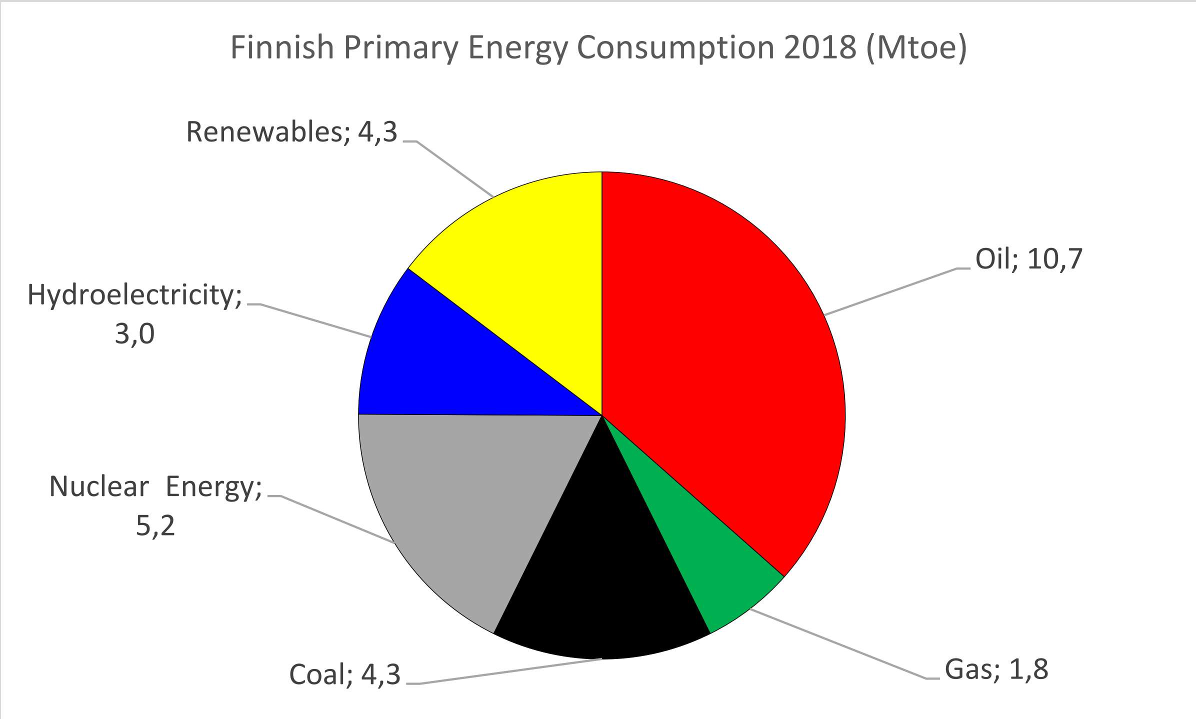

Figure L89. Finnish primary energy consumption by raw material source
(Source: BP Statistical Review of World Energy 2019 & Appendix A)

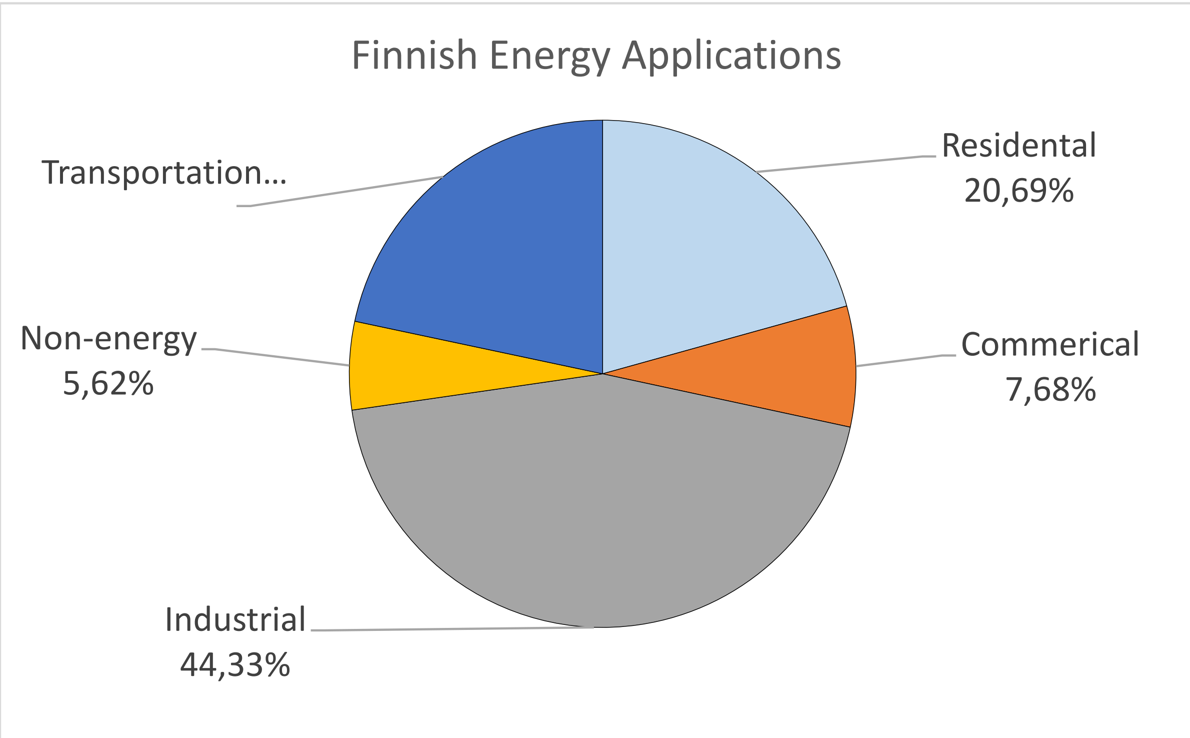

Figure L90. Finnish energy applications
(Source: Lawrence Livermore National Laboratory 2017, EIA 2017)

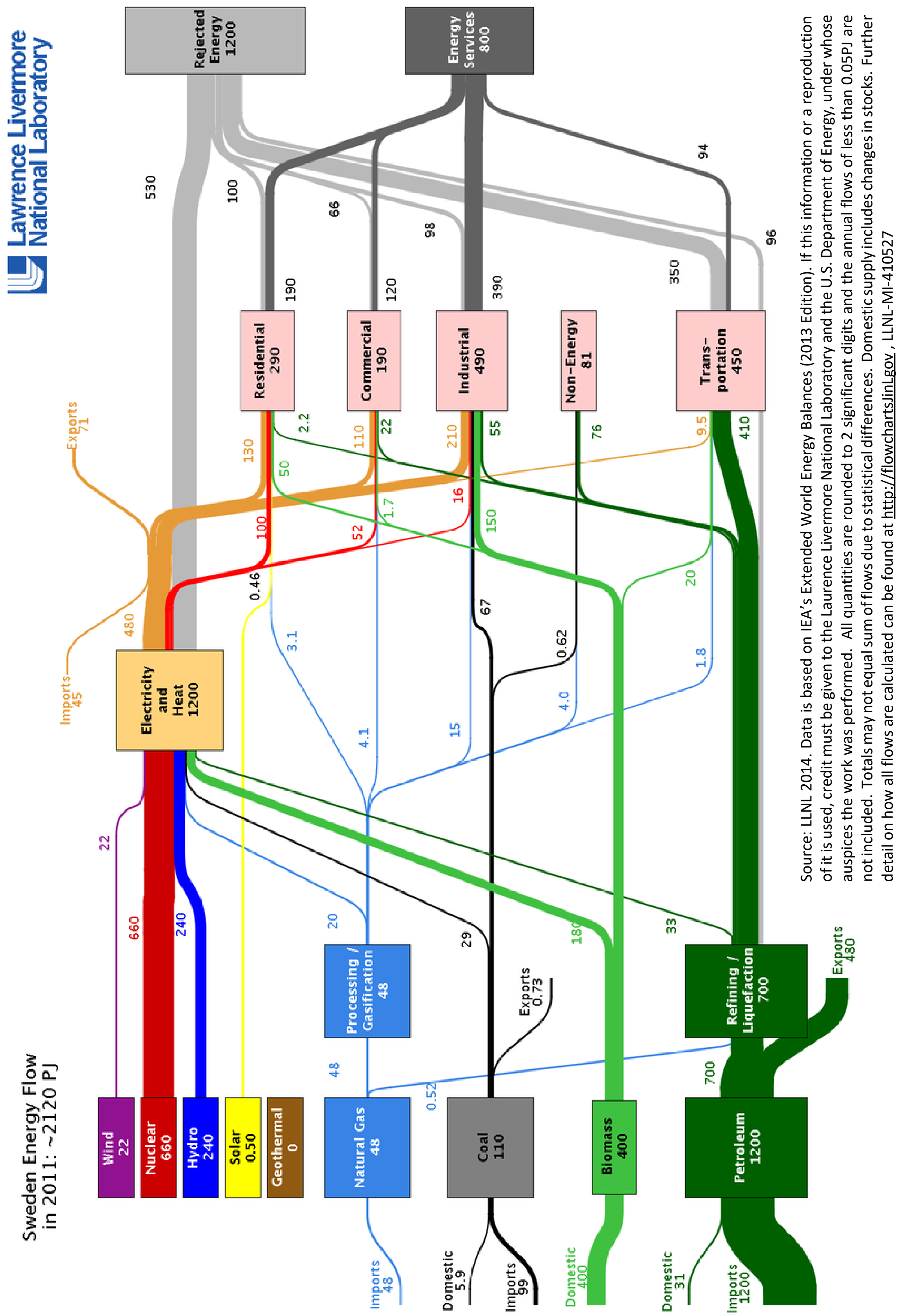

Figure L91. Sweden energy flow between energy source and application
(Source: Lawrence Livermore National Laboratory Energy Flow Charts)

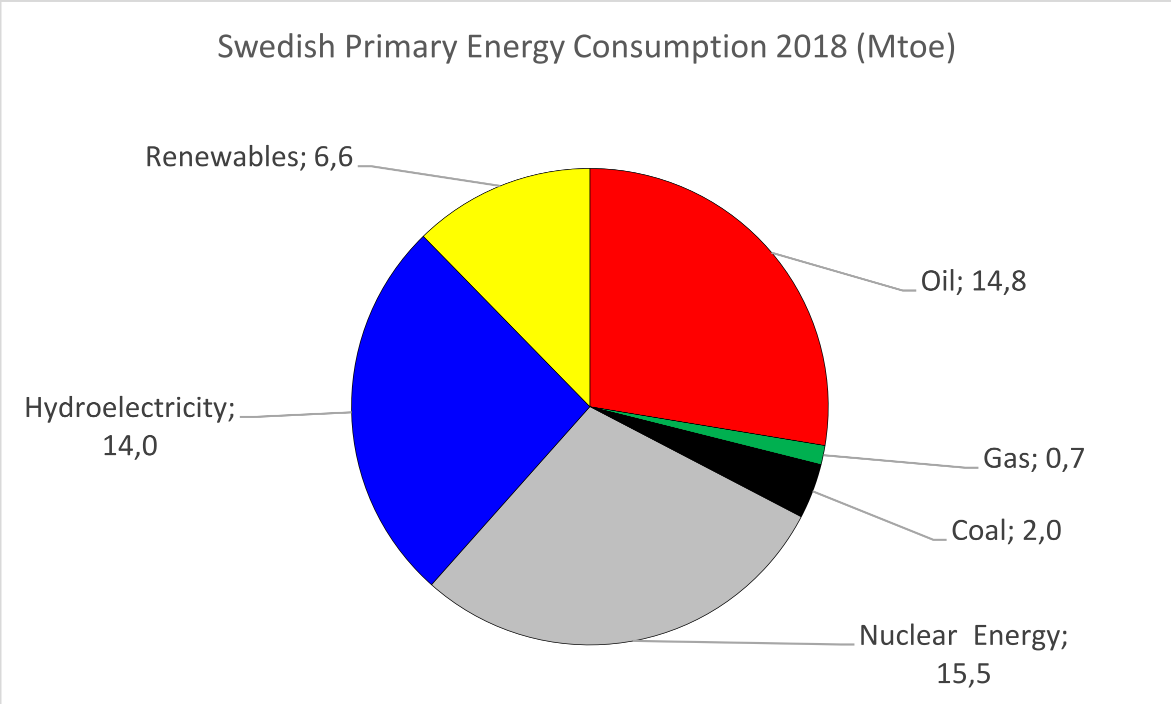

Figure L92. Swedish primary energy consumption by raw material source
(Source: BP Statistical Review of World Energy 2019 & Appendix A)

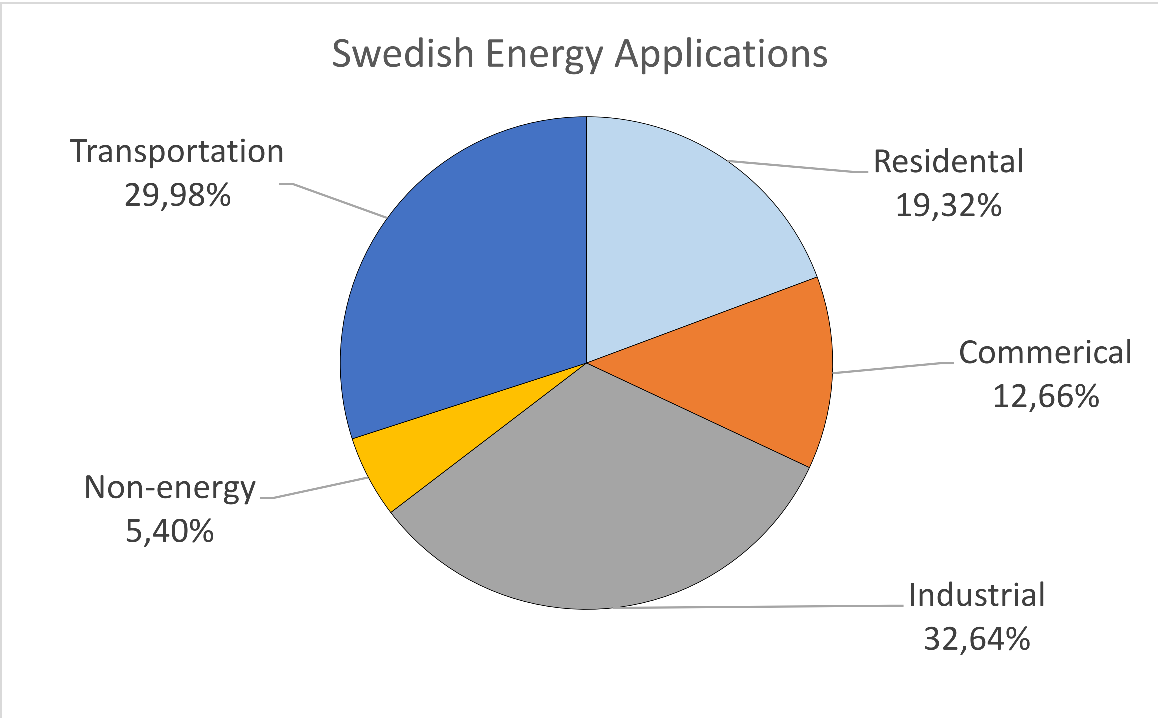

Figure L93. Swedish energy applications
(Source: Lawrence Livermore National Laboratory 2017, EIA 2017)

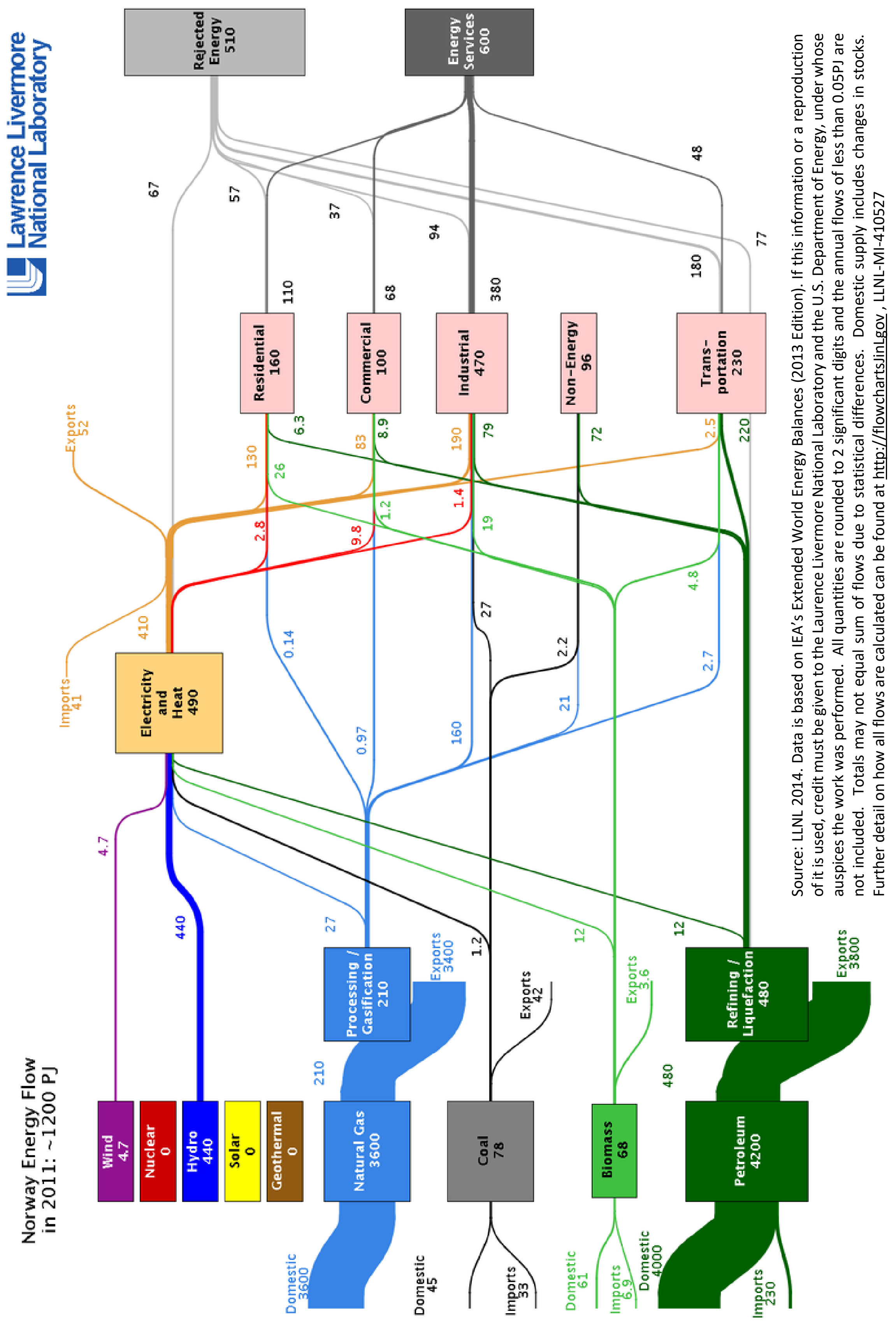

Figure L94. Norwegian energy flow between energy source and application
(Source: Lawrence Livermore National Laboratory Energy Flow Charts)

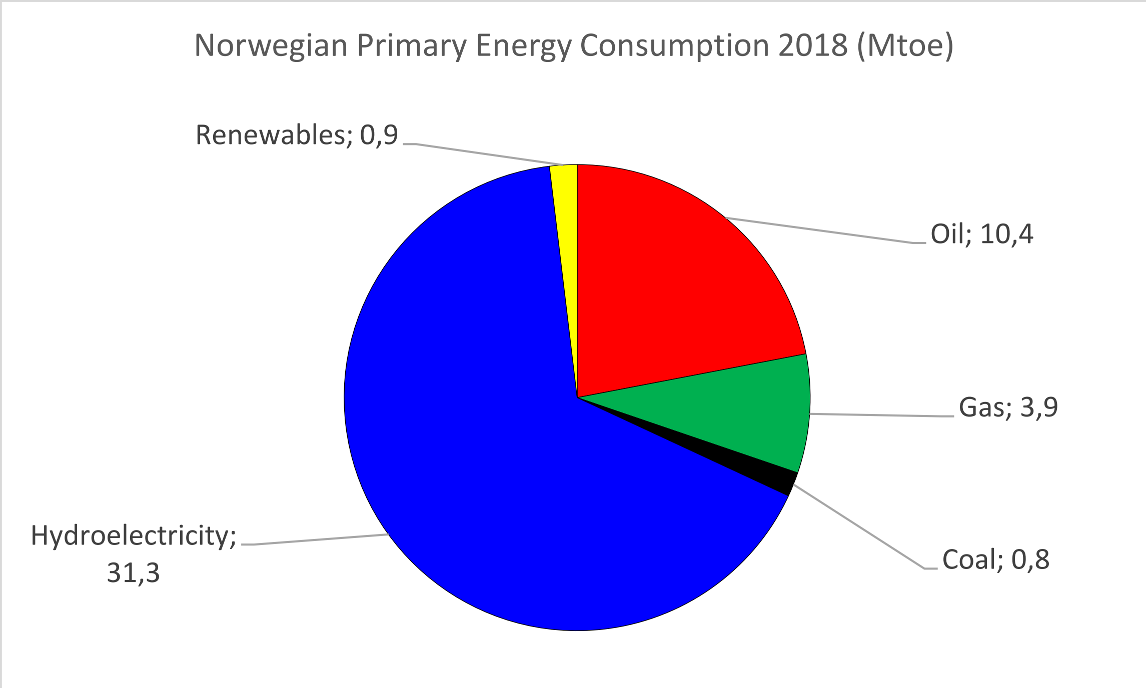

Figure L95. Norwegian primary energy consumption by raw material source
(Source: BP Statistical Review of World Energy 2019 & Appendix A)

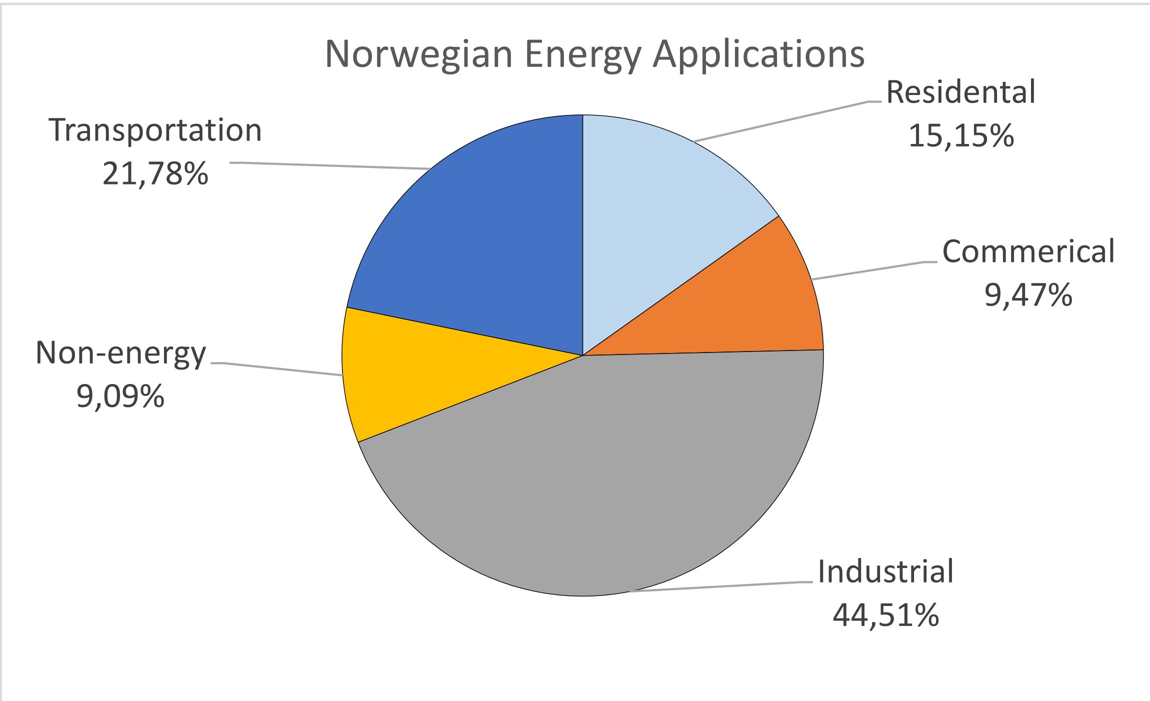

Figure L96. Norwegian energy applications
(Source: Lawrence Livermore National Laboratory 2017, EIA 2017)

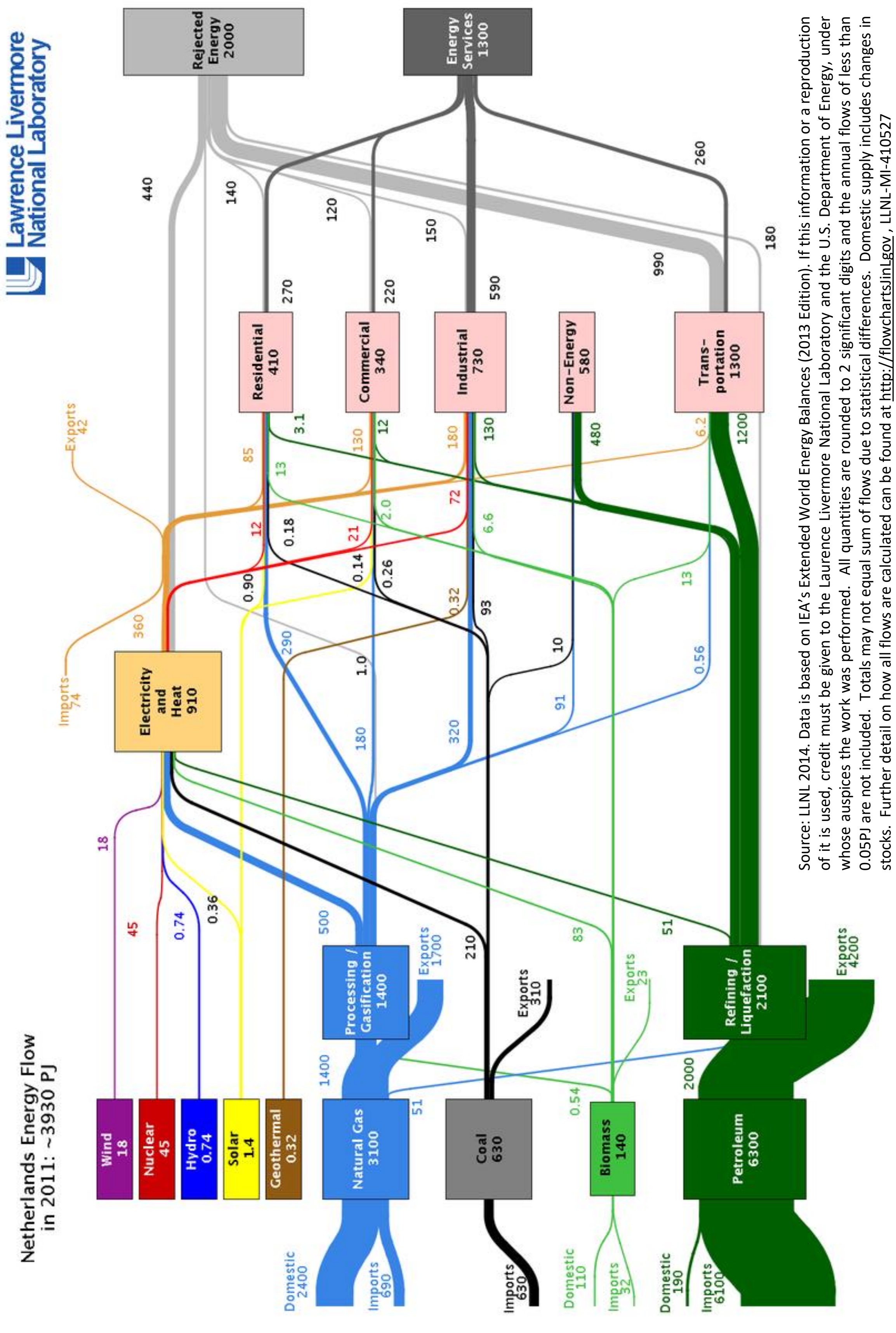

Figure L97. Netherlands energy flow between energy source and application
(Source: Lawrence Livermore National Laboratory Energy Flow Charts)
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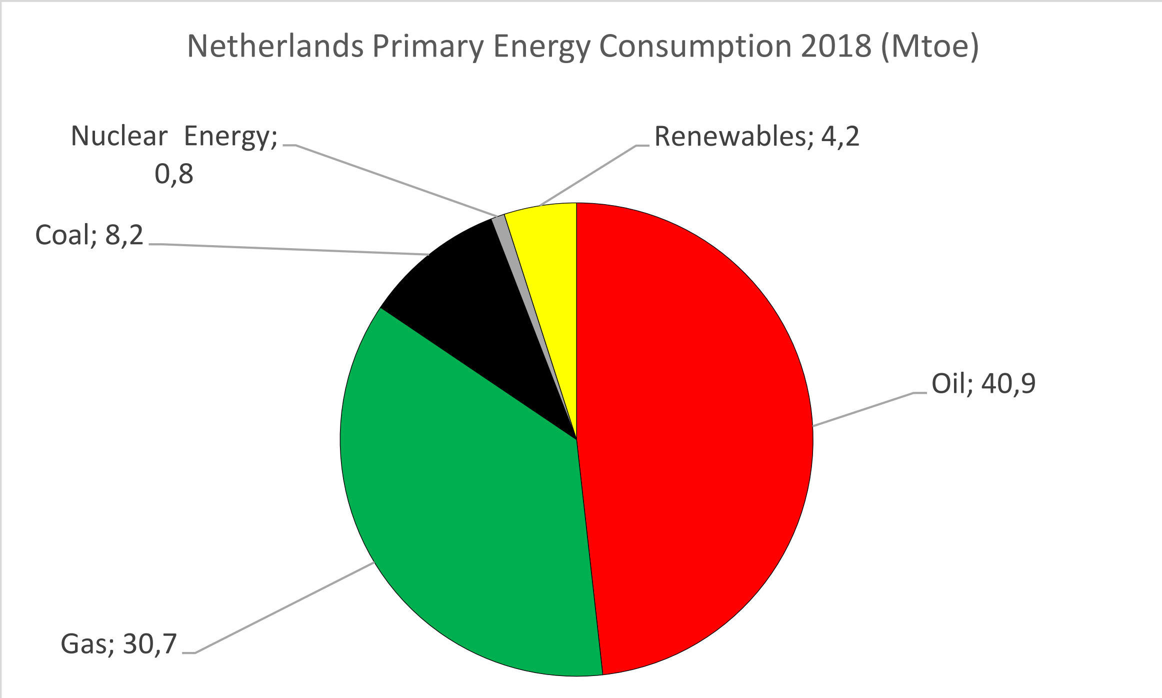

Figure L98. Netherlands primary energy consumption by raw material source
(Source: BP Statistical Review of World Energy 2019 & Appendix A)

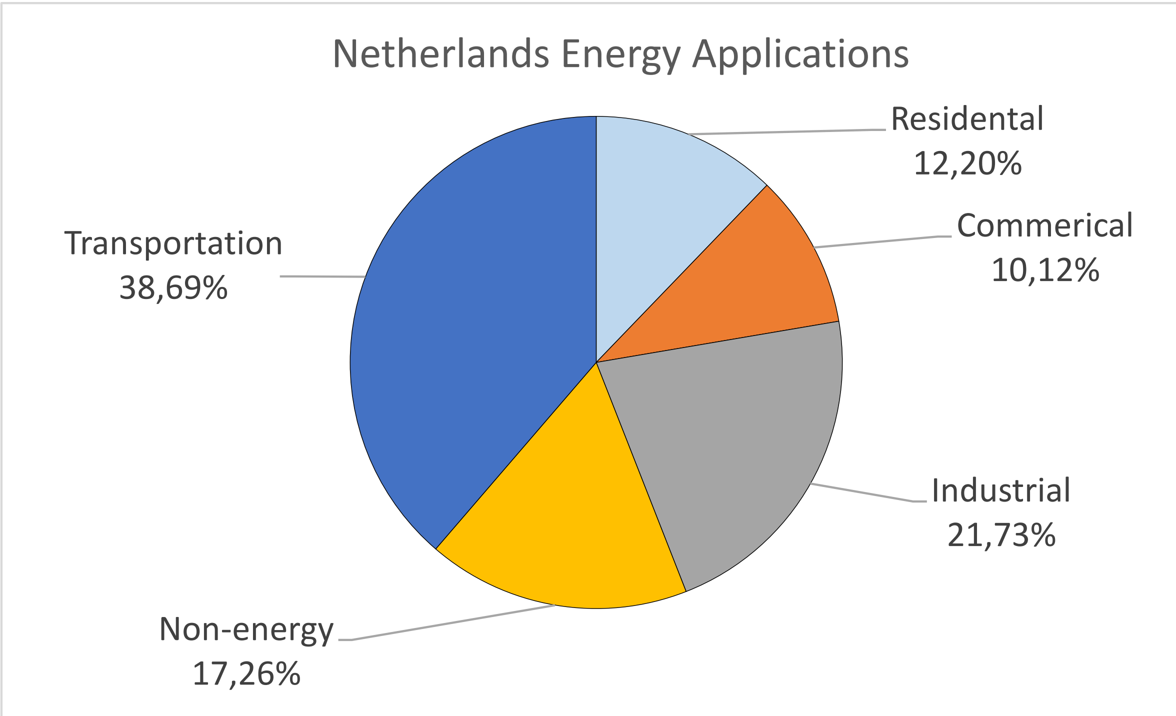

Figure L99. Netherlands energy applications
(Source: Lawrence Livermore National Laboratory 2017, EIA 2017)

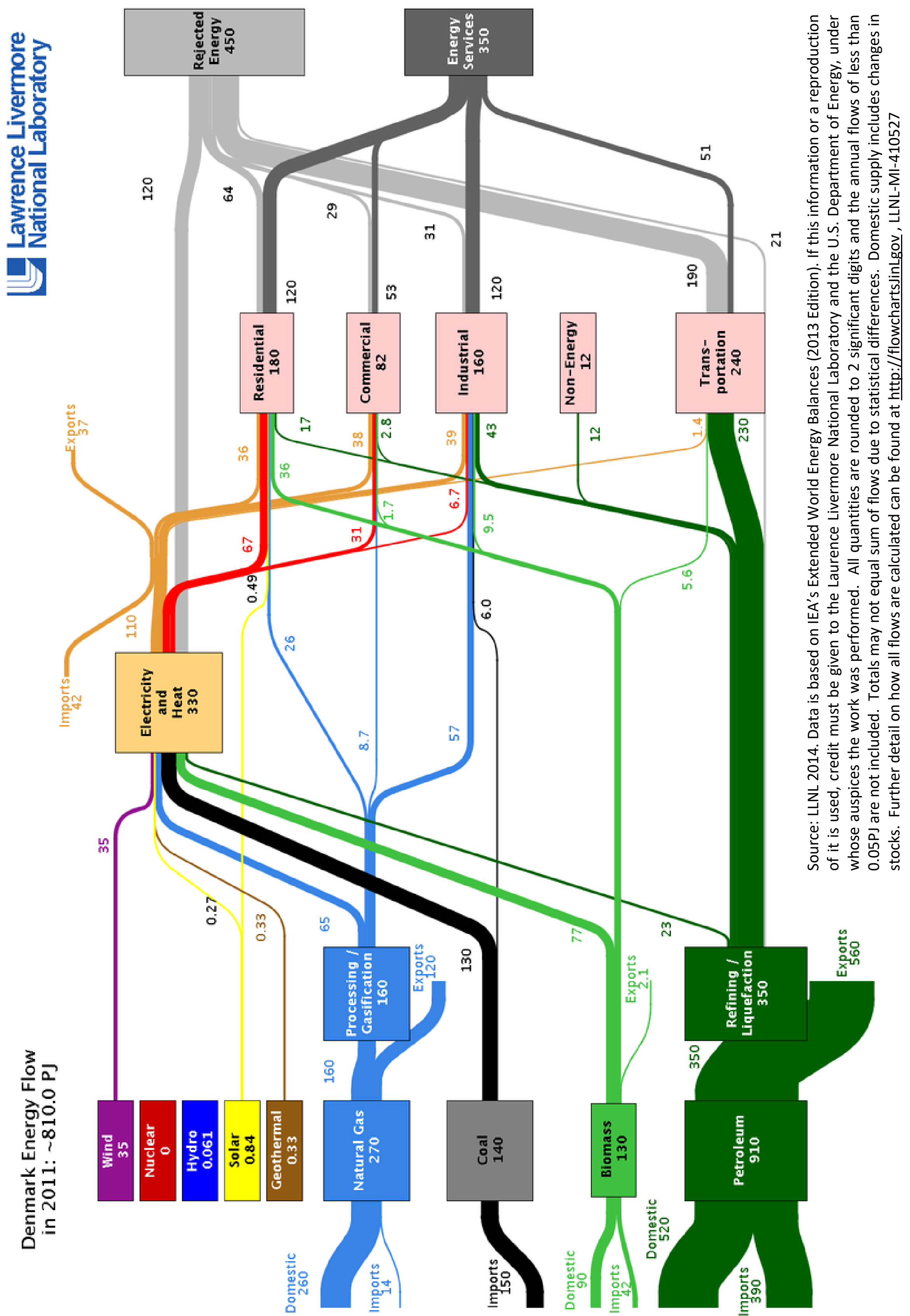

Figure L100. Danish energy flow between energy source and application
(Source: Lawrence Livermore National Laboratory Energy Flow Charts)

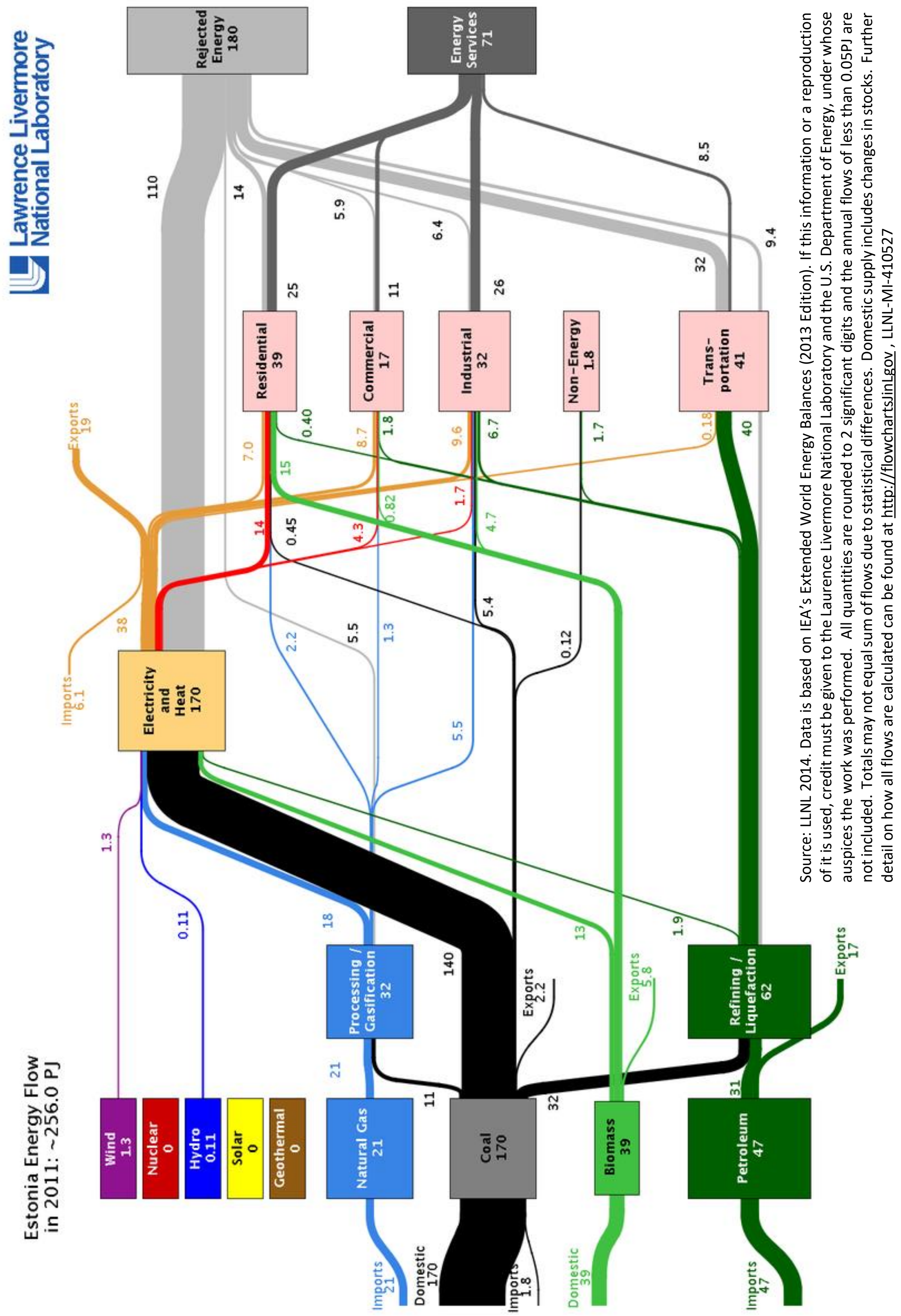

Figure L101. Estonia energy flow between energy source and application
(Source: Lawrence Livermore National Laboratory Energy Flow Charts)
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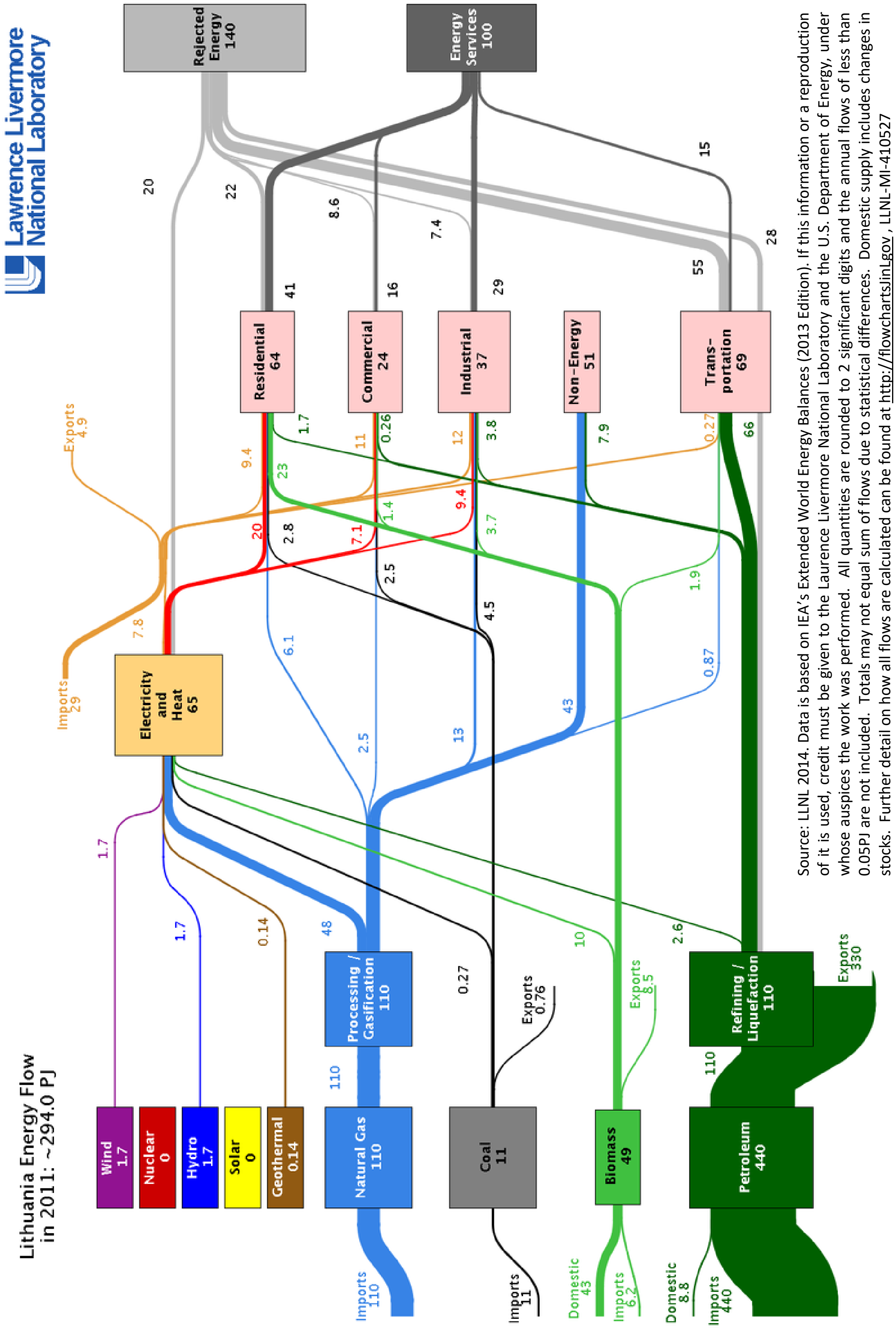


Figure L102. Lithuania energy flow between energy source and application
(Source: Lawrence Livermore National Laboratory Energy Flow Charts)

42 APPENDIX M – EUROPEAN ELECTRICAL POWER NETWORK ENTSO-E TRANSMISSION SYSTEM MAP

This appendix shows several extracts from the electrical power network map developed by the European Distribution System Operators' Association (E.DSO) and the European Network of Transmission System Operators for Electricity (ENTSO-E)

ENTSO-E Transmission System Map

https://www.entsoe.eu/data/map/

This map is a comprehensive illustration of the transmission system network operated by members of the European Network of Transmission System Operators. This means that network elements are not located at their real geographic location.

In general the map shows all transmission lines designed for 220kV voltage and higher and generation stations with net generation capacity of more than 100MW.

Data correct up to 01/01/2019

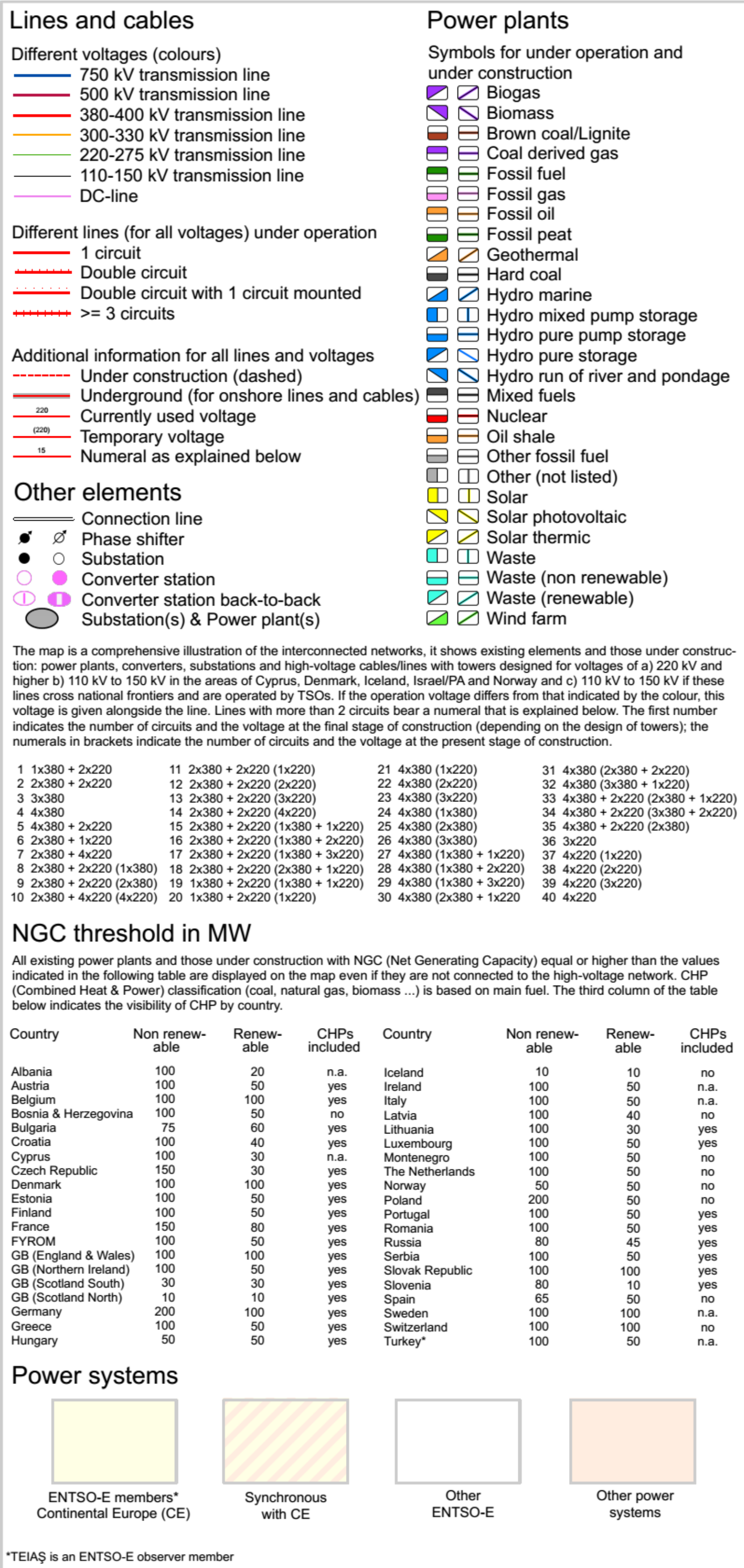


Figure M1. Legend for ENSTO-E maps
(Source: ENTSO-E Transmission System Map, https://www.entsoe.eu/data/map/)

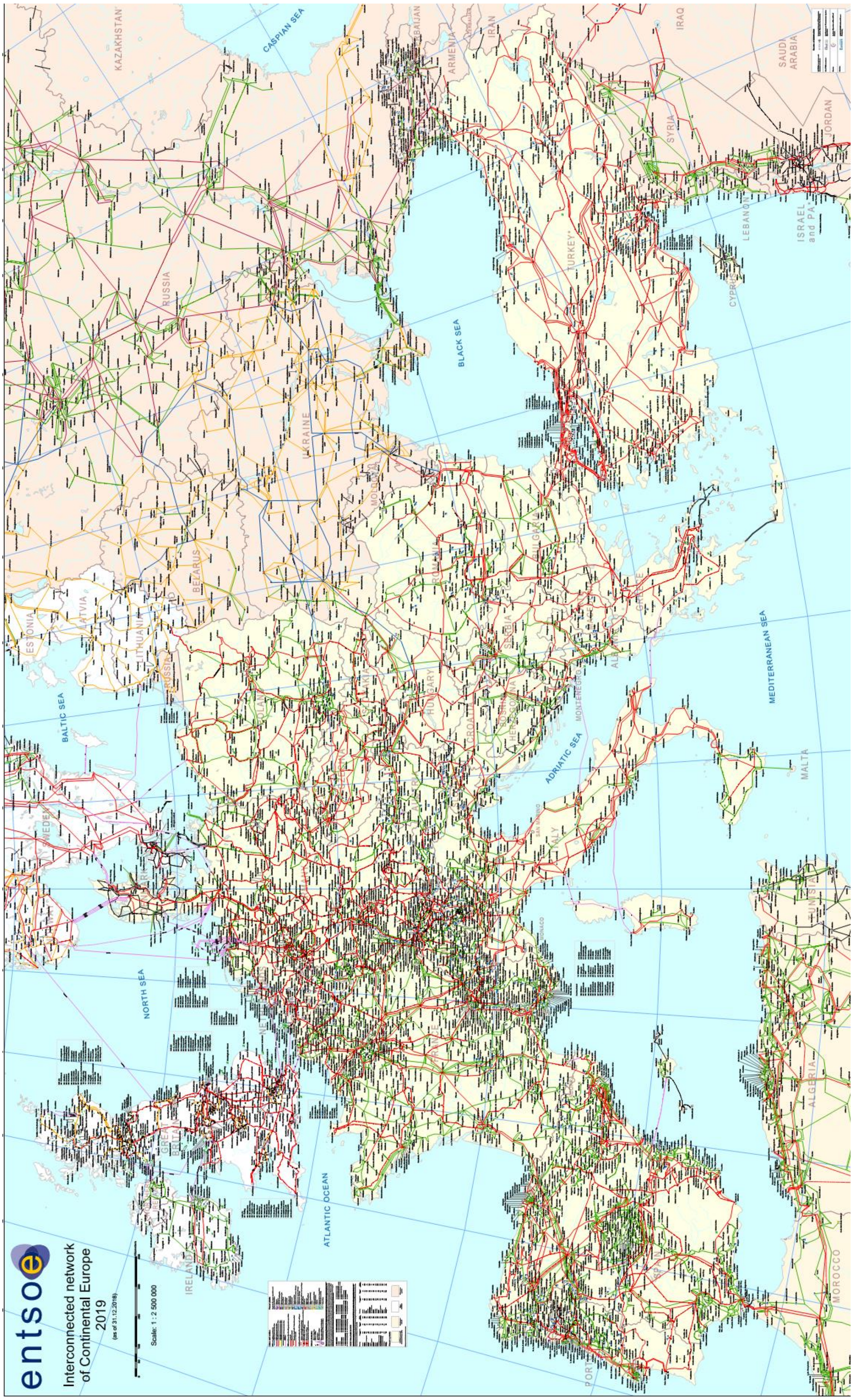


Figure M2. Electrical power network across Continental Europe
(Source: ENTSO-E Transmission System Map, https://www.entsoe.eu/data/map/)

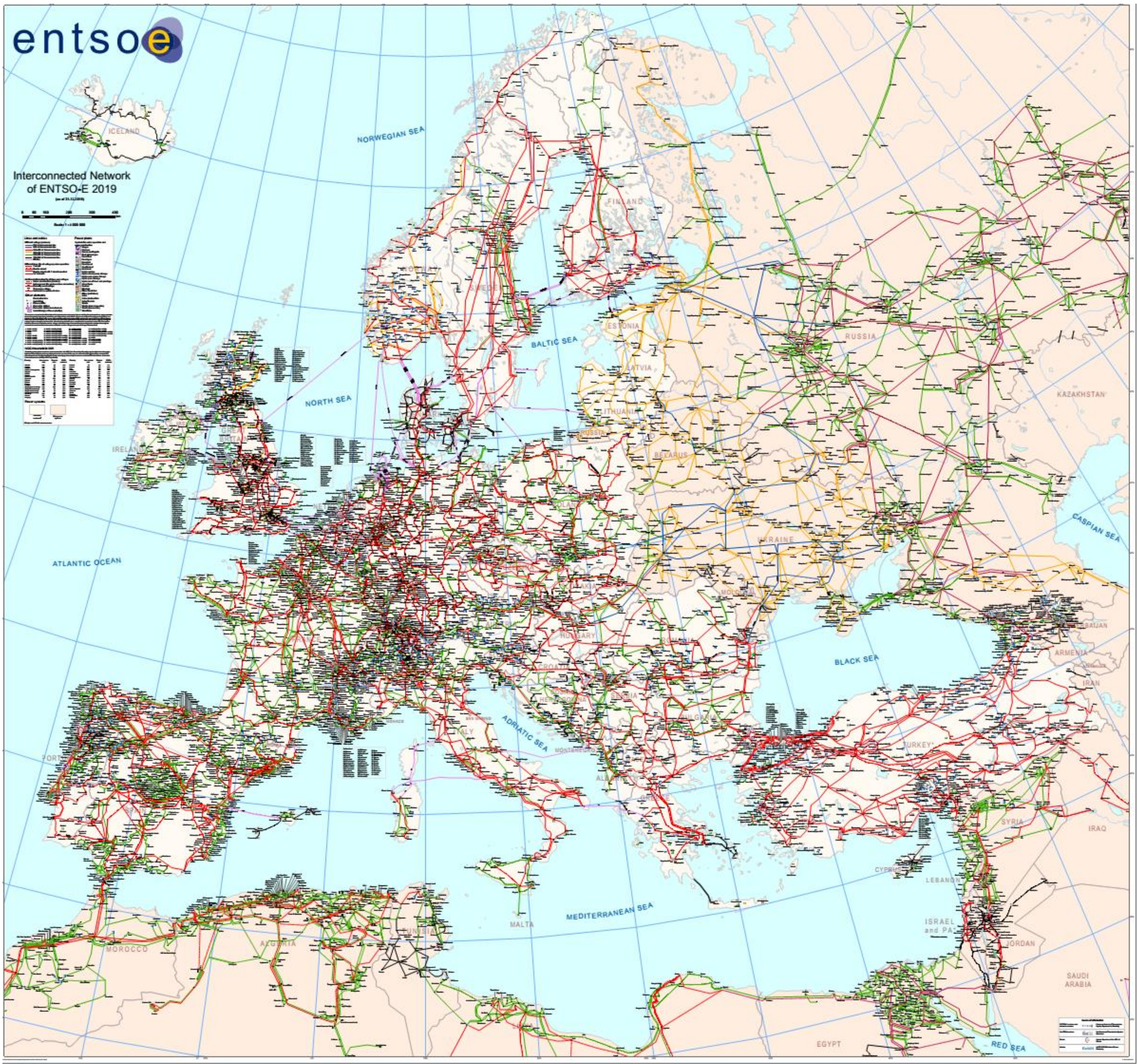


Figure M3. Interconnected electrical power network across Continental Europe
(Source: ENTSO-E Transmission System Map, https://www.entsoe.eu/data/map/)

Figure M4. Interconnected electrical power network in Northern Europe
(Source: ENTSO-E Transmission System Map, https://www.entsoe.eu/data/map/)

43 APPENDIX N – MARITIME SHIPPING STATISTICS & DATA

This appendix is a compilation of useful statistics for the size and form of the maritime fleet.

43.1 Maritime terms definitions

- **Gross tonnage** (GT, G.T. or gt) is a nonlinear measure of a ship's overall internal volume. Gross tonnage is different from gross register tonnage. Neither gross tonnage nor gross register tonnage should be confused with measures of mass or weight such as deadweight tonnage or displacement. Gross tonnage (GT) is a function of the volume of all of a ship's enclosed spaces (from keel to funnel) measured to the outside of the hull framing. The numerical value for a ship's GT is always smaller than the numerical values of gross register tonnage (GRT).

- A **nautical mile** is a unit of measurement used in air, marine, and space navigation, and for the definition of territorial waters. Historically, it was defined as one minute (160 of a degree) of latitude along any line of longitude.

- In maritime tonnage. **Deadweight tonnage** is a measurement of total contents of a ship including cargo, fuel, crew, passengers, food, and water aside from boiler water. It is expressed in long tons of 2,240 lbs (1 016.04 kg).

- Shipping containers come in different sizes, but most are the standard **twenty-foot equivalent units** (**TEU**)—rectangular prisms 6.1 meters (20 feet) long and 2.4 meters wide. The first small container ships of the 1960s carried mere hundreds of TEUs; now Maersk's Triple-E class ships load 18,000 TEUs, and OOCL Hong Kong holds the record, at 21,413 TEU's.

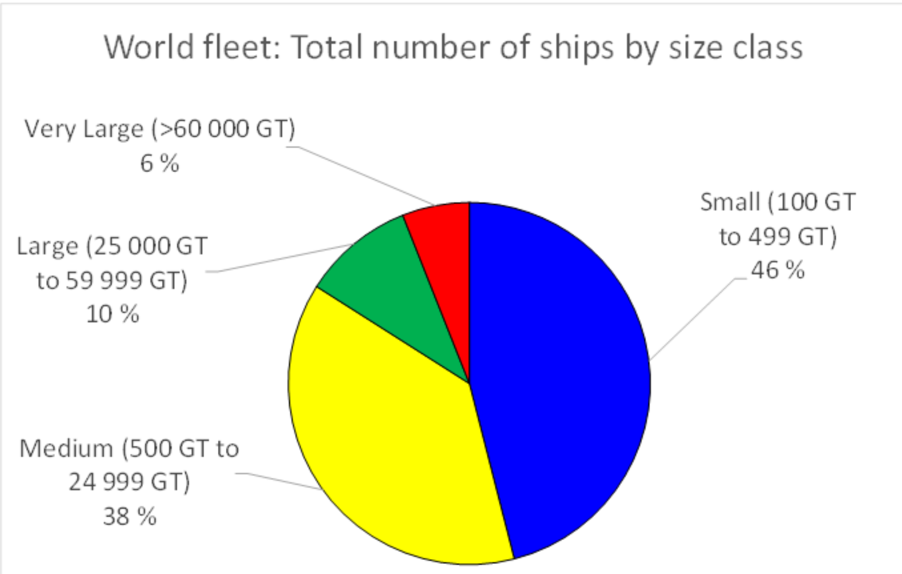
- **Tonne-mile** is defined as the distance covered by a quantity of cargo. For example, 1,000 tonnes carried 500 miles equals 500,000 tonne miles. A measure of demand for capacity. Calculated as the amount of freight times the transport in nautical miles.

- **Tonne-km** is defined as the distance covered by a quantity of cargo. For example, 1,000 tonnes carried 500 kilometers equals 500,000 tonne km. A measure of demand for capacity. Calculated as the amount of freight times the transport in nautical miles.

43.2 Number and size of vessels in global maritime fleet

Table N1. World Fleet: total number of ships by type and size
(Source: The World Merchant Fleet in 2018 Statistics from Equasis)

Ship Type	Small		Medium		Large		Very Large		Total	
	(number)	(%)	(number)	(%)	(number)	(%)	(number)	(%)	(number)	(%)
General Cargo Ships	4 346	8,1 %	11 659	26,1 %	245	2,0 %			**16 250**	13,9 %
Specialized Cargo Ships	8	0,0 %	227	0,5 %	61	0,5 %	5	0,1 %	**301**	0,3 %
Container Ships	19	0,0 %	2 213	5,0 %	1 538	12,8 %	1 441	22,8 %	**5 211**	4,5 %
Ro-Ro Cargo Ships	30	0,1 %	629	1,4 %	565	4,7 %	247	3,9 %	**1 471**	1,3 %
Bulk Carriers	316	0,6 %	3 788	8,5 %	6 119	51,1 %	1 706	27,0 %	**11 929**	10,2 %
Oil and Chemcial Tankers	1 931	3,6 %	7 241	16,2 %	2 642	22,0 %	1 943	30,8 %	**13 757**	11,8 %
Gas Tankers	36	0,1 %	1 116	2,5 %	362	3,0 %	481	7,6 %	**1 995**	1,7 %
Other Tankers	396	0,7 %	698	1,6 %	12	0,1 %			**1 106**	0,9 %
Passenger Ships	4 094	7,6 %	2 793	6,2 %	277	2,4 %	184	2,9 %	**7 348**	6,3 %
Offshore Vessels	2 727	5,1 %	5 297	11,9 %	149	1,2 %	294	4,8 %	**8 467**	7,2 %
Service Ships	2 744	5,1 %	2 750	6,1 %	27	0,2 %	6	0,1 %	**5 527**	4,7 %
Tugs	17 848	33,1 %	1 041	2,3 %					**18 889**	16,2 %
Fishing Vessels	19 359	35,9 %	5 244	11,7 %	3	0,0 %			**24 606**	21,1 %
Total	**53 854**	100,0 %	**44 696**	100,0 %	**12 000**	100,0 %	**6 307**	100,0 %	**116 857**	100,0 %



Ships are grouped by size into four categories:
(Source: The World Merchant Fleet in 2018 Statistics from Equasis)

- Small Ships 100 GT to 499 GT
- Medium ships 500 GT to 24 999 GT
- Large ships 25 000 GT to 59 999 GT
- Very large ships greater than 60 000 GT

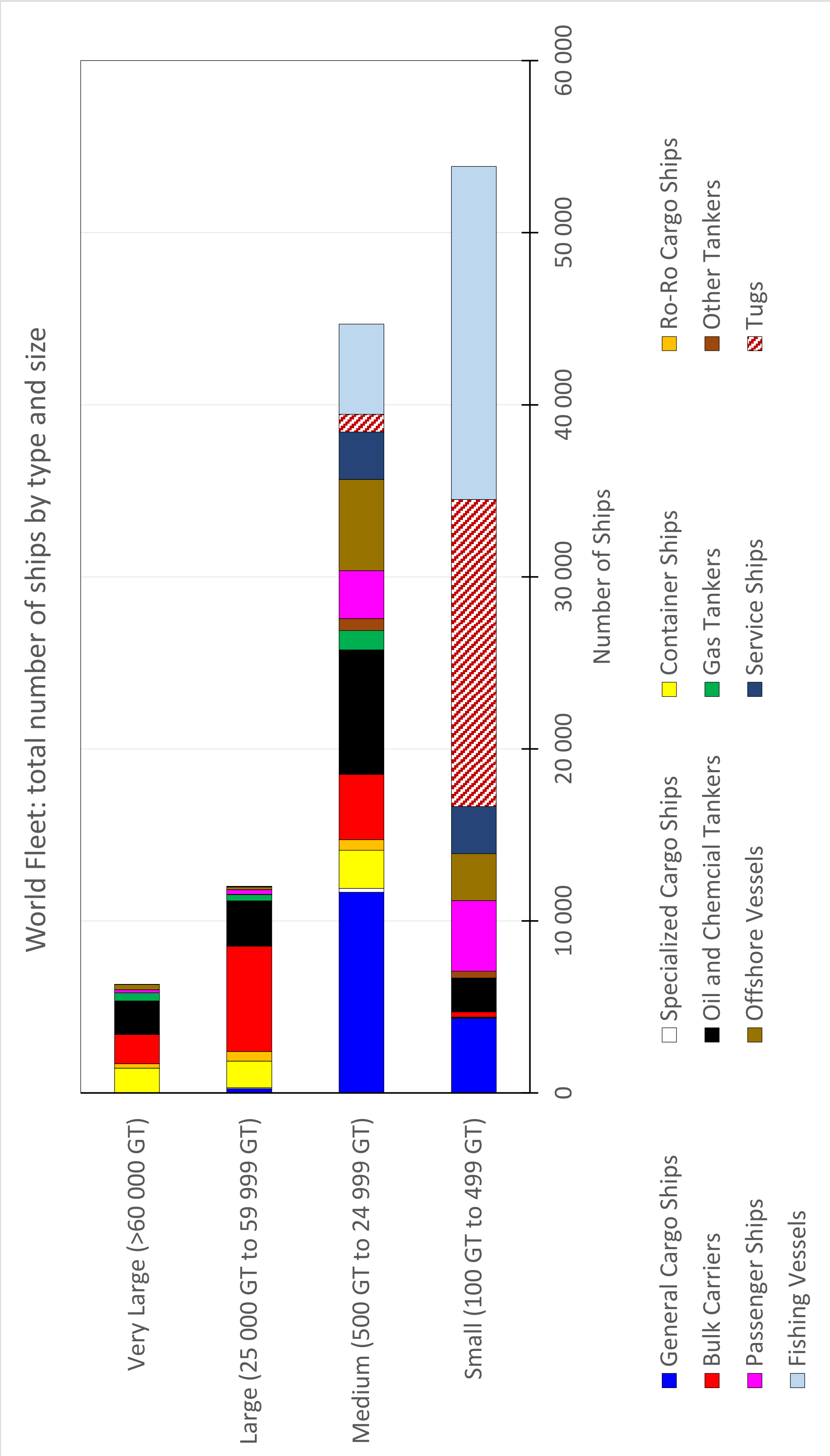
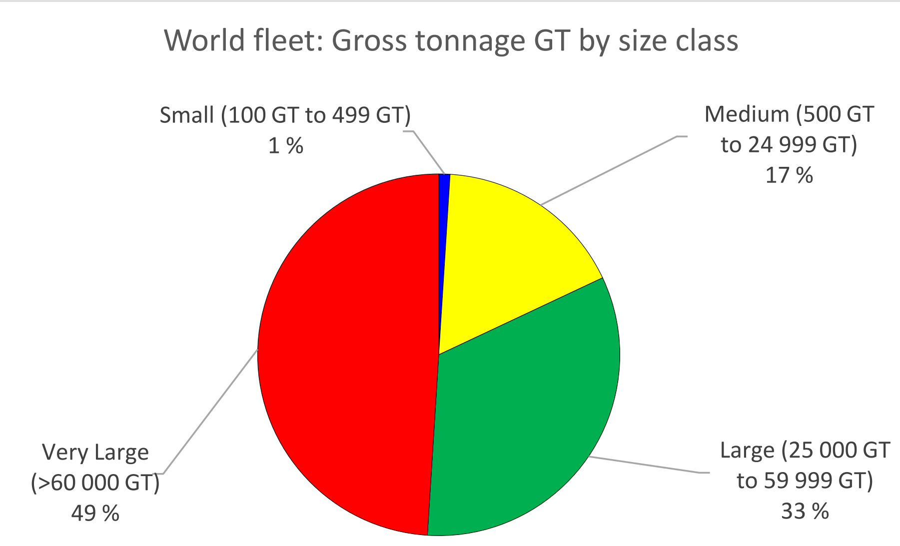


Figure N1. World Fleet: total number of ships by type and size
(Source: The World Merchant Fleet in 2018 Statistics from Equasis)

Table N2. World Fleet: gross tonnage (in 1000 GT), by type and size
(Source: The World Merchant Fleet in 2018 Statistics from Equasis)

Ship Type	Small		Medium		Large		Very Large		Total	
	(1000 GT)	(%)	(1000 GT)	(%)	(1000 GT)	(%)	(1000 GT)	(%)	(1000 GT)	(%)
General Cargo Ships	1 474	11,0 %	49 643	21,0 %	8 089	1,8 %			**59 206**	4,3 %
Specialized Cargo Ships	3	0,0 %	1 767	0,7 %	2 323	0,5 %	371	0,1 %	**4 464**	0,3 %
Container Ships	8	0,1 %	25 754	10,9 %	58 096	12,9 %	156 077	23,6 %	**239 935**	17,6 %
Ro-Ro Cargo Ships	10	0,1 %	6 265	2,6 %	26 898	6,0 %	16 605	2,5 %	**49 778**	3,7 %
Bulk Carriers	125	0,9 %	56 675	23,9 %	227 640	50,5 %	173 208	26,2 %	**457 648**	33,6 %
Oil and Chemcial Tankers	622	4,6 %	43 923	18,6 %	94 293	20,8 %	206 707	31,3 %	**345 545**	25,4 %
Gas Tankers	14	0,1 %	7 098	3,0 %	15 671	3,5 %	53 896	8,2 %	**76 679**	5,6 %
Other Tankers	118	0,9 %	2 022	0,9 %	355	0,1 %			**2 495**	0,2 %
Passenger Ships	1 053	7,9 %	11 357	4,8 %	9 965	2,2 %	19 458	2,9 %	**41 833**	3,1 %
Offshore Vessels	765	5,7 %	15 274	6,4 %	6 710	1,5 %	33 412	5,1 %	**56 161**	4,1 %
Service Ships	671	5,0 %	8 888	3,8 %	994	0,2 %	891	0,1 %	**11 444**	0,8 %
Tugs	4 296	32,1 %	1 024	0,4 %					**5 320**	0,4 %
Fishing Vessels	4 228	31,6 %	7 070	3,0 %	114	0,0 %			**11 412**	0,8 %
Total	**13 387**	100,0 %	**236 760**	100,0 %	**451 148**	100,0 %	**660 625**	100,0 %	**1 361 920**	100,0 %



Ships are grouped by size into four categories:
(Source: The World Merchant Fleet in 2018 Statistics from Equasis)

- Small Ships 100 GT to 499 GT
- Medium ships 500 GT to 24 999 GT
- Large ships 25 000 GT to 59 999 GT
- Very large ships greater than 60 000 GT

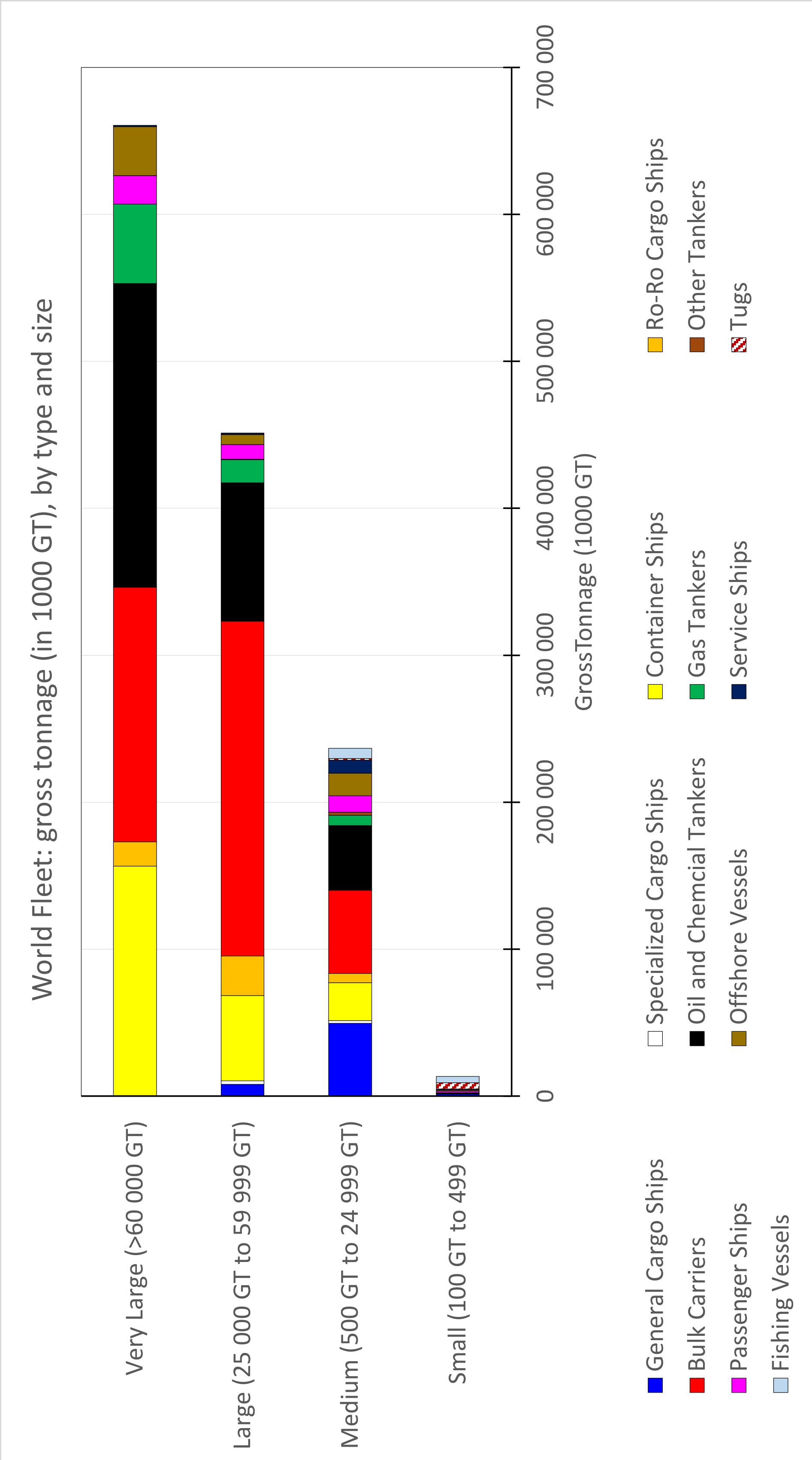


Figure N2. World Fleet: gross tonnage (in 1000 GT), by type and size
(Source: The World Merchant Fleet in 2018 Statistics from Equasis)

43.3 World fleet by principal vessel type, dead-weight tonnes capacity in 2018

In tonnage. Deadweight tonnage is a measurement of total contents of a ship including cargo, fuel, crew, passengers, food, and water aside from boiler water. It is expressed in long tons of 2,240 lbs (1,016 kg).

Table N3. World fleet by principal vessel type, dead-weight tonnes capacity in 2018
(Source: The World Merchant Fleet in 2018 Statistics from Equasis)

Ship Type	Dead-Weight Tons (1000's tonnes)	Dead-Weight Tons (%)
General Cargo Ships	73 951	3,84 %
Container Ships	253 275	13,15 %
Bulk Carriers	818 921	42,52 %
Oil and Chemcial Tankers	606 492	31,49 %
Gas Tankers	64 407	3,34 %
Passenger Ships	6 922	0,36 %
Offshore Vessels	78 269	4,06 %
Other	23 946	1,24 %
Total	1 926 183	100,0 %

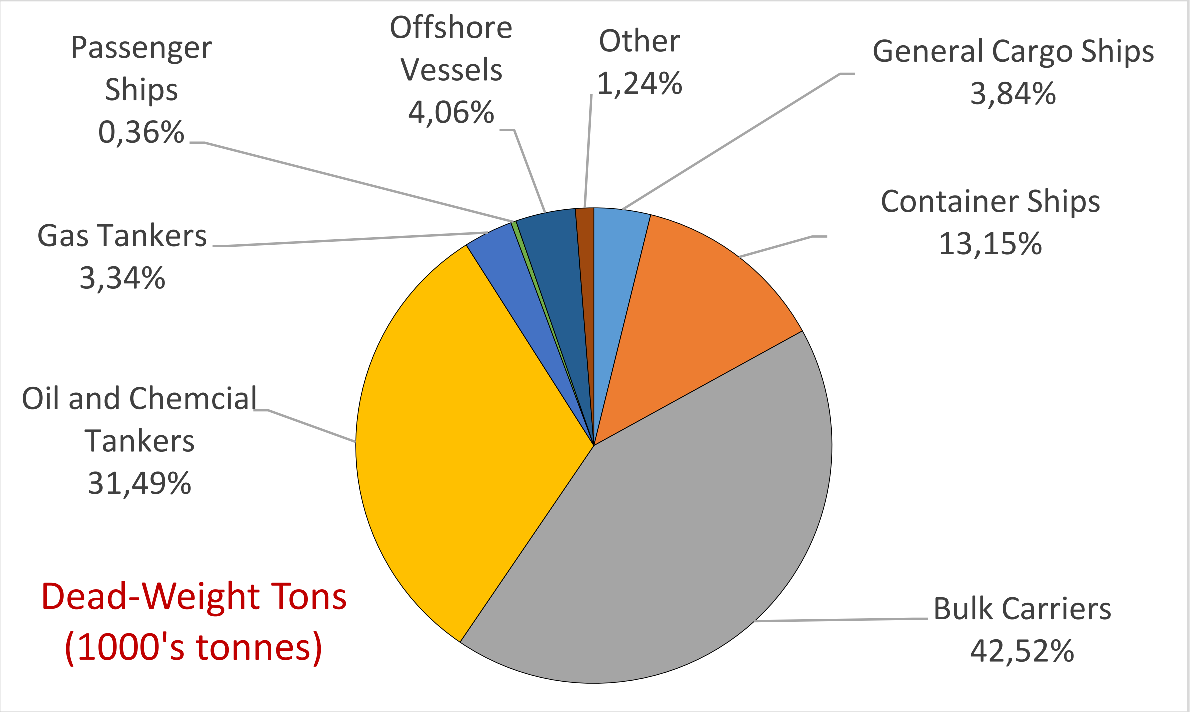


Figure N3. World fleet by principal vessel type, dead-weight tonnes capacity in 2018
(Source: The World Merchant Fleet in 2018 Statistics from Equasis)

43.4 Maritime Trade - Major dry bulks and steel: Producers, users, exporters and importers

Table N4. Steel producers and users/consumers in 2018
(Source: UNCTAD 2019 Review of maritime transport 2019, United Nations Conference on Trade and Development)

Country	Steel Producers (%)		Country	Streel Users (%)
China	51 %		China	49 %
India	6 %		United States	6 %
United States	6 %		India	6 %
Republic of Korea	5 %		Japan	4 %
Russian Federation	4 %		Republic of Korea	3 %
Germany	4 %		Germany	2 %
Turkey	2 %		Russian Federation	2 %
Brazil	2 %		Turkey	2 %
Other	18 %		Italy	2 %
			Mexico	1 %
			Other	23 %

Table N5. Iron Ore - exporters and importers, in 2018
(Source: UNCTAD 2019 Review of maritime transport 2019, United Nations Conference on Trade and Development)

Country	Iron Ore Exporters (%)		Country	Iron Ore Importers (%)
Australia	57 %		China	71 %
Brazil	26 %		Japan	8 %
South Africa	4 %		Europe	7 %
Canada	3 %		Republic of Korea	5 %
Sweden	2 %		Other	9 %
India	1 %			
Other	7 %			

Table N6. Coal - exporters and importers, in 2018
(Source: UNCTAD 2019 Review of maritime transport 2019, United Nations Conference on Trade and Development)

Country	Coal Exporters (%)		Country	Coal Importers (%)
Indonesia	33 %		China	19 %
Australia	30 %		India	18 %
Russian Federation	11 %		Japan	15 %
United States	8 %		European Union	11 %
Colombia	6 %		Republic of Korea	11 %
South Africa	6 %		Taiwan Province of China	5 %
Canada	2 %		Malaysia	3 %
Other	4 %		Other	18 %

Table N7. Grain - exporters and importers, in 2018
(Source: UNCTAD 2019 Review of maritime transport 2019, United Nations Conference on Trade and Development)

Country	Grain Exporters (%)		Country	Grain Importers (%)
United States	26 %		East & South Asia	45 %
Brazil	23 %		Africa	14 %
Russian Federation	11 %		Western Asia	14 %
Ukraine	9 %		South & Central America	12 %
Argentina	9 %		European Union	10 %
European Union	7 %		Other	3 %
Canada	6 %			
Australia	4 %			
Other	5 %			

43.5 Shipping route distance and estimated time at sea

To calculate the requirements for the maritime shipping fleet to transition to electric propulsion, it was necessary to document several examples of shipping routes and their distances.

Table N8. Shipping route distance and estimated time at sea
(Source: Ports.com, Shipping Trade Route Calculator)
(http://ports.com/sea-route/port-of-shanghai,china/port-of-hamburg,germany/)

Origin	Destination	Distance in Nautical Miles (nm)	Distance in kilometers (km)	Estimated time at sea (days)	Speed of Ship (knots)
Port of Shanghai (China)	Port of Hamburg (Germany)	12 277	22 737	25,6	20
Port of Hamburg (Germany)	Port of Melbourne (Australia)	13 372	24 765	27,8	20
Port of Hamburg (Germany)	Port of Osaka (Japan)	12 999	24 074	27,1	20
Port of Hamburg (Germany)	Port Hong Kong	11 416	21 142	23,8	20
Port of Amsterdam (Netherlands)	Port Los Angelas (United States)	10 279	19 037	21,4	20
Port of Amsterdam (Holland)	Port of Singapore	9 378	17 368	19,6	20
Port of Shanghai (China)	Port Los Angelas (United States)	19 270	35 688	40,1	20
Port of Shanghai (China)	Port of Cape Town (South Africa)	9 250	17 131	19,3	20

The speed of ship selected in Table N8 was based on the most cost effective and economical speed that large ships use in current industrial practice. The four basic classifications of speed were (Source: Fuel Consumption by Containership Size and Speed https://transportgeography.org/?page_id=5955):

5. **Normal** (20-25 knots; 37.0 – 46.3 km/hr). Represents the optimal cruising speed a containership and its engine have been designed to travel at. It also reflects the hydrodynamic limits of the hull to perform within acceptable fuel consumption levels. Most containerships are designed to travel at speeds around 24 knots.

6. **Slow steaming** (18-20 knots; 33.3 – 37.0 km/hr). Running ship engines below capacity to save fuel consumption but at the expense an additional travel time, particularly over long distances (compounding effect). This is likely to become the dominant operational speed as more than 50% of the global container shipping capacity was operating under such conditions as of 2011.

7. **Extra slow steaming** (15-18 knots; 27.8 – 33.3 km/hr). Also known as super slow steaming or economical speed. A substantial decline in speed for the purpose of achieving a minimal level of fuel consumption while still maintaining a commercial service. It can be applied on specific short-distance routes.

8. **Minimal cost** (12-15 knots; 22.2 – 27.8 km/hr). The lowest speed technically possible, since lower speeds do not lead to any significant additional fuel economy. The level of service is however commercially unacceptable, so it is unlikely that maritime shipping companies would adopt such speeds.

As shown in Figure N4, a Maersk's Triple-E class ship (capacity load of 18,340 TEUs) TEU diesel fuel oil consumption, while travelling at 20 knots (Slow Steaming speed 2 above), is estimated at 175 tons per day.

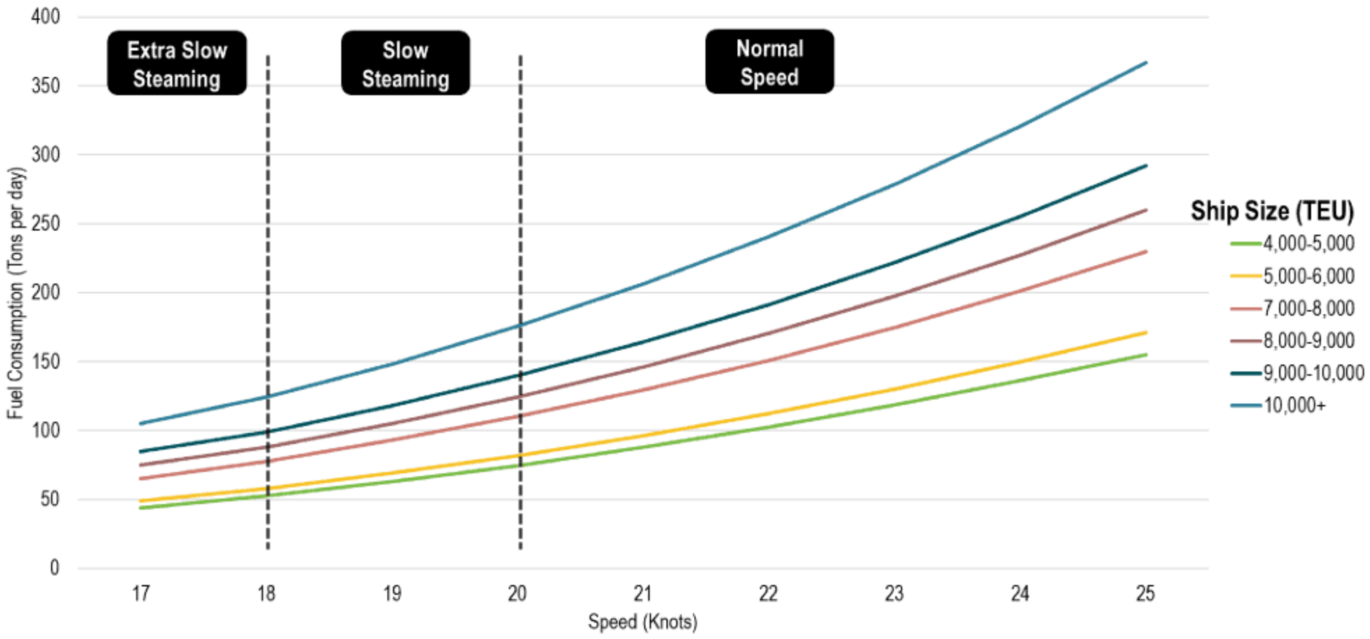


Figure N4. Fuel Consumption by Containership Size and Speed
(Source: adapted from Notteboom & Carriou 2009)

43.6 Maersk Triple E-class container ship specifications

The Maersk Triple E-class container ship is used for the example in the calculation of energy consumption of an EV very large ship (Source: https://www.ship-technology.com/projects/triple-e-class-container-ship/).

Class overview

Builders:	Daewoo Shipbuilding
Operators:	Maersk
Preceded by:	Mærsk E class
Planned:	31
Building:	0
Completed:	31
Active:	31

General characteristics

Type:	Container ship
Tonnage:	196,000 DWT
Displacement:	55,000 tonnes (empty)
Length:	399.2 m (1,310 ft)
Beam:	59 m (194 ft)
Draft:	16 m (52 ft)
Decks:	4
Propulsion:	Twin MAN engines, 29,680 kilowatts (39,800 hp) each
Speed:	Design cruise: 16 knots (30 km/h; 18 mph) Max: 23 knots (43 km/h)
Capacity:	18,340 TEU
Notes:	Cost $185 million

43.7 Goods loaded and goods unloaded

Table N9. Goods loaded – million tonnes
(Source: UNCTAD 2019 Review of maritime transport 2019, United Nations Conference on Trade and Development)

Country group	Crude oil (million tonnes)	Other tanker Trade (million tonnes)	Dry Cargo (million tonnes)	Total (million tonnes)
World	1 886,2	1 308,1	7 810,7	11 005,0
Developed economies	157,7	511,2	3 152,7	3 821,6
Transition economies	203,8	39,8	469,9	713,5
Developing economies	1 524,7	757,3	4 188,0	6 470,0
Africa	289,3	73,8	404,0	767,1
America	219,3	78,3	1 106,1	1 403,7
Asia	1 014,4	604,1	2 672,1	4 290,6
Oceania	1,6	1,0	5,8	8,4

Table N10. Goods loaded – Percentage proportion
(Source: UNCTAD 2019 Review of maritime transport 2019, United Nations Conference on Trade and Development)

Country group	Crude oil (%)	Other tanker Trade (%)	Dry Cargo (%)	Total (%)
World	17,1 %	11,9 %	71,0 %	100,0 %
Developed economies	4,1 %	13,4 %	82,5 %	100,0 %
Transition economies	28,6 %	5,6 %	65,9 %	100,0 %
Developing economies	23,6 %	11,7 %	64,7 %	100,0 %
Africa	37,7 %	9,6 %	52,7 %	100,0 %
America	15,6 %	5,6 %	78,8 %	100,0 %
Asia	23,6 %	14,1 %	62,3 %	100,0 %
Oceania	19,0 %	11,9 %	69,0 %	100,0 %

Table N11. Goods unloaded – million tonnes
(Source: UNCTAD 2019 Review of maritime transport 2019, United Nations Conference on Trade and Development)

Country group	Crude oil (million tonnes)	Other tanker Trade (million tonnes)	Dry Cargo (million tonnes)	Total (million tonnes)
World	2 048,5	1 321,8	7 631,9	11 002,2
Developed economies	946,5	495,8	2 380,5	3 822,8
Transition economies	0,3	4,8	81,3	86,4
Developing economies	1 101,6	821,2	5 170,0	7 092,8
Africa	42,5	93,9	380,0	516,4
America	51,8	149,0	451,8	652,6
Asia	1 006,5	572,5	4 329,3	5 908,3
Oceania	0,8	5,8	9,0	15,6

Table N12. Goods unloaded – Percentage proportion
(Source: UNCTAD 2019 Review of maritime transport 2019, United Nations Conference on Trade and Development)

Country group	Crude oil (%)	Other tanker Trade (%)	Dry Cargo (%)	Total (%)
World	18,6 %	12,0 %	69,4 %	100,0 %
Developed economies	24,8 %	13,0 %	62,3 %	100,0 %
Transition economies	0,3 %	5,6 %	94,1 %	100,0 %
Developing economies	15,5 %	11,6 %	72,9 %	100,0 %
Africa	8,2 %	18,2 %	73,6 %	100,0 %
America	7,9 %	22,8 %	69,2 %	100,0 %
Asia	17,0 %	9,7 %	73,3 %	100,0 %
Oceania	5,1 %	37,2 %	57,7 %	100,0 %

44 APPENDIX O – AVIATION TRANSPORT STATISTICS & DATA

This appendix is a compilation of useful statistics for the size and form of the aviation fleet.

Table O1. Commercial transport fleet of ICAO Member States at the end of each year (Source: ICAO 2018, Reed Business Information RBI)

	Turbojet		Turboprop		Total Aircraft
Year	Number	Percentage	Number	Percentage	All Types
2009	20 332	87,4 %	2 932	12,6 %	23 264
2010	20 904	87,5 %	976	12,5 %	21 880
2011	21 543	87,7 %	3 009	12,3 %	24 552
2012	22 255	88,1 %	2 997	11,9 %	25 252
2013	22 893	88,1 %	3 061	11,9 %	25 954
2014	23 587	88,5 %	3 066	11,5 %	26 653
2015	24 259	88,7 %	3 093	11,3 %	27 352
2016	25 060	88,9 %	3 117	11,1 %	28 177
2017	26 100	89,3 %	3 136	10,7 %	29 236
2018	27 183	89,5 %	3 196	10,5 %	30 379

Note: Active and parked aircraft are included;

Note: Aircraft having a maximum take-off mass of less than 9 000kg are not included

Table O2. World Scheduled Passenger and Cargo Traffic 2018 (Source: World Air Transport Statistics 2019)

World	International		Domestic		Global System	
	2018	% Change	2018	% Change	2018	% Change
Passengers Carried (thousands)	1 811 324	7,0 %	2 566 346	6,8 %	4 377 670	6,9 %
Freight Tonnes carried (thousands)	42 450	2,9 %	20 037	2,9 %	62 487	2,9 %
Passenger-Kilometeres (millions)	5 332 852	7,2 %	2 996 924	7,6 %	8 329 776	7,4 %
Available Seat-Kilometres (millions)	6 569 395	6,7 %	3 605 433	7,2 %	10 174 828	6,9 %
Passenger Load Factor	81,2 %	0,4 %	83,1 %	0,3 %	81,9 %	0,4 %
Freight and Mail Tonne-Kilometres (millions)	299 328	3,4 %	33 005	3,8 %	332 333	3,4 %
Available Freight Tonne-Kilometres (millions)	416 834	4,8 %	115 166	6,7 %	532 000	5,2 %
Freight Load Factor	55,0 %	-0,8 %	28,7 %	-0,8 %	49,3 %	-0,8 %
Revenue Tonne-Kilometres (millions)	738 132	5,9 %	305 970	7,0 %	1 044 102	6,2 %
Avialable Tonne-Kilometres (millions)	1 046 283	5,8 %	447 262	6,8 %	1 493 545	6,1 %
Weight Load Factor	70,5 %	0,1 %	68,4 %	0,1 %	69,9 %	0,1 %

Table O3. World Scheduled Cargo Traffic 2018 (Source: World Air Transport Statistics 2019)

World	All Cargo Operations		Mixed Operations		Total	
	2018	% Change	2018	% Change	2018	% Change
Freight Tonnes carried (thousands)	34 425	2,8 %	28 063	3,0 %	62 487	2,9 %
Freight and Mail Tonne-Kilometres (millions)	136 583	3,6 %	125 750	3,2 %	262 333	3,4 %
Available Freight Tonne-Kilometres (millions)	204 645	5,4 %	327 356	5,1 %	532 000	5,2 %
Freight Load Factor	66,7 %	-1,1 %	38,4 %	-0,7 %	49,3 %	-0,8 %

Note: Estimates produced by IATA Statistics www.iata.org/statistics

All-cargo operations refer to traffic carried out by dedictaed cargo aircraft, which by design or configuration, are operating exclusively for

the transportation of cargo. Mixed operations refer to traffic operated y aircraft that transport both passengers and cargo

Table 04 -1. Freight tonne-kilometres performed on scheduled services (countries and groups of countries whose airlines performed more than 25 million freight tonne-kilometres in 2018) (Source: ICAO 2018, Reed Business Information RBI)

Country or group of countries	Freight Tonne-Kilometres (millions)							
	Total Services (International and domestic)				International Services			
	Rank number in 2018	2018	2017	Increase or decrease (%)	Rank number in 2018	2018	2017	Increase or decrease (%)
United States	1	42 985	41 592	3	1	25 865	24 727	5
China	2	25 256	23 324	8	2	18 136	16 502	10
Hong Kong SAR		12 677	12 415	2		12 677	12 415	2
Macao SAR		32	33	-3		32	33	-3
United Arab Emirates	3	15 963	16 616	-4	3	15 963	1 616	-4
Qatar	4	12 677	10 970	15	4	12 667	10 970	15
Republic of Korea	5	11 930	11 512	4	5	11 877	11 455	4
Japan	6	9 421	10 685	-12	6	8 486	9 700	-13
Germany	7	7 970	7 902	1	7	7 932	7 861	1
Luxembourg	8	7 323	7 321	0	8	7 323	7 321	0
Russian Federation	9	6 811	6 845	-1	10	6 130	6 167	-1
United Kingdom	10	6 198	5 916	5	9	6 198	5 915	5
Turkey	11	5 949	4 800	24	11	5 916	4 736	25
Netherelands	12	5 887	5 855	1	12	5 887	5 855	1
Singapore	13	5 195	5 063	3	13	5 195	5 083	3
France	14	4 444	4 261	4	14	3 972	3 823	4
Canada	15	3 434	2 841	21	15	2 770	2 311	20
India	16	2 704	2 407	12	19	1 893	1 662	14
Thailand	17	2 666	2 512	6	16	2 637	2 485	6
Ethiopia	18	2 089	2 076	1	17	2 089	2 076	1
Australia	19	2 028	1 983	2	18	1 899	1 857	2
Brazil	20	1 846	1 737	6	24	1 309	1 210	8
Switzerland	21	1 841	1 581	16	20	1 841	1 581	16
Italy	22	1 418	1 437	-1	21	1 416	1 435	-1
Malaysia	23	1 404	1 455	-3	22	1 331	1 340	-1
Colombia	24	1 349	1 274	6	26	1 274	1 200	6
New Zealand	25	1 349	1 336	1	23	1 327	1 313	1
Belgium	26	1 285	1 574	-18	25	1 285	1 574	-18
Chile	27	1 226	1 238	-1	27	1 167	175	-1
Indonesia	28	1 132	1 052	8	36	581	564	3
Spain	29	1 117	1 079	4	28	1 102	1 060	4
Mexico	30	1 090	929	17	31	969	820	18
Saudi Arabia	31	1 085	868	25	29	1 048	826	27
Israel	32	995	913	9	30	995	913	9
Finland	33	958	852	12	32	957	852	12
Philippines	34	836	753	11	35	604	560	8
Scandinavia	35	741	762	-3	33	737	760	-3
South Africa	36	716	833	-14	34	649	779	-17
Oman	37	510	435	17	37	507	434	17
Viet Nam	38	481	453	6	44	300	279	8
Portugal	39	454	422	8	38	445	412	8
Egypt	40	438	404	8	39	437	404	8
Sri Lanka	41	436	398	9	40	436	398	10
Bahrain	42	421	390	8	41	421	390	8
Kuwait	43	392	310	27	42	392	310	27
Austria	44	374	391	-5	43	373	391	-5
Peru	45	313	317	-1	45	295	298	-1
Argentina	46	312	305	2	46	294	287	2

Table O4 -2. Freight tonne-kilometres performed on scheduled services (countries and groups of countries whose airlines performed more than 25 million freight tonne-kilometres in 2018) (Source: ICAO 2018, Reed Business Information RBI)

Country or group of countries	Freight Tonne-Kilometres (millions)							
	Total Services (International and domestic)				International Services			
	Rank number in 2018	2018	2017	Increase or decrease (%)	Rank number in 2018	2018	2017	Increase or decrease (%)
Kenya	47	295	276	7	47	292	273	7
Iran (Islamic Republic of)	48	291	326	-11	51	187	209	-11
Poland	49	271	222	22	48	271	222	22
Mauritius	50	234	196	19	49	234	196	19
Pakistan	51	218	215	1	50	204	204	0
Jordan	52	176	159	11	52	176	159	11
Ireland	53	169	154	9	53	169	154	9
Iceland	54	164	167	-2	54	163	166	-1
Brunei Darussalam	55	129	133	-2	55	129	133	-2
Fiji	56	107	103	4	56	107	103	4
Morocco	57	98	78	25	57	97	78	25
Uzbekistan	58	89	127	-29	58	89	127	-29
Angola	59	78	67	16	59	77	67	16
Ukraine	60	75	54	40	60	75	54	40
Zambia	61	75	82	-8	61	75	81	-7
Ecuador	62	64	58	11	62	57	51	11
Bangladesh	63	64	62	3	64	48	47	3
Lebanon	64	57	53	6	63	57	53	6
Kazakhstan	65	50	50	1	68	37	37	1
Panama	66	48	46	4	65	48	46	4
Azerbaijan	67	44	62	-28	66	43	60	-29
Trinidad and Tobago	68	41	37	10	67	41	37	10
Suriname	69	33	23	43	69	33	23	43
Papua New Guinea	70	31	29	6	71	27	25	8
Afghanistan	71	30	21	38	75	20	15	30
Algeria	72	28	25	14	70	28	24	15
Nambia	73	26	22	18	72	26	22	18
Czechia	74	25	28	-9	73	25	28	-9
Total for above countries		221 158	213 299	4		190 870	183 807	4
Rest of World		9 809	9 697			9 782	9 671	
World Total		230 967	222 996			200 652	193 478	

Table O5 -1. Top Passenger countries by Region, 2018 (Source: World Air Transport Statistics 2019, IATA PaxIS-Plus)

Country	Number	Growth (%)
Africa		
South Africa	25 253 344	3,9
Egypt	23 996 516	15,3
Morocco	18 785 269	13,5
Algeria	9 998 802	-11,6
Tunisia	8 216 465	22,3
Nugeria	7 443 155	6,1
Kenya	6 783 334	12,2
Ethiopia	5 559 202	1,8
United Republic of Tanzania	3 763 319	8,6
Mauritius	3 614 373	3,8
Sudan	3 488 252	11,0
Senegal	2 427 899	9,0
Ghana	2 366 070	-8,4
Reunion	2 184 862	-1,6
Cote d'lvoire	1 984 485	3,6
Cape Verde	1 885 534	11,4
Zimbabwe	1 859 307	20,6
Angola	1 744 596	-7,3
Uganda	1 634 462	18,0
Cameroon	1 556 441	2,9
Asia/Pacific		
Peoples Republic of China	668 024 219	15,3
Japan	187 233 922	7,3
India	176 719 682	15,8
Indonesia	138 807 314	10,1
Thailand	105 905 344	8,5
Republic of Korea	102 304 402	15,3
Australia	97 486 223	3,9
Malaysia	65 683 220	5,6
Chinese Taipai	60 879 324	10,7
Vietnam	60 507 574	12,0
Hong Kong (SAR) China	54 180 456	4,2
Philippines	51 972 645	10,1
Singapore	49 196 273	2,7
New Zealand	24 891 447	3,1
Pakistan	19 129 335	-0,7
Bangladesh	11 558 845	10,2
Cambodia	10 831 317	23,2
Sri Lanka	8 225 013	7,3
Kazakhstan	8 154 588	0,7
Maco (SAR), China	7 941 893	14,2
Myanmar	7 934 861	-8,2
Nepal	6 460 065	12,5
Maldives	4 912 348	11,6
Uzbekistan	4 086 419	22,0
Lao People's Democratic Republic	3 195 881	17,4

The top passenger-country rankings as presented in this table have been source from IATA's PaxIS Plus. It covers all scheduled traffic, on all airlines world-wide. The data reflect all passenger counts to, from, or within the respective country.

Table O5 -2. Top Passenger countries by Region, 2018 (Source: World Air Transport Statistics 2019, IATA PaxIS-Plus)

Country	Number	Growth (%)
Kyrgystan	2 593 997	-7,1
Papua New Guinea	2 536 141	-12,5
Fiji	2 230 401	3,2
Afghanistan	2 103 344	-0,8
Tajikistan	2 064 336	0,7
Turkmenistan	1 929 485	-7,4
Europe		
United Kingdom	251 370 641	4,7
Spain	200 814 594	5,5
Germany	171 126 916	3,7
Italy	146 984 636	7,8
France	140 165 675	9,1
Russian Federation	100 491 546	16,0
Turkey	95 792 929	20,4
Netherlands	51 585 542	8,3
Switzerland	49 110 761	4,5
Greece	47 516 575	17,2
Portugal	44 407 341	7,2
Poland	36 794 934	12,3
Norway	35 237 424	-0,6
Sweden	34 543 554	-0,4
Ireland	33 808 200	5,3
Belgium	29 052 869	1,4
Denmark	28 460 089	2,4
Austria	24 105 166	8,4
Romania	19 733 335	7,2
Czech Republic	16 615 189	11,3
Ukraine	16 147 113	15,5
Hungary	15 253 317	14,2
Finland	15 225 481	7,9
Cyprus	12 471 405	8,6
Bulgaria	10 332 473	14,0
Croatia	9 264 070	10,4
Iceland	7 704 538	2,2
Malta	6 787 694	14,2
Serbia	6 416 125	4,5
Lithuania	5 775 709	16,4
Georgia	4 773 206	28,5
Latvia	4 627 181	-2,2
Luxembourg	3 978 051	10,8
Azerbaijan	3 893 894	10,4
Albania	2 975 434	25,8
Slovakia	2 847 678	15,2
Armenia	2 835 430	14,2
Republic of Moldova	2 622 417	0,8
Estonia	2 609 003	9,1
The former Yugoslav Republic of Macedonia	2 292 068	17,9
Belarus	2 207 182	-7,7
Montenegro	2 045 407	12,8
Bosnia and Herzegovina	1 681 853	8,6
Slovenia	1 511 773	6,6

The top passenger-country rankings as presented in this table have been source from IATA's PaxIS Plus. It covers all scheduled traffic, on all airlines world-wide. The data reflect all passenger counts to, from, or within the respective country.

Table O5 -3. Top Passenger countries by Region, 2018 (Source: World Air Transport Statistics 2019, IATA PaxIS-Plus)

Country	Number	Growth (%)
Latin America and Caribbean		
Brazil	93 266 806	3,7
Mexico	88 900 965	9,9
Colombia	33 879 040	11,6
Argentina	26 788 122	9,0
Chile	22 174 381	15,6
Peru	19 984 490	11,8
Dominican Republic	13 388 987	4,4
Cuba	8 912 003	-8,5
Ecuador	7 638 667	6,2
Panama	6 284 299	-12,9
Costa Rica	6 171 253	0,5
Jamaica	5 916 836	7,0
Bolivia (Plurinational State of)	5 392 683	-1,7
Bahamas	4 093 422	11,3
Venezuela (Bolivarian Republic of)	3 913 136	-28,1
Guatemala	3 118 559	7,3
Trinidad and Tobago	2 625 430	-9,2
Belize	2 584 571	3,2
Aruba	2 562 903	3,4
El Salvador	2 466 987	-16,0
Uruguay	2 315 998	1,8
Honduras	1 990 942	-0,5
Guadeloupe	1 921 961	-19,4
Barbados	1 847 092	-3,4
Haiti	1 726 743	6,4
Martinique	1 707 781	-1,8
Paraguay	1 500 804	23,3
Middle East		
Saudi Arabia	60 170 002	2,8
United Arab Emirates	53 573 211	0,3
Israel	21 588 660	21,1
Iran (Islamic Republic of)	19 403 070	16,4
Kuwait	12 181 830	6,0
Qatar	9 733 992	-11,2
Oman	9 491 502	3,5
Lebanon	7 967 300	9,0
Iraq	7 382 934	5,4
Jordan	6 583 885	8,1
Bahrain	4 968 478	-8,0
North America		
United States	796 877 823	5,8
Canada	97 545 561	8,4

The top passenger-country rankings as presented in this table have been source from IATA's PaxIS Plus. It covers all scheduled traffic, on all airlines world-wide. The data reflect all passenger counts to, from, or within the respective country.

Table O6-1. Top freight country-pairs, international and regional traffic
(Source: World Air Transport Statistics 2019, IATA Statistics)

Freight Tonnes Carried				
Rank			**2018**	**(%) Change**
1		**From People's Republic of China**	**3 254 447**	**2,3**
	1	United States	642 145	5,1
	2	Japan	322 861	-4
	3	Republic of Korea	276 037	-3,6
	4	Hong Kong (SAR), China	236 252	0,8
	5	Germany	218 362	8,1
	6	Chinese Taipei	195 363	2,3
	7	Netherlands	159 819	1,1
	8	Singapore	114 139	-7,2
	9	Luxembourg	92 202	-4,7
	10	United Arab Emirates	84 747	-6,7
2		**From United States**	**3 077 624**	**1,8**
	1	People's Republic of China	286 017	13,1
	2	United Kingdom	236 234	3,8
	3	Japan	246 913	-4
	4	Republic of Korea	199 972	5,8
	5	Germany	193 543	3,3
	6	Brazil	159 486	9,6
	7	Chinese Taipei	154 273	-11,4
	8	Hong Kong (SAR), China	138 897	-8,3
	9	Luxembourg	132 540	19,8
	10	Belgium	98 457	21,1
3		**From Hong Kong (SAR), China**	**2 486 162**	**-3,3**
	1	United States	392 219	-12,3
	2	People's Republic of China	240 039	1,9
	3	Chinese Taipei	237 083	-0,3
	4	Japan	185 435	-3,3
	5	United Arab Emirates	157 658	5,2
	6	India	152 820	3,4
	7	Republic of Korea	136 869	-6,2
	8	Singapore	106 609	-1,3
	9	Thailand	98 160	20,3
	10	Australia	65 178	2,4
4		**From Hong Kong (SAR), China**	**1 795 717**	**-3,8**
	1	India	149 158	-3,3
	2	Germany	119 165	2,3
	3	United Kingdom	117 092	-9,1
	4	Turkey	93 059	0,2
	5	Saudi Arabia	91 159	9,3
	6	United States	77 426	-3,3
	7	Singapore	76 031	9,9
	8	Australia	66 516	4,3
	9	People's Republic of China	62 913	-5,4
	10	South Africa	42 954	-8,1

The top freight country-pair rankings as presented in this table are estimated by IATA. It covers all scheduled traffic, on all airlines world-wide, however excluding integrator traffic. The data are uni-directional and compiled on an on-flight origin-destination counting basis. this means that, for example, freight (in tonnage terms) that is shipped from China, P.R. to Germany with an intermediate connection in United Arab Emirates, will be presented twice, once under China, P.R. to United Arab Emirates, and once under United Arab Emirates to Germany.

Table O6-2. Top freight country-pairs, international and regional traffic
(Source: World Air Transport Statistics 2019, IATA Statistics)

Rank			2018	(%) Change
		Freight Tonnes Carried		
5		**From Japan**	**1 691 811**	**5,7**
	1	United States	349 358	0,9
	2	People's Republic of China	222 703	-3,3
	3	Republic of Korea	190 453	14
	4	Chinese Taipei	184 139	13,8
	5	Hong Kong (SAR), China	134 895	5,5
	6	Thailand	83 938	10,1
	7	Singapore	80 493	-4,7
	8	Germany	67 166	0,4
	9	Indonesia	34 513	22,2
	10	Vietnam	34 010	19,1
6		**From Republic of Korea**	**1 439 666**	**2,4**
	1	United States	298 521	6,4
	2	People's Republic of China	251 022	5,2
	3	Japan	153 225	-3,3
	4	Vietnam	131 934	4,8
	5	Hong Kong (SAR), China	88 623	-7,3
	6	Russian Federation	56 312	6,1
	7	Germany	46 931	-3,2
	8	Singapore	46 022	0,9
	9	Thailand	34 659	-9
	10	Chinese Taipei	27 422	2,2
7		**From Germany**	**1 437 683**	**-1,1**
	1	United States	272 145	0,5
	2	People's Republic of China	216 274	4,7
	3	United Arab Emirates	113 909	-4,3
	4	Turkey	91 557	22
	5	Republic of Korea	76 953	-7,4
	6	Japan	70 020	-8,6
	7	India	64 170	-10,2
	8	Qatar	40 667	-4,7
	9	Brazil	32 230	7,1
	10	Mexico	32 104	-5,8
8		**From Qatar**	**1 121 475**	**7,1**
	1	United Kingdom	70 673	-9,7
	2	United States	48 794	-38,3
	3	Germany	40 381	-4,8
	4	Thailand	39 365	27,4
	5	Italy	37 917	22,7
	6	People's Republic of China	37 731	2,8
	7	Vietnam	37 448	67,4
	8	Spain	36 786	12,8
	9	Belgium	30 970	19,9
	10	Indonesia	23 813	14,4

The top freight country-pair rankings as presented in this table are estimated by IATA. It covers all scheduled traffic, on all airlines world-wide, however excluding integrator traffic. The data are uni-directional and compiled on an on-flight origin-destination counting basis. this means that, for example, freight (in tonnage terms) that is shipped from China, P.R. to Germany with an intermediate connection in United Arab Emirates, will be presented twice, once under China, P.R. to United Arab Emirates, and once under United Arab Emirates to Germany.

Table O6-3. Top freight country-pairs, international and regional traffic
(Source: World Air Transport Statistics 2019, IATA Statistics)

Freight Tonnes Carried				
Rank			**2018**	**(%) Change**
9		**From United of Kingdom**	**1 100 082**	**2,2**
	1	United States	387 864	0,2
	2	United Arab Emirates	113 138	-1,8
	3	Qatar	49 997	7,2
	4	India	48 514	10,7
	5	Canada	40 693	3,2
	6	People's Republic of China	39 107	3,9
	7	Hong Kong (SAR), China	35 173	-0,1
	8	Singapore	32 845	-3,7
	9	Germany	31 636	31,5
	10	Turkey	25 678	19,3
10		**From India**	**1 080 969**	**0,8**
	1	United Arab Emirates	261 493	-6,5
	2	Hong Kong (SAR), China	90 511	7,0
	3	Germany	83 942	7,6
	4	United Kingdom	71 500	7,4
	5	Thailand	37 940	15,1
	6	Turkey	28 535	60,5
	7	Sri Lanka	27 443	21,3
	8	France	20 771	11,0
	9	Netherlands	20 231	42,0
	10	Kuwait	20 129	-18,0

The top freight country-pair rankings as presented in this table are estimated by IATA. It covers all scheduled traffic, on all airlines world-wide, however excluding integrator traffic. The data are uni-directional and compiled on an on-flight origin-destination counting basis. this means that, for example, freight (in tonnage terms) that is shipped from China, P.R. to Germany with an intermediate connection in United Arab Emirates, will be presented twice, once under China, P.R. to United Arab Emirates, and once under United Arab Emirates to Germany.

45 APPENDIX P – SCENARIO E NUCLEAR SIMULATION DATA RESULTS

This appendix is a compilation of the outcomes of the simulations done in Scenario E. These tables are shown graphically in Section 25. The nuclear power fleet will be expanded as fast as possible to supply the needed electrical power required by the Scenario F hybrid solution (Section 26), which was 37 670.6 TWh

Scenario E – Reference Case – Section 25.1

The NPP fleet stays on its current path of development. The global NPP fleet expands at the rate of 2 new Generation III+ reactors (of average size) every 10 years. SNF reprocessing and MOX production stays the same.

Scenario E – Generation II Reactors – Section 25.2

The global nuclear power plant fleet is expanded at an ambitious rate of a net gain of 25 new average reactors are connected to the power grid each year, starting in 2026. It is assumed that it now takes only 5 years to construct a nuclear power plant (ambitious) and all necessary supporting infrastructure is also constructed according to the assumptions shown in Section 25.2. Each new nuclear power plant is assumed to be a Generation II reactor of 1000 MWe size 7 888.5 GWh for a 365 day time period. The capacity for reprocessing of SNF and the fabrication of MOX fuel was also expanded every ten years by 500 tonnes p.a. each.

Scenario E – Generation III+ Reactors – Section 25.3

In this simulation, all new reactors will be Generation III+, which is the current state of the art industrial engineering for nuclear technology that is considered reliable. The APR1400 reactor is used, which has a capacity of 1400 MWe capacity (KHNP 2011). It is also assumed that each reactor will be available 91.5% of the time (or 336 days in a year.

Scenario E – Generation IV Reactors – Section 25.4

In this simulation, the development and industrial scale rollout of Generation IV nuclear reactors will be used to expand the nuclear power plant fleet. Each new Generation IV station was assumed to be a Travelling Wave Reactor (TWR) (Weaver *et al* 2009). It is also assumed that each new TWR is of the same size as the average sized nuclear power plant in 2016 (1400 MWe installed capacity), which was 2046 MW installed capacity. From 2025 to 2030, 10 new Generation III+ reactors are connected to the grid per year. From 2030 onwards, 10 Generation IV TWR reactors are connected each year.

Table P1.1. Scenario E – Reference Case

Year	Annual mining and mineral processing of Uranium to meet reactor requirements (tonnes)	Cumulative sum mined from resources at 90% mining efficiency from 2016 (tonnes)	UOX pelletization (converted UF6) (tonnes)	Rod/assembly fabrication (UOX+MOX) (tonnes)	Number of Nuclear Power Plants (NPP) (number)	Number of Generation II NPP (number)	Number of Generation III NPP (number)	Number of Generation III+ NPP (number)	Electrical power generated by global nuclear fleet (TWh)	Annual mass of Spent Nuclear Fuel generated and put in powered underwater cooled storage (tonnes)	Fabrication of MOX fuel (tonnes)	Mass of Spent Nuclear Fuel (SNF) in power cooled storage pools for 10 years (tonnes)
2010						Historical Data				12,000	1,597	172,200
2011										12,000	1,162	184,200
2012										12,000	1,200	196,200
2013	59,331				434				2,367	12,000	992	208,200
2014	56,173				438				2,432	12,000	1,072	220,200
2015	60,291				441				2,451	12,000	997	232,200
2016	62,071	62,071	13,849	15,276	447				2,474	12,000	992	244,200
2017	62,071	131,039	13,849	15,277	448				2,485	12,000	992	256,200
2018	62,071	200,007	13,849	15,277	450				2,507	12,000	992	268,200
2019	62,071	268,974	13,849	15,277	443	399	4	40	2,429	12,000	992	280,200
2020	62,071	337,942	13,849	15,277	443	399	4	40	2,429	12,000	992	292,200
2021	62,071	406,910	13,849	15,277	443	399	4	40	2,429	12,000	992	304,200
2022	62,071	475,878	13,849	15,277	443	399	4	40	2,429	12,000	992	316,200
2023	62,071	544,845	13,849	15,277	443	399	4	40	2,429	12,000	992	328,200
2024	62,071	613,813	13,849	15,277	443	399	4	40	2,429	12,000	992	340,200
2025	62,510	683,269	14,345	15,337	445	379	3	63	2,529	12,060	992	351,268
2026	62,510	752,725	14,455	15,447	445	359	3	83	2,596	12,171	992	362,446
2027	62,510	822,181	14,566	15,558	445	339	3	103	2,662	12,281	992	373,736
2028	62,510	891,637	14,677	15,669	445	319	3	123	2,729	12,392	992	385,135
2029	62,510	961,093	14,787	15,779	445	299	3	143	2,796	12,503	992	396,646
2030	62,510	1,030,549	14,898	15,890	445	279	2	164	2,873	12,613	992	408,267
2031	62,510	1,100,005	14,979	15,971	445	259		186	2,963	12,694	992	419,969
2032	62,510	1,169,461	15,000	15,992	445	239		206	3,029	12,715	992	431,693
2033	62,510	1,238,917	15,021	16,013	445	219		226	3,096	12,736	992	443,437
2034	62,510	1,308,373	15,042	16,034	445	199		246	3,163	12,757	992	455,202
2035	62,950	1,378,317	15,123	16,115	447	179		268	3,252	12,838	992	467,048
2036	62,950	1,448,261	15,144	16,136	447	159		288	3,318	12,859	992	478,915
2037	62,950	1,518,205	15,165	16,157	447	139		308	3,385	12,880	992	490,802
2038	62,950	1,588,149	15,186	16,178	447	119		328	3,452	12,901	992	502,711
2039	62,950	1,658,093	15,207	16,199	447	99		348	3,518	12,922	992	514,641
2040	62,950	1,728,037	15,228	16,220	447	79		368	3,585	12,943	992	526,592
2041	62,950	1,797,981	15,249	16,241	447	59		388	3,652	12,964	992	538,564
2042	62,950	1,867,925	15,270	16,262	447	39		408	3,718	12,985	992	550,557
2043	62,950	1,937,869	15,291	16,283	447	19		428	3,785	13,006	992	562,571
2044	62,950	2,007,813	15,311	16,303	447	0		447	3,849	13,026	992	574,605
2045	63,389	2,078,246	15,371	16,363	449	Last of Gen II reactors decommissioned		449	3,871	13,086	992	586,699
2046	63,389	2,148,678	15,371	16,363	449			449	3,871	13,086	992	598,792
2047	63,389	2,219,110	15,371	16,363	449			449	3,871	13,086	992	610,886
2048	63,389	2,289,542	15,371	16,363	449			449	3,871	13,086	992	622,980
2049	63,389	2,359,975	15,371	16,363	449			449	3,871	13,086	992	635,074
2050	63,389	2,430,407	15,371	16,363	449			449	3,871	13,086	992	647,167
2051	63,389	2,500,839	15,371	16,363	449			449	3,871	13,086	992	659,261
2052	63,389	2,571,271	15,371	16,363	449			449	3,871	13,086	992	671,355
2053	63,389	2,641,704	15,371	16,363	449			449	3,871	13,086	992	683,449
2054	63,389	2,712,136	15,371	16,363	449			449	3,871	13,086	992	695,542
2055	63,828	2,783,056	15,430	16,422	451			451	3,893	13,146	992	707,696

Reasonably Assured resources (RAR)

Table P1.2. Scenario E – Reference Case

Year	Annual mining and mineral processing of Uranium to meet reactor requirements (tonnes)	Cumulative sum mined from resources at 90% mining efficiency from 2016 (tonnes)	UOX pelletization (converted UF6) (tonnes)	Rod/assembly fabrication (UOX+MOX) (tonnes)	Number of Nuclear Power Plants (NPP) (number)	Number of Generation II NPP (number)	Number of Generation III NPP (number)	Number of Generation III+ NPP (number)	Electrical power generated by global nuclear fleet (TWh)	Annual mass of Spent Nuclear Fuel generated and put in powered underwater cooled storage (tonnes)	Fabrication of MOX fuel (tonnes)	Mass of Spent Nuclear Fuel (SNF) in power cooled storage pools for 10 years (tonnes)
2056	63,828	2,853,977	15,430	16,422	451			451	3,893	13,146	992	719,849
2057	63,828	2,924,897	15,430	16,422	451			451	3,893	13,146	992	732,003
2058	63,828	2,995,817	15,430	16,422	451			451	3,893	13,146	992	744,157
2059	63,828	3,066,738	15,430	16,422	451			451	3,893	13,146	992	756,310
2060	63,828	3,137,658	15,430	16,422	451			451	3,893	13,146	992	768,464
2061	63,828	3,208,579	15,430	16,422	451			451	3,893	13,146	992	780,617
2062	63,828	3,279,499	15,430	16,422	451			451	3,893	13,146	992	792,771
2063	63,828	3,350,419	15,430	16,422	451			451	3,893	13,146	992	804,924
2064	63,828	3,421,340	15,430	16,422	451			451	3,893	13,146	992	817,078
2065	64,268	3,492,748	15,490	16,482	453			453	3,916	13,205	992	829,291
2066	64,268	3,564,157	15,490	16,482	453			453	3,916	13,205	992	841,505
2067	64,268	3,635,566	15,490	16,482	453			453	3,916	13,205	992	853,718
2068	64,268	(RAR) 3,706,974	15,490	16,482	453			453	3,916	13,205	992	865,931
2069	64,268	3,778,383	15,490	16,482	453			453	3,916	13,205	992	878,145
2070	64,268	3,849,791	15,490	16,482	453			453	3,916	13,205	992	890,358
2071	64,268	3,921,200	15,490	16,482	453			453	3,916	13,205	992	902,571
2072	64,268	3,992,608	15,490	16,482	453			453	3,916	13,205	992	914,785
2073	64,268	4,064,017	15,490	16,482	453			453	3,916	13,205	992	926,998
2074	64,268	4,135,425	15,490	16,482	453			453	3,916	13,205	992	939,211
2075	64,707	4,207,322	15,550	16,542	455			455	3,938	13,265	992	951,485
2076	64,707	4,279,219	15,550	16,542	455			455	3,938	13,265	992	963,758
2077	64,707	4,351,116	15,550	16,542	455			455	3,938	13,265	992	976,031
2078	64,707	4,423,012	15,550	16,542	455			455	3,938	13,265	992	988,304
2079	64,707	4,494,909	15,550	16,542	455			455	3,938	13,265	992	1,000,577
2080	64,707	4,566,806	15,550	16,542	455			455	3,938	13,265	992	1,012,850
2081	64,707	4,638,702	15,550	16,542	455			455	3,938	13,265	992	1,025,123
2082	64,707	4,710,599	15,550	16,542	455			455	3,938	13,265	992	1,037,397
2083	64,707	4,782,496	15,550	16,542	455			455	3,938	13,265	992	1,049,670
2084	64,707	4,854,393	15,550	16,542	455			455	3,938	13,265	992	1,061,943
2085	65,146	4,926,777	15,610	16,602	457			457	3,961	13,325	992	1,074,276
2086	65,146	4,999,162	15,610	16,602	457			457	3,961	13,325	992	1,086,609
2087	65,146	5,071,547	15,610	16,602	457			457	3,961	13,325	992	1,098,942
2088	65,146	5,143,932	15,610	16,602	457			457	3,961	13,325	992	1,111,275
2089	65,146	5,216,317	15,610	16,602	457			457	3,961	13,325	992	1,123,608
2090	65,146	5,288,702	15,610	16,602	457			457	3,961	13,325	992	1,135,941
2091	65,146	5,361,087	15,610	16,602	457			457	3,961	13,325	992	1,148,274
2092	65,146	5,433,471	15,610	16,602	457			457	3,961	13,325	992	1,160,607
2093	65,146	5,505,856	15,610	16,602	457			457	3,961	13,325	992	1,172,939
2094	65,146	(IR) 5,578,241	15,610	16,602	457			457	3,961	13,325	992	1,185,272
2095	65,586	5,651,114	15,670	16,662	459			459	3,983	13,385	992	1,197,665
2096	65,586	5,723,987	15,670	16,662	459			459	3,983	13,385	992	1,210,058
2097	65,586	5,796,860	15,670	16,662	459			459	3,983	13,385	992	1,222,451
2098	65,586	5,869,733	15,670	16,662	459			459	3,983	13,385	992	1,234,843
2099	65,586	5,942,606	15,670	16,662	459			459	3,983	13,385	992	1,247,236
2100	65,586	6,015,479	15,670	16,662	459			459	3,983	13,385	992	1,259,629
2101	65,586	6,088,352	15,670	16,662	459			459	3,983	13,385	992	1,272,022

Table P1.3. Scenario E – Reference Case

Year	Annual mining and mineral processing of Uranium to meet reactor requirements (tonnes)	Cumulative sum mined from resources at 90% mining efficiency from 2016 (tonnes)	UOX pelletization (converted UF6) (tonnes)	Rod/assembly fabrication (UOX+MOX) (tonnes)	Number of Nuclear Power Plants (NPP) (number)	Number of Generation II NPP (number)	Number of Generation III NPP (number)	Number of Generation III+ NPP (number)	Electrical power generated by global nuclear fleet (TWh)	Annual mass of Spent Nuclear Fuel generated and put in powered underwater cooled storage (tonnes)	Fabrication of MOX fuel (tonnes)	Mass of Spent Nuclear Fuel (SNF) in power cooled storage pools for 10 years (tonnes)
2102	65,586	6,161,225	15,670	16,662	459			459	3,983	13,385	992	1,284,414
2103	65,586	6,234,098	15,670	16,662	459			459	3,983	13,385	992	1,296,807
2104	65,586	6,306,971	15,670	16,662	459			459	3,983	13,385	992	1,309,200
2105	66,025	6,380,333	15,729	16,721	461			461	4,006	13,445	992	1,321,653
2106	66,025	6,453,694	15,729	16,721	461			461	4,006	13,445	992	1,334,105
2107	66,025	6,527,055	15,729	16,721	461			461	4,006	13,445	992	1,346,558
2108	66,025	6,600,416	15,729	16,721	461			461	4,006	13,445	992	1,359,010
2109	66,025	6,673,777	15,729	16,721	461			461	4,006	13,445	992	1,371,463
2110	66,025	6,747,139	15,729	16,721	461			461	4,006	13,445	992	1,383,915
2111	66,025	6,820,500	15,729	16,721	461			461	4,006	13,445	992	1,396,368
2112	66,025	6,893,861	15,729	16,721	461			461	4,006	13,445	992	1,408,820
2113	66,025	6,967,222	15,729	16,721	461			461	4,006	13,445	992	1,421,273
2114	66,025	7,040,583	15,729	16,721	461			461	4,006	13,445	992	1,433,726
2115	66,464	(IR) 7,114,433	15,789	16,781	463			463	4,028	13,504	992	1,446,238
2116	66,464	7,188,282	15,789	16,781	463			463	4,028	13,504	992	1,458,750
2117	66,464	7,262,131	15,789	16,781	463			463	4,028	13,504	992	1,471,263
2118	66,464	7,335,981	15,789	16,781	463			463	4,028	13,504	992	1,483,775
2119	66,464	7,409,830	15,789	16,781	463			463	4,028	13,504	992	1,496,287
2120	66,464	7,483,679	15,789	16,781	463			463	4,028	13,504	992	1,508,800
2121	66,464	7,557,529	15,789	16,781	463			463	4,028	13,504	992	1,521,312
2122	66,464	7,631,378	15,789	16,781	463			463	4,028	13,504	992	1,533,824
2123	66,464	7,705,227	15,789	16,781	463			463	4,028	13,504	992	1,546,337
2124	66,464	7,779,077	15,789	16,781	463			463	4,028	13,504	992	1,558,849
2125	66,904	7,853,414	15,849	16,841	465			465	4,051	13,564	992	1,571,421
2126	66,904	7,927,752	15,849	16,841	465			465	4,051	13,564	992	1,583,993
2127	66,904	8,002,089	15,849	16,841	465			465	4,051	13,564	992	1,596,566
2128	66,904	8,076,427	15,849	16,841	465			465	4,051	13,564	992	1,609,138
2129	66,904	8,150,764	15,849	16,841	465			465	4,051	13,564	992	1,621,710
2130	66,904	8,225,101	15,849	16,841	465			465	4,051	13,564	992	1,634,282
2131	66,904	8,299,439	15,849	16,841	465			465	4,051	13,564	992	1,646,854
2132	66,904	8,373,776	15,849	16,841	465			465	4,051	13,564	992	1,659,426
2133	66,904	8,448,114	15,849	16,841	465			465	4,051	13,564	992	1,671,998
2134	66,904	8,522,451	15,849	16,841	465			465	4,051	13,564	992	1,684,571
2135	67,343	8,597,277	15,909	16,901	467			467	4,073	13,624	992	1,697,203
2136	67,343	8,672,103	15,909	16,901	467			467	4,073	13,624	992	1,709,834
2137	67,343	8,746,928	15,909	16,901	467			467	4,073	13,624	992	1,722,466
2138	67,343	8,821,754	15,909	16,901	467			467	4,073	13,624	992	1,735,098
2139	67,343	8,896,580	15,909	16,901	467			467	4,073	13,624	992	1,747,730
2140	67,343	(PR) 8,971,405	15,909	16,901	467			467	4,073	13,624	992	1,760,362
2141	67,343	9,046,231	15,909	16,901	467			467	4,073	13,624	992	1,772,994
2142	67,343	9,121,057	15,909	16,901	467			467	4,073	13,624	992	1,785,626
2143	67,343	9,195,882	15,909	16,901	467			467	4,073	13,624	992	1,798,258
2144	67,343	9,270,708	15,909	16,901	467			467	4,073	13,624	992	1,810,890
2145	67,782	9,346,022	15,969	16,961	469			469	4,095	13,684	992	1,823,582
2146	67,782	9,421,335	15,969	16,961	469			469	4,095	13,684	992	1,836,274
2147	67,782	9,496,649	15,969	16,961	469			469	4,095	13,684	992	1,848,965

Table P1.4. Scenario E – Reference Case

Year	Annual mining and mineral processing of Uranium to meet reactor requirements (tonnes)	Cumulative sum mined from resources at 90% mining efficiency from 2016 (tonnes)	UOX pelletization (converted UF6) (tonnes)	Rod/assembly fabrication (UOX+MOX) (tonnes)	Number of Nuclear Power Plants (NPP) (number)	Number of Generation II NPP (number)	Number of Generation III NPP (number)	Number of Generation III+ NPP (number)	Electrical power generated by global nuclear fleet (TWh)	Annual mass of Spent Nuclear Fuel generated and put in powered underwater cooled storage (tonnes)	Fabrication of MOX fuel (tonnes)	Mass of Spent Nuclear Fuel (SNF) in power cooled storage pools for 10 years (tonnes)
2148	67,782	9,571,963	15,969	16,961	469			469	4,095	13,684	992	1,861,657
2149	67,782	9,647,277	15,969	16,961	469			469	4,095	13,684	992	1,874,349
2150	67,782	9,722,591	15,969	16,961	469			469	4,095	13,684	992	1,887,041
2151	67,782	9,797,904	15,969	16,961	469			469	4,095	13,684	992	1,899,732
2152	67,782	9,873,218	15,969	16,961	469			469	4,095	13,684	992	1,912,424
2153	67,782	9,948,532	15,969	16,961	469			469	4,095	13,684	992	1,925,116
2154	67,782	10,023,846	15,969	16,961	469			469	4,095	13,684	992	1,937,808
2155	68,222	10,099,648	16,028	17,020	471			471	4,118	13,744	992	1,950,559
2156	68,222	10,175,450	16,028	17,020	471			471	4,118	13,744	992	1,963,311
2157	68,222	10,251,252	16,028	17,020	471			471	4,118	13,744	992	1,976,062
2158	68,222	10,327,054	16,028	17,020	471			471	4,118	13,744	992	1,988,814
2159	68,222	10,402,856	16,028	17,020	471			471	4,118	13,744	992	2,001,565
2160	68,222	10,478,658	16,028	17,020	471			471	4,118	13,744	992	2,014,317
2161	68,222	10,554,460	16,028	17,020	471			471	4,118	13,744	992	2,027,069
2162	68,222	10,630,262	16,028	17,020	471			471	4,118	13,744	992	2,039,820
2163	68,222	10,706,063	16,028	17,020	471			471	4,118	13,744	992	2,052,572
2164	68,222	10,781,865	16,028	17,020	471			471	4,118	13,744	992	2,065,323
2165	68,661	10,858,156	16,088	17,080	473			473	4,140	13,803	992	2,078,135
2166	68,661	10,934,446	16,088	17,080	473			473	4,140	13,803	992	2,090,946
2167	68,661	11,010,736	16,088	17,080	473			473	4,140	13,803	992	2,103,757
2168	68,661	11,087,026	16,088	17,080	473			473	4,140	13,803	992	2,116,569
2169	68,661	(SR) 11,163,316	16,088	17,080	473			473	4,140	13,803	992	2,129,380
2170	68,661	11,239,606	16,088	17,080	473			473	4,140	13,803	992	2,142,191
2171	68,661	11,315,896	16,088	17,080	473			473	4,140	13,803	992	2,155,003
2172	68,661	11,392,186	16,088	17,080	473			473	4,140	13,803	992	2,167,814
2173	68,661	11,468,476	16,088	17,080	473			473	4,140	13,803	992	2,180,625
2174	68,661	11,544,767	16,088	17,080	473			473	4,140	13,803	992	2,193,437
2175	69,100	11,621,545	16,148	17,140	475			475	4,163	13,863	992	2,206,308
2176	69,100	11,698,323	16,148	17,140	475			475	4,163	13,863	992	2,219,179
2177	69,100	11,775,101	16,148	17,140	475			475	4,163	13,863	992	2,232,050
2178	69,100	11,851,880	16,148	17,140	475			475	4,163	13,863	992	2,244,921
2179	69,100	11,928,658	16,148	17,140	475			475	4,163	13,863	992	2,257,792
2180	69,100	12,005,436	16,148	17,140	475			475	4,163	13,863	992	2,270,664
2181	69,100	12,082,214	16,148	17,140	475			475	4,163	13,863	992	2,283,535
2182	69,100	12,158,993	16,148	17,140	475			475	4,163	13,863	992	2,296,406
2183	69,100	12,235,771	16,148	17,140	475			475	4,163	13,863	992	2,309,277
2184	69,100	12,312,549	16,148	17,140	475			475	4,163	13,863	992	2,322,148
2185	69,540	12,389,816	16,208	17,200	477			477	4,185	13,923	992	2,335,079
2186	69,540	12,467,082	16,208	17,200	477			477	4,185	13,923	992	2,348,010
2187	69,540	12,544,348	16,208	17,200	477			477	4,185	13,923	992	2,360,941
2188	69,540	12,621,615	16,208	17,200	477			477	4,185	13,923	992	2,373,872
2189	69,540	12,698,881	16,208	17,200	477			477	4,185	13,923	992	2,386,803
2190	69,540	12,776,148	16,208	17,200	477			477	4,185	13,923	992	2,399,734
2191	69,540	12,853,414	16,208	17,200	477			477	4,185	13,923	992	2,412,665
2192	69,540	12,930,681	16,208	17,200	477			477	4,185	13,923	992	2,425,596
2193	69,540	13,007,947	16,208	17,200	477			477	4,185	13,923	992	2,438,527

Table P1.5. Scenario E – Reference Case

Year	Annual mining and mineral processing of Uranium to meet reactor requirements (tonnes)	Cumulative sum mined from resources at 90% mining efficiency from 2016 (tonnes)	UOX pelletization (converted UF6) (tonnes)	Rod/assembly fabrication (UOX+MOX) (tonnes)	Number of Nuclear Power Plants (NPP) (number)	Number of Generation II NPP (number)	Number of Generation III NPP (number)	Number of Generation III+ NPP (number)	Electrical power generated by global nuclear fleet (TWh)	Annual mass of Spent Nuclear Fuel generated and put in powered underwater cooled storage (tonnes)	Fabrication of MOX fuel (tonnes)	Mass of Spent Nuclear Fuel (SNF) in power cooled storage pools for 10 years (tonnes)
2194	69,540	13,085,213	16,208	17,200	477			477	4,185	13,923	992	2,451,458
2195	69,979	13,162,968	16,268	17,260	479			479	4,208	13,983	992	2,464,449
2196	69,979	13,240,723	16,268	17,260	479			479	4,208	13,983	992	2,477,439
2197	69,979	13,318,477	16,268	17,260	479			479	4,208	13,983	992	2,490,430
2198	69,979	13,396,232	16,268	17,260	479			479	4,208	13,983	992	2,503,421
2199	69,979	13,473,986	16,268	17,260	479			479	4,208	13,983	992	2,516,412
2200	69,979	13,551,741	16,268	17,260	479			479	4,208	13,983	992	2,529,402
2201	69,979	13,629,495	16,268	17,260	479			479	4,208	13,983	992	2,542,393
2202	69,979	13,707,250	16,268	17,260	479			479	4,208	13,983	992	2,555,384
2203	69,979	13,785,005	16,268	17,260	479			479	4,208	13,983	992	2,568,375
2204	69,979	13,862,759	16,268	17,260	479			479	4,208	13,983	992	2,581,365
2205	70,418	13,941,002	16,327	17,319	481			481	4,230	14,043	992	2,594,416
2206	70,418	14,019,245	16,327	17,319	481			481	4,230	14,043	992	2,607,466
2207	70,418	14,097,487	16,327	17,319	481			481	4,230	14,043	992	2,620,517
2208	70,418	(SR) 14,175,730	16,327	17,319	481			481	4,230	14,043	992	2,633,568
2209	70,418	14,253,973	16,327	17,319	481			481	4,230	14,043	992	2,646,618
2210	70,418	14,332,216	16,327	17,319	481			481	4,230	14,043	992	2,659,669
2211	70,418	14,410,458	16,327	17,319	481			481	4,230	14,043	992	2,672,719
2212	70,418	14,488,701	16,327	17,319	481			481	4,230	14,043	992	2,685,770
2213	70,418	14,566,944	16,327	17,319	481			481	4,230	14,043	992	2,698,820
2214	70,418	14,645,187	16,327	17,319	481			481	4,230	14,043	992	2,711,871
2215	70,858	14,723,917	16,387	17,379	483			483	4,253	14,102	992	2,724,981
2216	70,858	14,802,648	16,387	17,379	483			483	4,253	14,102	992	2,738,092
2217	70,858	14,881,379	16,387	17,379	483			483	4,253	14,102	992	2,751,202
2218	70,858	14,960,110	16,387	17,379	483			483	4,253	14,102	992	2,764,312
2219	70,858	15,038,841	16,387	17,379	483			483	4,253	14,102	992	2,777,423
2220	70,858	15,117,572	16,387	17,379	483			483	4,253	14,102	992	2,790,533
2221	70,858	15,196,303	16,387	17,379	483			483	4,253	14,102	992	2,803,643
2222	70,858	15,275,034	16,387	17,379	483			483	4,253	14,102	992	2,816,754
2223	70,858	15,353,765	16,387	17,379	483			483	4,253	14,102	992	2,829,864
2224	70,858	15,432,495	16,387	17,379	483			483	4,253	14,102	992	2,842,974
2225	71,297	15,511,714	16,447	17,439	485			485	4,275	14,162	992	2,856,145
2226	71,297	15,590,934	16,447	17,439	485			485	4,275	14,162	992	2,869,315
2227	71,297	15,670,153	16,447	17,439	485			485	4,275	14,162	992	2,882,485
2228	71,297	15,749,372	16,447	17,439	485			485	4,275	14,162	992	2,895,655
2229	71,297	15,828,591	16,447	17,439	485			485	4,275	14,162	992	2,908,825
2230	71,297	15,907,810	16,447	17,439	485			485	4,275	14,162	992	2,921,995
2231	71,297	15,987,029	16,447	17,439	485			485	4,275	14,162	992	2,935,165
2232	71,297	16,066,248	16,447	17,439	485			485	4,275	14,162	992	2,948,336
2233	71,297	(UR) 16,145,467	16,447	17,439	485			485	4,275	14,162	992	2,961,506
2234	71,297	16,224,686	16,447	17,439	485			485	4,275	14,162	992	2,974,676
2235	71,736	16,304,393	16,507	17,499	487			487	4,297	14,222	992	2,987,906
2236	71,736	16,384,100	16,507	17,499	487			487	4,297	14,222	992	3,001,136
2237	71,736	16,463,807	16,507	17,499	487			487	4,297	14,222	992	3,014,366
2238	71,736	16,543,515	16,507	17,499	487			487	4,297	14,222	992	3,027,596
2239	71,736	16,623,222	16,507	17,499	487			487	4,297	14,222	992	3,040,826

Table P1.6. Scenario E – Reference Case

Year	Annual mining and mineral processing of Uranium to meet reactor requirements (tonnes)	Cumulative sum mined from resources at 90% mining efficiency from 2016 (tonnes)	UOX pelletization (converted UF6) (tonnes)	Rod/assembly fabrication (UOX+MOX) (tonnes)	Number of Nuclear Power Plants (NPP) (number)	Number of Generation II NPP (number)	Number of Generation III NPP (number)	Number of Generation III+ NPP (number)	Electrical power generated by global nuclear fleet (TWh)	Annual mass of Spent Nuclear Fuel generated and put in powered underwater cooled storage (tonnes)	Fabrication of MOX fuel (tonnes)	Mass of Spent Nuclear Fuel (SNF) in power cooled storage pools for 10 years (tonnes)
2240	71,736	16,702,929	16,507	17,499	487			487	4,297	14,222	992	3,054,056
2241	71,736	16,782,636	16,507	17,499	487			487	4,297	14,222	992	3,067,286
2242	71,736	16,862,343	16,507	17,499	487			487	4,297	14,222	992	3,080,516
2243	71,736	16,942,051	16,507	17,499	487			487	4,297	14,222	992	3,093,746
2244	71,736	17,021,758	16,507	17,499	487			487	4,297	14,222	992	3,106,975
2245	72,176	17,101,953	16,567	17,559	489			489	4,320	14,282	992	3,120,265
2246	72,176	17,182,149	16,567	17,559	489			489	4,320	14,282	992	3,133,555
2247	72,176	17,262,344	16,567	17,559	489			489	4,320	14,282	992	3,146,845
2248	72,176	17,342,539	16,567	17,559	489			489	4,320	14,282	992	3,160,134
2249	72,176	17,422,735	16,567	17,559	489			489	4,320	14,282	992	3,173,424
2250	72,176	17,502,930	16,567	17,559	489			489	4,320	14,282	992	3,186,714
2251	72,176	17,583,125	16,567	17,559	489			489	4,320	14,282	992	3,200,004
2252	72,176	17,663,321	16,567	17,559	489			489	4,320	14,282	992	3,213,294
2253	72,176	17,743,516	16,567	17,559	489			489	4,320	14,282	992	3,226,583
2254	72,176	17,823,711	16,567	17,559	489			489	4,320	14,282	992	3,239,873
2255	72,615	17,904,395	16,626	17,618	491			491	4,342	14,342	992	3,253,223
2256	72,615	17,985,078	16,626	17,618	491			491	4,342	14,342	992	3,266,572
2257	72,615	18,065,762	16,626	17,618	491			491	4,342	14,342	992	3,279,922
2258	72,615	18,146,445	16,626	17,618	491			491	4,342	14,342	992	3,293,271
2259	72,615	18,227,129	16,626	17,618	491			491	4,342	14,342	992	3,306,621
2260	72,615	18,307,813	16,626	17,618	491			491	4,342	14,342	992	3,319,970
2261	72,615	18,388,496	16,626	17,618	491			491	4,342	14,342	992	3,333,320
2262	72,615	(UR) 18,469,180	16,626	17,618	491			491	4,342	14,342	992	3,346,669
2263	72,615	18,549,863	16,626	17,618	491			491	4,342	14,342	992	3,360,019
2264	72,615	18,630,547	16,626	17,618	491			491	4,342	14,342	992	3,373,369
2265	73,054	18,711,718	16,686	17,678	493			493	4,365	14,401	992	3,386,778
2266	73,054	18,792,890	16,686	17,678	493			493	4,365	14,401	992	3,400,187
2267	73,054	18,874,062	16,686	17,678	493			493	4,365	14,401	992	3,413,597
2268	73,054	18,955,233	16,686	17,678	493			493	4,365	14,401	992	3,427,006
2269	73,054	19,036,405	16,686	17,678	493			493	4,365	14,401	992	3,440,415
2270	73,054	19,117,577	16,686	17,678	493			493	4,365	14,401	992	3,453,825
2271	73,054	19,198,748	16,686	17,678	493			493	4,365	14,401	992	3,467,234
2272	73,054	19,279,920	16,686	17,678	493			493	4,365	14,401	992	3,480,643
2273	73,054	19,361,092	16,686	17,678	493			493	4,365	14,401	992	3,494,053
2274	73,054	19,442,263	16,686	17,678	493			493	4,365	14,401	992	3,507,462
2275	73,494	19,523,923	16,746	17,738	495			495	4,387	14,461	992	3,520,931
2276	73,494	19,605,583	16,746	17,738	495			495	4,387	14,461	992	3,534,400
2277	73,494	19,687,243	16,746	17,738	495			495	4,387	14,461	992	3,547,870
2278	73,494	19,768,903	16,746	17,738	495			495	4,387	14,461	992	3,561,339
2279	73,494	19,850,562	16,746	17,738	495			495	4,387	14,461	992	3,574,808
2280	73,494	19,932,222	16,746	17,738	495			495	4,387	14,461	992	3,588,277
2281	73,494	20,013,882	16,746	17,738	495			495	4,387	14,461	992	3,601,746
2282	73,494	20,095,542	16,746	17,738	495			495	4,387	14,461	992	3,615,215
2283	73,494	20,177,202	16,746	17,738	495			495	4,387	14,461	992	3,628,684
2284	73,494	20,258,861	16,746	17,738	495			495	4,387	14,461	992	3,642,154
2285	73,933	20,341,009	16,806	17,798	497			497	4,410	14,521	992	3,655,683

Table P1.7. Scenario E – Reference Case

Year	Annual mining and mineral processing of Uranium to meet reactor requirements (tonnes)	Cumulative sum mined from resources at 90% mining efficiency from 2016 (tonnes)	UOX pelletization (converted UF6) (tonnes)	Rod/assembly fabrication (UOX+MOX) (tonnes)	Number of Nuclear Power Plants (NPP) (number)	Number of Generation II NPP (number)	Number of Generation III NPP (number)	Number of Generation III+ NPP (number)	Electrical power generated by global nuclear fleet (TWh)	Annual mass of Spent Nuclear Fuel generated and put in powered underwater cooled storage (tonnes)	Fabrication of MOX fuel (tonnes)	Mass of Spent Nuclear Fuel (SNF) in power cooled storage pools for 10 years (tonnes)
2286	73,933	20,423,157	16,806	17,798	497			497	4,410	14,521	992	3,669,212
2287	73,933	20,505,305	16,806	17,798	497			497	4,410	14,521	992	3,682,740
2288	73,933	20,587,453	16,806	17,798	497			497	4,410	14,521	992	3,696,269
2289	73,933	20,669,601	16,806	17,798	497			497	4,410	14,521	992	3,709,798
2290	73,933	20,751,749	16,806	17,798	497			497	4,410	14,521	992	3,723,327
2291	73,933	20,833,897	16,806	17,798	497			497	4,410	14,521	992	3,736,856
2292	73,933	20,916,045	16,806	17,798	497			497	4,410	14,521	992	3,750,385
2293	73,933	20,998,193	16,806	17,798	497			497	4,410	14,521	992	3,763,914
2294	73,933	21,080,341	16,806	17,798	497			497	4,410	14,521	992	3,777,443
2295	74,373	21,162,977	16,866	17,858	499			499	4,432	14,581	992	3,791,032
2296	74,373	21,245,613	16,866	17,858	499			499	4,432	14,581	992	3,804,621
2297	74,373	21,328,250	16,866	17,858	499			499	4,432	14,581	992	3,818,209
2298	74,373	21,410,886	16,866	17,858	499			499	4,432	14,581	992	3,831,798
2299	74,373	21,493,522	16,866	17,858	499			499	4,432	14,581	992	3,845,387
2300	74,373	21,576,158	16,866	17,858	499			499	4,432	14,581	992	3,858,976
2301	74,373	21,658,794	16,866	17,858	499			499	4,432	14,581	992	3,872,564
2302	74,373	21,741,430	16,866	17,858	499			499	4,432	14,581	992	3,886,153
2303	74,373	21,824,066	16,866	17,858	499			499	4,432	14,581	992	3,899,742
2304	74,373	21,906,703	16,866	17,858	499			499	4,432	14,581	992	3,913,331
2305	74,812	21,989,827	16,925	17,917	501			501	4,455	14,641	992	3,926,979
2306	74,812	(UR) 22,072,951	16,925	17,917	501			501	4,455	14,641	992	3,940,628
2307	74,812	22,156,075	16,925	17,917	501			501	4,455	14,641	992	3,954,276
2308	74,812	22,239,200	16,925	17,917	501	All existing U resources depleted 2325		501	4,455	14,641	992	3,967,925
2309	74,812	22,322,324	16,925	17,917	501			501	4,455	14,641	992	3,981,573
2310	74,812	22,405,448	16,925	17,917	501			501	4,455	14,641	992	3,995,222
2311	74,812	22,488,573	16,925	17,917	501			501	4,455	14,641	992	4,008,871
2312	74,812	22,571,697	16,925	17,917	501			501	4,455	14,641	992	4,022,519
2313	74,812	22,654,821	16,925	17,917	501			501	4,455	14,641	992	4,036,168
2314	74,812	22,737,945	16,925	17,917	501			501	4,455	14,641	992	4,049,816
2315	75,251	22,821,558	16,985	17,977	503			503	4,477	14,700	992	4,063,525
2316	75,251	22,905,170	16,985	17,977	503			503	4,477	14,700	992	4,077,233
2317	75,251	22,988,783	16,985	17,977	503			503	4,477	14,700	992	4,090,941
2318	75,251	23,072,395	16,985	17,977	503			503	4,477	14,700	992	4,104,650
2319	75,251	23,156,008	16,985	17,977	503			503	4,477	14,700	992	4,118,358
2320	75,251	23,239,620	16,985	17,977	503			503	4,477	14,700	992	4,132,066
2321	75,251	23,323,233	16,985	17,977	503			503	4,477	14,700	992	4,145,775
2322	75,251	23,406,845	16,985	17,977	503			503	4,477	14,700	992	4,159,483
2323	75,251	23,490,457	16,985	17,977	503			503	4,477	14,700	992	4,173,191
2324	75,251	23,574,070	16,985	17,977	503			503	4,477	14,700	992	4,186,900
2325	75,251	23,657,682	16,985	17,977	503			503	4,477	14,700	992	4,200,608
2326												

Table P2.1. Scenario E – Generation III+ reactors

Year	Annual mining and mineral processing of Uranium to meet reactor requirements (tonnes)	Cumulative sum mined from resources at 90% mining efficiency from 2016 (tonnes)	UOX pelletization (converted UF6) (tonnes)	Rod/assembly fabrication (UOX+MOX) (tonnes)	Number of nuclear power stations (number)	Number of Generation II Nuclear Power Plants (number)	Number of Generation III Nuclear Power Plants (number)	Number of Generation III+ Nuclear Power Plants (number)	Electrical power generated by global nuclear fleet (TWh)
2010									
2011									
2012									
2013	59,331				434				2,367
2014	56,173				438				2,432
2015	60,291				441				2,451
2016	62,071	62,071	13,849	15,276	447				2,474
2017	62,071	131,039	13,849	15,277	448				2,499
2018	62,071	200,007	13,849	15,277	450				2,525
2019	62,071	268,974	13,849	15,277	443	399	4	40	2,550
2020	62,071	337,942	13,849	15,277	443	399	4	40	2,576
2021	62,071	406,910	13,849	15,277	443	399	4	40	2,602
2022	62,071	475,878	13,849	15,277	443	399	4	40	2,602
2023	62,071	544,845	13,849	15,277	443	399	4	40	2,602
2024	62,071	613,813	13,849	15,277	443	399	4	40	2,602
2025	62,510	683,269	14,345	15,337	445	379	3	63	2,736
2026	68,002	758,827	14,703	16,195	470	359	3	108	3,116
2027	73,494	840,487	15,561	17,053	495	339	3	153	3,497
2028	78,986	928,249	16,419	17,911	520	319	3	198	3,878
2029	84,477	1,022,112	17,277	18,769	545	299	3	243	4,259
2030	89,969	1,122,078	18,136	19,628	570	279	2	289	4,640
2031	95,461	1,228,146	18,964	20,456	595	259		336	5,010
2032	100,953	1,340,315	19,732	21,224	620	239		381	5,357
2033	106,444	1,458,587	20,501	21,993	645	219		426	5,704
2034	111,936	1,582,960	21,269	22,761	670	199		471	6,052
2035	117,428	1,713,435	21,538	23,530	695	179		516	6,399
2036	122,920	1,850,013	22,306	24,298	720	159		561	6,746
2037	128,411	1,992,692	23,075	25,067	745	139		606	7,094
2038	133,903	2,141,473	23,843	25,835	770	119		651	7,441
2039	139,395	2,296,356	24,612	26,604	795	99		696	7,788
2040	144,887	2,457,341	25,380	27,372	820	79		741	8,135
2041	150,378	2,624,429	26,149	28,141	845	59		786	8,483
2042	155,870	2,797,618	26,917	28,909	870	39		831	8,830
2043	161,362	2,976,908	27,686	29,678	895	19		876	9,177
2044	166,854	3,162,301	28,453	30,445	920	0		920	9,672
2045	172,345	3,353,796	28,701	31,193	945			945	9,953
2046	177,837	3,551,393	29,448	31,940	970			970	10,233
2047	183,329	3,755,092	30,196	32,688	995			995	10,514
2048	188,821	3,964,892	30,943	33,435	1,020			1,020	10,794
2049	194,312	4,180,795	31,691	34,183	1,045			1,045	11,075
2050	199,804	4,402,799	32,438	34,930	1,070			1,070	11,355
2051	205,296	4,630,906	33,186	35,678	1,095			1,095	11,636
2052	210,788	4,865,114	33,933	36,425	1,120			1,120	11,916
2053	216,279	5,105,425	34,681	37,173	1,145			1,145	12,197
2054	221,771	5,351,837	35,428	37,920	1,170			1,170	12,477
2055	227,263	5,604,351	35,676	38,668	1,195			1,195	12,758
2056	232,755	5,862,968	36,423	39,415	1,220			1,220	13,039
2057	238,246	6,127,686	37,171	40,163	1,245			1,245	13,319
2058	243,738	6,398,506	37,918	40,910	1,270			1,270	13,600
2059	249,230	6,675,428	38,666	41,658	1,295			1,295	13,880
2060	254,722	6,958,452	39,413	42,405	1,320			1,320	14,161
2061	260,213	7,247,578	40,161	43,153	1,345			1,345	14,441
2062	265,705	7,542,806	40,908	43,900	1,370			1,370	14,722
2063	271,197	7,844,135	41,656	44,648	1,395			1,395	15,002
2064	276,689	8,151,567	42,403	45,395	1,420			1,420	15,283
2065	282,180	8,465,101	42,651	46,143	1,445			1,445	15,563
2066	287,672	8,784,737	43,398	46,890	1,470			1,470	15,844
2067	293,164	9,110,474	44,146	47,638	1,495			1,495	16,124
2068	298,656	9,442,314	44,893	48,385	1,520			1,520	16,405
2069	304,147	9,780,255	45,641	49,133	1,545			1,545	16,686
2070	309,639	10,124,299	46,388	49,880	1,570			1,570	16,966
2071	315,131	10,474,444	47,136	50,628	1,595			1,595	17,247
2072	320,623	10,830,691	47,883	51,375	1,620			1,620	17,527
2073	326,114	11,193,041	48,631	52,123	1,645			1,645	17,808
2074	331,606	11,561,492	49,378	52,870	1,670			1,670	18,088
2075	337,098	11,936,045	49,626	53,618	1,695			1,695	18,369

Annotations within the table:
- Historical Data (2010–2018)
- (RAR) (cumulative sum, to 2052); (IR) (2053–2063); (PR) (2064–2069); (SR) (2070–2075)
- 2025: Start of fleet expansion. Gen III+ only at 25 new systems per year.
- 2044: Last of Gen II reactors decommissioned
- 2058: Last of historical SNF generated before 2025 is taken out of power cooled storage

Table P2.2. Scenario E – Generation III+ reactors

Year	Annual mining and mineral processing of Uranium to meet reactor requirements	Cumulative sum mined from resources at 90% mining efficiency from 2016	UOX pelletization (converted UF6)	Rod/assembly fabrication (UOX+MOX)	Number of nuclear power stations	Number of Generation II Nuclear Power Plants	Number of Generation III Nuclear Power Plants	Number of Generation III+ Nuclear Power Plants	Electrical power generated by global nuclear fleet
	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(number)	(number)	(number)	(number)	(TWh)
2076	342,590	12,316,700	50,373	54,365	1,720			1,720	18,649
2077	348,081	12,703,457	51,121	55,113	1,745			1,745	18,930
2078	353,573	13,096,316	51,868	55,860	1,770			1,770	19,210
2079	359,065	13,495,277	52,616	56,608	1,795			1,795	19,491
2080	364,557	13,900,340 (SR)	53,363	57,355	1,820			1,820	19,772
2081	370,048	14,311,505	54,111	58,103	1,845			1,845	20,052
2082	375,540	14,728,772	54,858	58,850	1,870			1,870	20,333
2083	381,032	15,152,140	55,606	59,598	1,895			1,895	20,613
2084	386,524	15,581,611	56,353	60,345	1,920			1,920	20,894
2085	392,015	16,017,183	56,601	61,093	1,945			1,945	21,174
2086	397,507	16,458,858	57,348	61,840	1,970			1,970	21,455
2087	402,999	16,906,635	58,096	62,588	1,995			1,995	21,735
2088	408,491	17,360,513	58,843	63,335	2,020			2,020	22,016
2089	413,982	17,820,493	59,591	64,083	2,045			2,045	22,296
2090	419,474	18,286,576	60,338	64,830	2,070			2,070	22,577
2091	424,966	18,758,760	61,086	65,578	2,095			2,095	22,857
2092	430,458	19,237,046	61,833	66,325	2,120			2,120	23,138
2093	435,949	19,721,434 (UR)	62,581	67,073	2,145			2,145	23,419
2094	441,441	20,211,924	63,328	67,820	2,170			2,170	23,699
2095	446,933	20,708,516	63,576	68,568	2,195			2,195	23,980
2096	452,425	21,211,210	64,323	69,315	2,220			2,220	24,260
2097	457,916	21,720,006	65,071	70,063	2,245			2,245	24,541
2098	463,408	22,234,904	65,818	70,810	2,270			2,270	24,821
2099	468,900	22,755,904	66,566	71,558	2,295			2,295	25,102
2100	474,392	23,283,006	67,313	72,305	2,320			2,320	25,382
2101	479,883	23,816,210	68,061	73,053	2,345			2,345	25,663
2102									

All existing U resources depleted 2101

Table P2.3. Scenario E – Generation III+ reactors

Year	Annual mass of Spent Nuclear Fuel generated and put in powered underwater cooled storage (tonnes)	Fabrication of MOX fuel (tonnes)	Mass of Spent Nuclear Fuel (SNF) in power cooled storage pools for 10 years (tonnes)	Annual mass of Spent Nuclear Fuel taken out of powered underwater cooled storage (tonnes)	Total Stockpile mass of SNF to be disposed of into long term storage (tonnes)	Stable waste disposal of SNF (LLW) (tonnes)	Long term storage of SNF in near surface depth facilities (depth 30m) (VLLW) (tonnes)	Long term storage of SNF in intermediate depth facilities (depth 90-300m) (ILW) (tonnes)	Long term storage of SNF in deep underground geological repository facilities (depth 500-1000m) (HLW) (tonnes)
2010	12,000	1,597	172,200		73,800	51,033	21,513	1,203	44
2011	12,000	1,162	184,200		73,800	51,033	21,513	1,203	44
2012	12,000	1,200	196,200		73,800	51,033	21,513	1,203	44
2013	12,000	992	208,200		73,800	51,033	21,513	1,203	44
2014	12,000	1,072	220,200		73,800	51,033	21,513	1,203	44
2015	12,000	997	232,200		73,800	51,033	21,513	1,203	44
2016	12,000	992	244,200		73,800	51,033	21,513	1,203	44
2017	12,000	992	255,208		85,800	51,033	21,513	1,203	44
2018	12,000	992	266,216		97,800	51,033	21,513	1,203	44
2019	12,000	992	277,224		109,800	51,033	21,513	1,203	44
2020	12,000	992	288,232		121,800	51,033	21,513	1,203	44
2021	12,000	992	299,240		133,800	51,033	21,513	1,203	44
2022	12,000	992	310,248		145,800	51,033	21,513	1,203	44
2023	12,000	992	321,256		157,800	51,033	21,513	1,203	44
2024	12,000	992	332,264		169,800	51,033	21,513	1,203	44
2025	12,060	992	343,272	22,000	201,800	73,161	30,841	1,725	63
2026	12,918	1,492	332,698	22,000	233,800	95,289	40,169	2,246	83
2027	13,776	1,492	322,982	22,000	265,800	117,417	49,497	2,768	102
2028	14,634	1,492	314,125	22,000	297,800	139,545	58,825	3,289	121
2029	15,493	1,492	306,125	22,000	329,800	161,673	68,153	3,811	140
2030	16,351	1,492	298,984	22,000	361,800	183,801	77,481	4,333	159
2031	17,179	1,492	292,671	22,000	393,800	205,929	86,809	4,854	179
2032	17,948	1,492	287,127	22,000	425,800	228,057	96,137	5,376	198
2033	18,716	1,492	282,351	22,000	457,800	250,185	105,465	5,897	217
2034	19,485	1,492	278,343	22,000	489,800	272,313	114,793	6,419	236
2035	20,253	1,992	274,605	22,060	521,860	294,482	124,138	6,942	256
2036	21,022	1,992	271,574	22,918	554,778	317,245	133,734	7,478	275
2037	21,790	1,992	268,454	23,776	588,554	340,601	143,579	8,029	296
2038	22,559	1,992	265,245	24,634	623,188	364,551	153,675	8,593	316
2039	23,327	1,992	261,946	25,493	658,681	389,094	164,022	9,172	338
2040	24,096	1,992	258,557	26,351	695,032	414,230	174,618	9,764	359
2041	24,864	1,992	255,078	27,179	732,211	439,940	185,455	10,370	382
2042	25,633	1,992	251,539	27,948	770,159	466,181	196,517	10,989	404
2043	26,401	1,992	248,001	28,716	808,875	492,953	207,803	11,620	428
2044	27,169	1,992	244,461	29,485	848,359	520,256	219,313	12,263	451
2045	27,916	2,492	240,401	30,253	888,612	548,091	231,046	12,920	476
2046	28,664	2,492	236,319	31,022	929,634	576,458	243,004	13,588	500
2047	29,411	2,492	232,217	31,790	971,424	605,356	255,186	14,269	525
2048	30,159	2,492	228,094	32,559	1,013,983	634,785	267,592	14,963	551
2049	30,906	2,492	223,949	33,327	1,057,310	664,746	280,222	15,669	577
2050	31,654	2,492	219,784	34,096	1,101,405	695,238	293,076	16,388	603
2051	32,401	2,492	215,597	34,864	1,146,269	726,261	306,154	17,119	630
2052	33,149	2,492	211,390	35,633	1,191,902	757,816	319,455	17,863	658
2053	33,896	2,492	207,161	36,401	1,238,303	789,903	332,981	18,620	685
2054	34,644	2,492	202,912	37,169	1,285,472	822,520	346,731	19,388	714
2055	35,391	2,992	198,142	37,916	1,333,388	855,654	360,699	20,169	742
2056	36,139	2,992	193,373	38,664	1,382,052	889,305	374,884	20,963	772
2057	36,886	2,992	188,603	39,411	1,431,463	923,472	389,287	21,768	801
2058	37,634	2,992	183,834	40,159	1,481,621	958,157	403,909	22,586	831
2059	38,381	2,992	189,064	30,906	1,512,528	979,529	412,918	23,089	850
2060	39,129	2,992	194,295	31,654	1,544,181	1,001,417	422,145	23,605	869
2061	39,876	2,992	199,525	32,401	1,576,582	1,023,823	431,590	24,133	888
2062	40,624	2,992	204,756	33,149	1,609,731	1,046,745	441,253	24,674	908
2063	41,371	2,992	209,986	33,896	1,643,627	1,070,184	451,133	25,226	929
2064	42,119	2,992	215,217	34,644	1,678,271	1,094,140	461,232	25,791	949
2065	42,866	3,492	219,947	35,391	1,713,662	1,118,613	471,548	26,368	971
2066	43,614	3,492	224,678	36,139	1,749,801	1,143,603	482,083	26,957	992
2067	44,361	3,492	229,408	36,886	1,786,687	1,169,110	492,835	27,558	1,014
2068	45,109	3,492	234,139	37,634	1,824,320	1,195,134	503,805	28,172	1,037
2069	45,856	3,492	238,869	38,381	1,862,702	1,221,674	514,994	28,797	1,060
2070	46,604	3,492	243,600	39,129	1,901,830	1,248,732	526,400	29,435	1,083
2071	47,351	3,492	248,330	39,876	1,941,706	1,276,306	538,023	30,085	1,107
2072	48,099	3,492	253,061	40,624	1,982,330	1,304,397	549,865	30,747	1,132
2073	48,846	3,492	257,791	41,371	2,023,701	1,333,005	561,925	31,422	1,157
2074	49,594	3,492	262,522	42,119	2,065,820	1,362,130	574,202	32,108	1,182
2075	50,341	3,992	266,752	42,866	2,108,686	1,391,772	586,698	32,807	1,208

Historical Data

25 new Gen III+ systems per year

Last of Gen II reactors decommissioned

Last of historical SNF taken out of power cooled storage

Table P2.4. Scenario E – Generation III+ reactors

Year	Annual mass of Spent Nuclear Fuel generated and put in powered underwater cooled storage (tonnes)	Fabrication of MOX fuel (tonnes)	Mass of Spent Nuclear Fuel (SNF) in power cooled storage pools for 10 years (tonnes)	Annual mass of Spent Nuclear Fuel taken out of powered underwater cooled storage (tonnes)	Total Stockpile mass of SNF to be disposed of into long term storage (tonnes)	Stable waste disposal of SNF (LLW) (tonnes)	Long term storage of SNF in near surface depth facilities (depth 30m) (VLLW) (tonnes)	Long term storage of SNF in intermediate depth facilities (depth 90-300m) (ILW) (tonnes)	Long term storage of SNF in deep underground geological repository facilities (depth 500-1000m) (HLW) (tonnes)
2076	51,089	3,992	270,983	43,614	2,152,300	1,421,931	599,411	33,518	1,234
2077	51,836	3,992	275,213	44,361	2,196,661	1,452,607	612,343	34,241	1,260
2078	52,584	3,992	279,444	45,109	2,241,769	1,483,800	625,492	34,976	1,287
2079	53,331	3,992	283,674	45,856	2,287,626	1,515,509	638,859	35,723	1,315
2080	54,079	3,992	287,905	46,604	2,334,229	1,547,736	652,444	36,483	1,343
2081	54,826	3,992	292,135	47,351	2,381,580	1,580,479	666,247	37,255	1,371
2082	55,574	3,992	296,366	48,099	2,429,679	1,613,739	680,267	38,039	1,400
2083	56,321	3,992	300,596	48,846	2,478,525	1,647,516	694,506	38,835	1,430
2084	57,069	3,992	304,827	49,594	2,528,119	1,681,810	708,963	39,644	1,459
2085	57,816	4,492	313,049	50,341	2,578,460	1,716,621	723,637	40,464	1,489
2086	58,564	4,492	321,272	51,089	2,629,549	1,751,949	738,529	41,297	1,520
2087	59,311	4,492	329,494	51,836	2,681,385	1,787,794	753,640	42,142	1,551
2088	60,059	4,492	337,717	52,584	2,733,968	1,824,155	768,968	42,999	1,583
2089	60,806	4,492	345,939	53,331	2,787,300	1,861,034	784,514	43,868	1,615
2090	61,554	4,492	354,162	54,079	2,841,378	1,898,429	800,278	44,750	1,647
2091	62,301	4,492	362,384	54,826	2,896,204	1,936,341	816,260	45,643	1,680
2092	63,049	4,492	370,607	55,574	2,951,778	1,974,771	832,459	46,549	1,713
2093	63,796	4,492	378,829	56,321	3,008,099	2,013,717	848,877	47,467	1,747
2094	64,544	4,492	387,052	57,069	3,065,168	2,053,180	865,512	48,397	1,782
2095	65,291	4,992	395,274	57,816	3,122,984	2,093,159	882,366	49,340	1,816
2096	66,039	4,992	403,497	58,564	3,181,548	2,133,656	899,437	50,294	1,851
2097	66,786	4,992	411,719	59,311	3,240,859	2,174,670	916,726	51,261	1,887
2098	67,534	4992	419,942	60,059	3,300,918	2,216,200	934,233	52,240	1,923
2099	68,281	4992	428,164	60,806	3,361,724	2,258,248	951,958	53,231	1,959
2100	69,029	4992	436,387	61,554	3,423,277	2,300,812	969,901	54,235	1,996
2101	69,776	4992	**444,609**	62,301	3,485,578	2,343,894	988,062	55,250	2,034
2102			407,229	63,049	3,548,627	2,387,492	1,006,441	56,278	2,072
2103			369,400	63,796	3,612,423	2,431,607	1,025,037	57,318	2,110
2104			331,122	64,544	3,676,967	2,476,239	1,043,852	58,370	2,149
2105			292,396	65,291	3,742,258	2,521,387	1,062,884	59,434	2,188
2106			253,221	66,039	3,808,297	2,567,053	1,082,135	60,510	2,227
2107			213,598	66,786	3,875,083	2,613,236	1,101,603	61,599	2,267
2108			173,526	67,534	3,942,617	2,659,935	1,121,289	62,700	2,308
2109			133,006	68,281	4,010,898	2,707,152	1,141,193	63,813	2,349
2110			92,037	69,029	4,079,926	2,754,885	1,161,315	64,938	2,390
2111			50,620	69,776	4,149,703	2,803,135	1,181,654	66,075	2,432
2112			8,754	8,754	4,158,457	2,809,189	1,184,206	66,218	2,437

U resources depleted in 2101, remaining SNF in power cooled storage has to be managed without nuclear power sourced electricity

Table P3.1. Scenario E – Generation II reactors

Year	Mining and mineral processing of U annually to meet reactor requirements (tonnes)	Cumulative sum mined from resources at 90% mining efficiency from 2016 (tonnes)	UOX pelletization (converted UF6 + reprocessed SNF) (tonnes)	Rod/assembly fabrication (UOX+Recycled SNF+MOX) (tonnes)	Number of nuclear power stations (number)	Electrical power generated by global nuclear fleet (TWh)	Annual mass of Spent Nuclear Fuel generated and put in powered underwater cooled storage (tonnes)	Annual mass of Spent Nuclear Fuel taken out of powered underwater cooled storage (tonnes)
2010			Historical Data				12,000	
2011							12,000	
2012							12,000	
2013	59,331				434	2,367	12,000	
2014	56,173				438	2,432	12,000	
2015	60,291				441	2,451	12,000	
2016	62,071	62,071		15,276	447	2,474	12,000	
2017	62,071	131,039		15,276	448	2,499	12,000	
2018	62,071	200,007		15,276	450	2,525	12,000	
2019	62,071	268,974		15,276	443	2,550	12,000	
2020	62,071	337,942		15,276	443	2,576	12,000	
2021	62,071	406,910		15,276	443	2,602	12,000	
2022	62,071	475,878		15,276	443	2,602	12,000	
2023	62,071	544,845		15,276	443	2,602	12,000	
2024	62,071	613,813		15,276	443	2,602	12,000	
2025	62,591	683,359	13,262	15,334	445	2,617	12,058	12,000
2026	69,092	760,128	12,983	16,055	470	2,815	12,779	12,000
2027	75,593	844,120	13,704	16,776	495	3,012	13,500	12,000
2028	82,094	935,336	14,425	17,497	520	3,209	14,221	12,000
2029	88,595	1,033,775	15,147	18,219	545	3,406	14,943	12,000
2030	95,096	1,139,437	15,868	18,940	570	3,603	15,664	12,000
2031	101,597	1,252,323	16,589	19,661	595	3,801	16,385	12,000
2032	108,098	1,372,432	17,310	20,382	620	3,998	17,106	12,000
2033	114,599	(RAR) 1,499,764	18,032	21,104	645	4,195	17,828	12,000
2034	121,100	1,634,320	18,753	21,825	670	4,392	18,549	12,000
2035	127,601	1,776,099	18,974	22,546	695	4,590	19,270	12,058
2036	134,102	1,925,101	19,195	23,267	720	4,787	19,991	12,779
2037	140,603	2,081,327	19,917	23,989	745	4,984	20,713	13,500
2038	147,104	2,244,776	20,638	24,710	770	5,181	21,434	14,221
2039	153,605	2,415,448	21,359	25,431	795	5,378	22,155	14,943
2040	160,106	2,593,344	22,080	26,152	820	5,576	22,876	15,664
2041	166,607	2,778,463	22,802	26,874	845	5,773	23,598	16,385
2042	173,108	2,970,805	23,523	27,595	870	5,970	24,319	17,106
2043	179,609	3,170,370	24,244	28,316	895	6,167	25,040	17,828
2044	186,110	3,377,159	24,965	29,037	920	6,364	25,761	18,549
2045	192,611	3,591,172	25,187	29,759	945	6,562	26,483	19,270
2046	199,112	3,812,407	25,408	30,480	970	6,759	27,204	19,991
2047	205,613	4,040,866	26,129	31,201	995	6,956	27,925	20,713
2048	212,114	4,276,549	26,850	31,922	1,020	7,153	28,646	21,434
2049	218,615	4,519,454	27,572	32,644	1,045	7,351	29,368	22,155
2050	225,116	4,769,583	28,293	33,365	1,070	7,548	30,089	22,876
2051	231,617	5,026,936	29,014	34,086	1,095	7,745	30,810	23,598
2052	238,118	5,291,511	29,735	34,807	1,120	7,942	31,531	24,319
2053	244,619	5,563,310	30,457	35,529	1,145	8,139	32,253	25,040
2054	251,120	(IR) 5,842,333	31,178	36,250	1,170	8,337	32,974	25,761
2055	257,621	6,128,578	30,899	36,971	1,195	8,534	33,695	26,483
2056	264,122	6,422,047	31,620	37,692	1,220	8,731	34,416	27,204
2057	270,623	6,722,739	32,342	38,414	1,245	8,928	35,138	27,925
2058	277,124	7,030,655	33,063	39,135	1,270	9,125	35,859	28,646
2059	283,625	7,345,794	33,784	39,856	1,295	9,323	36,580	29,368
2060	290,126	7,668,156	34,505	40,577	1,320	9,520	37,301	30,089
2061	296,627	7,997,742	35,227	41,299	1,345	9,717	38,023	30,810
2062	303,128	8,334,551	35,948	42,020	1,370	9,914	38,744	31,531
2063	309,629	(PR) 8,678,583	36,669	42,741	1,395	10,111	39,465	32,253
2064	316,130	9,029,839	37,390	43,462	1,420	10,309	40,186	32,974
2065	322,631	9,388,318	37,112	44,184	1,445	10,506	40,908	33,695
2066	329,132	9,754,020	37,833	44,905	1,470	10,703	41,629	34,416
2067	335,633	10,126,946	38,554	45,626	1,495	10,900	42,350	35,138
2068	342,134	10,507,095	39,275	46,347	1,520	11,098	43,071	35,859
2069	348,635	10,894,467	39,997	47,069	1,545	11,295	43,793	36,580
2070	355,136	11,289,063	40,718	47,790	1,570	11,492	44,514	37,301
2071	361,637	11,690,882	41,439	48,511	1,595	11,689	45,235	38,023
2072	368,138	(SR) 12,099,924	42,160	49,232	1,620	11,886	45,956	38,744
2073	374,639	12,516,190	42,882	49,954	1,645	12,084	46,678	39,465
2074	381,140	12,939,679	43,603	50,675	1,670	12,281	47,399	40,186
2075	387,641	13,370,391	43,324	51,396	1,695	12,478	48,120	40,908
2076	394,142	13,808,327	44,045	52,117	1,720	12,675	48,841	41,629
2077	400,643	14,253,486	44,767	52,839	1,745	12,872	49,563	42,350
2078	407,144	14,705,868	45,488	53,560	1,770	13,070	50,284	43,071
2079	413,645	(UR) 15,165,474	46,209	54,281	1,795	13,267	51,005	43,793
2080	420,146	15,632,303	46,930	55,002	1,820	13,464	51,726	44,514

Start of fleet expansion. Gen II only at 25 new systems per year.

Last of historical SNF generated before 2025 is taken out of power cooled storage

Table P3.2. Scenario E – Generation II reactors

Year	Mining and mineral processing of U annually to meet reactor requirements (tonnes)	Cumulative sum mined from resources at 90% mining efficiency from 2016 (tonnes) (UR)	UOX pelletization (converted UF6 + reprocessed SNF) (tonnes)	Rod/assembly fabrication (UOX+Recycled SNF+MOX) (tonnes)	Number of nuclear power stations (number)	Electrical power generated by global nuclear fleet (TWh)	Annual mass of Spent Nuclear Fuel generated and put in powered underwater cooled storage (tonnes)	Annual mass of Spent Nuclear Fuel taken out of powered underwater cooled storage (tonnes)
2081	426,647	16,106,355	47,652	55,724	1,845	13,661	52,448	45,235
2082	433,148	16,587,631	48,373	56,445	1,870	13,859	53,169	45,956
2083	439,649	17,076,130	49,094	57,166	1,895	14,056	53,890	46,678
2084	446,150	17,571,852	49,815	57,887	1,920	14,253	54,611	47,399
2085	452,651	18,074,798	49,537	58,609	1,945	14,450	55,333	48,120
2086	459,152	18,584,967	50,258	59,330	1,970	14,647	56,054	48,841
2087	465,653	19,102,359	50,979	60,051	1,995	14,845	56,775	49,563
2088	472,154	19,626,974	51,700	60,772	2,020	15,042	57,496	50,284
2089	478,655	20,158,813	52,422	61,494	2,045	15,239	58,218	51,005
2090	485,156	20,697,876	53,143	62,215	2,070	15,436	58,939	51,726
2091	491,657	21,244,161	53,864	62,936	2,095	15,633	59,660	52,448
2092	498,158	21,797,670	54,585	63,657	2,120	15,831	60,381	53,169
2093	504,659	22,358,403	55,307	64,379	2,145	16,028	61,103	53,890
2094	511,160	22,926,358	56,028	65,100	2,170	16,225	61,824	54,611
2095	517,661	23,501,537	56,749	65,821	2,195	16,422	62,545	55,333
2096								56,054
2097								56,775
2098								57,496
2099								58,218
2100								58,939
2101								59,660
2102								60,381
2103								61,103
2104								61,824
2105								62,545
2106								

Table P3.3. Scenario E – Generation II reactors

Year	Reprocessing of Spent Nuclear Fuel (tonnes)	Fabrication of MOX fuel (tonnes)	Mass of Spent Nuclear Fuel (SNF) in power cooled storage pools for 10 years (tonnes)	Total Stockpile mass of SNF to be disposed of in long term storage (tonnes)	Stable waste disposal of SNF (LLW) (tonnes)	Long term storage of SNF in near surface depth facilities (depth 30m) (VLLW) (tonnes)	Long term storage of SNF in intermediate depth facilities (depth 90-300m) (ILW) (tonnes)	Long term storage of SNF in deep underground geological repository facilities (depth 500-1000m) (HLW) (tonnes)
2010	1,000	1,597	172,200	73,800	51,033	21,513	1,203	44
2011	1,000	1,162	184,200	73,800	51,033	21,513	1,203	44
2012	1,000	1,200	196,200	73,800	51,033	21,513	1,203	44
2013	1,000	992	208,200	73,800	51,033	21,513	1,203	44
2014	1,180	1,072	220,200	73,800	51,033	21,513	1,203	44
2015	1,170	997	232,200	73,800	51,033	21,513	1,203	44
2016	1,080	992	244,200	73,800	51,033	21,513	1,203	44
2017	1,080	992	256,200	73,800	51,033	21,550	1,181	44
2018	1,080	992	268,200	73,800	51,033	21,550	1,181	44
2019	1,080	992	280,200	73,800	51,033	21,550	1,181	44
2020	1,080	992	292,200	73,800	51,033	21,550	1,181	44
2021	1,080	992	304,200	73,800	51,033	21,550	1,181	44
2022	1,080	992	316,200	73,800	51,033	21,550	1,181	44
2023	1,080	992	328,200	73,800	51,033	21,550	1,181	44
2024	1,080	992	340,200	73,800	51,033	21,550	1,181	44
2025	1,080	992	330,258	96,797	66,935	28,216	1,578	58
2026	1,580	1,492	321,037	119,789	82,834	34,918	1,953	72
2027	1,580	1,492	312,537	142,781	98,733	41,621	2,327	86
2028	1,580	1,492	304,758	165,773	114,632	48,323	2,702	99
2029	1,580	1,492	297,701	188,765	130,531	55,025	3,077	113
2030	1,580	1,492	291,365	211,757	146,430	61,727	3,452	127
2031	1,580	1,492	285,750	234,749	162,329	68,429	3,826	141
2032	1,580	1,492	280,857	257,741	178,228	75,132	4,201	155
2033	1,580	1,492	276,684	280,733	194,127	81,834	4,576	168
2034	1,580	1,492	273,233	303,725	210,026	88,536	4,951	182
2035	1,580	1,992	270,446	326,775	225,965	95,255	5,326	196
2036	2,080	1,992	267,658	351,046	242,748	102,330	5,722	211
2037	2,080	1,992	264,871	376,038	260,030	109,615	6,129	226
2038	2,080	1,992	262,083	401,751	277,811	117,111	6,549	241
2039	2,080	1,992	259,296	428,186	296,091	124,816	6,979	257
2040	2,080	1,992	256,508	455,342	314,869	132,732	7,422	273
2041	2,080	1,992	253,721	483,219	334,146	140,858	7,876	290
2042	2,080	1,992	250,933	511,818	353,922	149,195	8,343	307
2043	2,080	1,992	248,146	541,137	374,196	157,742	8,821	325
2044	2,080	1,992	245,358	571,178	394,970	166,498	9,310	343
2045	2,080	2,492	242,571	602,440	416,588	175,611	9,820	361
2046	2,580	2,492	239,783	634,424	438,704	184,935	10,341	381
2047	2,580	2,492	236,996	667,129	461,319	194,468	10,874	400
2048	2,580	2,492	234,208	700,555	484,433	204,212	11,419	420
2049	2,580	2,492	231,421	734,702	508,046	214,166	11,976	441
2050	2,580	2,492	228,633	769,570	532,158	224,330	12,544	462
2051	2,580	2,492	225,846	805,160	556,768	234,704	13,124	483
2052	2,580	2,492	223,058	841,471	581,877	245,289	13,716	505
2053	2,580	2,492	220,271	878,503	607,485	256,084	14,320	527
2054	2,580	2,492	217,483	916,257	633,591	267,089	14,935	550
2055	3,080	2,992	214,696	955,231	660,542	278,450	15,570	573
2056	3,080	2,992	211,908	994,927	687,992	290,021	16,217	597
2057	3,080	2,992	209,121	1,035,344	715,941	301,803	16,876	621
2058	3,080	2,992	206,333	1,076,483	744,388	313,795	17,547	646
2059	3,080	2,992	213,546	1,108,343	766,419	323,082	18,066	665
2060	3,080	2,992	220,758	1,140,923	788,949	332,579	18,597	685
2061	3,080	2,992	227,971	1,174,226	811,977	342,287	19,140	705
2062	3,080	2,992	235,183	1,208,249	835,504	352,205	19,694	725
2063	3,080	2,992	242,396	1,242,994	859,530	362,333	20,261	746
2064	3,080	2,992	249,608	1,278,460	884,055	372,671	20,839	767
2065	3,580	3,492	256,821	1,315,147	909,424	383,365	21,437	789
2066	3,580	3,492	264,033	1,352,555	935,292	394,270	22,047	812
2067	3,580	3,492	271,246	1,390,685	961,659	405,385	22,668	834
2068	3,580	3,492	278,458	1,429,536	988,524	416,710	23,301	858
2069	3,580	3,492	285,671	1,469,108	1,015,888	428,245	23,946	881
2070	3,580	3,492	292,883	1,509,402	1,043,751	439,991	24,603	906
2071	3,580	3,492	300,096	1,550,416	1,072,113	451,946	25,272	930
2072	3,580	3,492	307,308	1,592,152	1,100,973	464,112	25,952	955
2073	3,580	3,492	314,521	1,634,610	1,130,333	476,489	26,644	981
2074	3,580	3,492	321,733	1,677,788	1,160,190	489,075	27,348	1,007
2075	4,080	3,992	328,946	1,722,188	1,190,893	502,018	28,072	1,033
2076	4,080	3,992	336,158	1,767,309	1,222,094	515,170	28,807	1,060
2077	4,080	3,992	343,371	1,813,151	1,253,794	528,533	29,554	1,088
2078	4,080	3,992	350,583	1,859,714	1,285,992	542,107	30,313	1,116
2079	4,080	3,992	357,796	1,906,999	1,318,690	555,890	31,084	1,144
2080	4,080	3,992	365,008	1,955,005	1,351,886	569,884	31,867	1,173

2025: Start of fleet expansion. Gen II only at 25 new systems per year.

2058: Last of historical SNF generated before 2025 is taken out of power cooled storage

Table P3.4. Scenario E – Generation II reactors

Year	Reprocessing of Spent Nuclear Fuel (tonnes)	Fabrication of MOX fuel (tonnes)	Mass of Spent Nuclear Fuel (SNF) in power cooled storage pools for 10 years (tonnes)	Total Stockpile mass of SNF to be disposed of in long term storage (tonnes)	Stable waste disposal of SNF (LLW) (tonnes)	Long term storage of SNF in near surface depth facilities (depth 30m) (VLLW) (tonnes)	Long term storage of SNF in intermediate depth facilities (depth 90-300m) (ILW) (tonnes)	Long term storage of SNF in deep underground geological repository facilities (depth 500-1000m) (HLW) (tonnes)
2081	4,080	3,992	372,221	2,003,732	1,385,581	584,088	32,661	1,202
2082	4,080	3,992	379,433	2,053,181	1,419,774	598,502	33,467	1,232
2083	4,080	3,992	386,646	2,103,350	1,454,467	613,127	34,285	1,262
2084	4,080	3,992	393,858	2,154,241	1,489,658	627,961	35,114	1,293
2085	4,580	4,492	401,071	2,206,353	1,525,693	643,152	35,964	1,324
2086	4,580	4,492	408,283	2,259,187	1,562,228	658,553	36,825	1,356
2087	4,580	4,492	415,496	2,312,742	1,599,261	674,164	37,698	1,388
2088	4,580	4,492	422,708	2,367,018	1,636,793	689,986	38,582	1,420
2089	4,580	4,492	429,921	2,422,015	1,674,823	706,017	39,479	1,453
2090	4,580	4,492	437,133	2,477,733	1,713,353	722,259	40,387	1,487
2091	4,580	4,492	444,346	2,534,173	1,752,381	738,711	41,307	1,521
2092	4,580	4,492	451,558	2,591,334	1,791,907	755,374	42,239	1,555
2093	4,580	4,492	458,771	2,649,216	1,831,933	772,246	43,182	1,590
2094	4,580	4,492	465,983	2,707,820	1,872,457	789,329	44,137	1,625
2095	4,580	4,492	**473,196**	2,767,644	1,913,826	806,768	45,113	1,661
2096			428,353	2,828,190	1,955,693	824,417	46,099	1,697
2097			382,932	2,889,457	1,998,060	842,277	47,098	1,734
2098			336,935	2,951,446	2,040,925	860,346	48,109	1,771
2099			290,361	3,014,156	2,084,289	878,626	49,131	1,808
2100			243,210	3,077,586	2,128,151	897,116	50,165	1,847
2101			195,482	3,141,739	2,172,512	915,817	51,210	1,885
2102			147,177	3,206,612	2,217,372	934,727	52,268	1,924
2103			98,294	3,272,207	2,262,731	953,848	53,337	1,963
2104			48,835	3,338,523	2,308,588	973,179	54,418	2,003
2105			0	3,405,560	2,354,945	992,721	55,511	2,043
2106								

U resources depleted in 2095, remaining SNF in power cooled storage has to be managed without nuclear power sourced electricity

Table P4.1. Scenario E – Generation IV reactors

Year	Annual mining and mineral processing of Uranium to meet reactor requirements (tonnes)	Cumulative sum mined from resources at 90% mining efficiency from 2016 (tonnes)	UOX pelletization of converted UF6 (tonnes)	Required supply of unprocessed SNF from cooled storage to be used directly in Gen IV TWR reactors (tonnes)	Rod/assembly fabrication (UOX+MOX+SNF) (tonnes)	Number of nuclear power stations (number)	Number of Generation II Nuclear Power Plants (number)	Number of Generation III Nuclear Power Plants (number)	Number of Generation III+ Nuclear Power Plants (number)	Number of Generation IV TWR Nuclear Power Plants (number)
2010										
2011										
2012										
2013	59,331					434				
2014	56,173					438				
2015	60,291					441				
2016	62,071	62,071	13,849		15,276	447				
2017	62,071	131,039	13,849		15,277	448				
2018	62,071	200,007	13,849		15,277	450				
2019	62,071	268,974	13,849		15,277	443	399	4	40	
2020	62,071	337,942	13,849		15,277	443	399	4	40	
2021	62,071	406,910	13,849		15,277	443	399	4	40	
2022	62,071	475,878	13,849		15,277	443	399	4	40	
2023	62,071	544,845	13,849		15,277	443	399	4	40	
2024	62,071	613,813	13,849		15,277	443	399	4	40	
2025	61,480	682,125	14,659		15,277	443	379	3	61	
2026	62,870	751,980	14,453		15,389	453	359	3	91	
2027	64,259	823,379	14,246		15,501	463	339	3	121	
2028	65,648	896,322	14,039		15,613	473	319	3	151	
2029	67,038	970,808	13,833		15,726	483	299	3	181	
2030	67,065	1,045,325	14,018	536	16,046	493	279	2	202	10
2031	67,312	1,120,116	14,233	700	16,426	503	259	0	224	20
2032	67,120	1,194,694	14,389	865	16,746	513	239		244	30
2033	66,928	1,269,059	14,545	1,029	17,066	523	219		264	40
2034	66,736	1,343,210	14,700	1,193	17,386	533	199		284	50
2035	66,544	1,417,148	14,856	858	17,706	543	179		304	60
2036	66,352	1,490,872	15,011	1,022	18,026	553	159		324	70
2037	66,160	1,564,383	15,167	1,187	18,346	563	139		344	80
2038	65,968	1,637,681	15,322	1,351	18,666	573	119		364	90
2039	65,776	1,710,765	15,478	1,516	18,986	583	99		384	100
2040	65,584	1,783,635	15,633	1,680	19,306	593	79		404	110
2041	65,391	1,856,293	15,789	1,845	19,626	603	59		424	120
2042	65,199	1,928,736	15,944	2,009	19,946	613	39		444	130
2043	65,007	2,000,967	16,100	2,173	20,266	623	19		464	140
2044	64,852	2,073,024	16,255	2,338	20,585	633	0		483	150
2045	65,467	2,145,765	16,329	2,062	20,884	643			483	160
2046	66,082	2,219,189	16,404	2,286	21,183	653			483	170
2047	66,697	2,293,297	16,479	2,511	21,482	663			483	180
2048	67,313	2,368,089	16,554	2,735	21,781	673			483	190
2049	67,928	2,443,565	16,628	2,959	22,080	683			483	200
2050	69,466	2,520,750	16,815	3,520	22,827	708			483	225

Historical Data

(RAR)

Start of fleet expansion. Gen III+ only at 25 new systems per year.

Gen IV reactors commissioned for the first time. 10 Gen IV reactors (1400 Mwe capacity) connected to the grid each year (accounting for decommissioning schedule for Gen II and Gen III+)

Last of Gen II reactors decommissioned

25 extra 1400 MWe Gen VI reactors connected the grid each year

Table P4.2. Scenario E – Generation IV reactors

Year	Annual mining and mineral processing of Uranium to meet reactor requirements (tonnes)	Cumulative sum mined from resources at 90% mining efficiency from 2016 (tonnes)	UOX pelletization of converted UF6 (tonnes)	Required supply of unprocessed SNF from cooled storage to be used directly in Gen IV TWR reactors (tonnes)	Rod/assembly fabrication (UOX+MOX+SNF) (tonnes)	Number of nuclear power stations (number)	Number of Generation II Nuclear Power Plants (number)	Number of Generation III Nuclear Power Plants (number)	Number of Generation III+ Nuclear Power Plants (number)	Number of Generation IV TWR Nuclear Power Plants (number)
2051	71,005	2,599,644	17,002	4,080	23,575	733			483	250
2052	72,543	2,680,247	17,189	4,641	24,322	758			483	275
2053	74,081	2,762,559	17,376	5,202	25,070	783			483	300
2054	75,619	2,846,580	17,563	5,762	25,817	808			483	325
2055	77,158	2,932,311	17,750	5,823	26,565	833			483	350
2056	78,696	3,019,751	17,937	6,384	27,312	858			483	375
2057	80,234	3,108,899	18,123	6,944	28,060	883			483	400
2058	81,772	3,199,758	18,310	7,505	28,807	908			483	425
2059	83,311	3,292,325	18,497	8,065	29,555	933			483	450
2060	84,849	3,386,601	18,684	8,626	30,302	958			483	475
2061	86,387	3,482,587	18,871	9,187	31,050	983			483	500
2062	87,925	3,580,281	19,058	9,747	31,797	1,008			483	525
2063	89,464	3,679,685	19,245	10,308	32,545	1,033			483	550
2064	91,002	3,780,798	19,432	10,869	33,292	1,058			483	575
2065	92,540	3,883,621	19,618	10,929	34,040	1,083			483	600
2066	94,078	3,988,152	19,805	11,490	34,787	1,108			483	625
2067	95,617	4,094,393	19,992	12,050	35,535	1,133			483	650
2068	97,155	4,202,342	20,179	12,611	36,282	1,158			483	675
2069	98,693	4,312,001	20,366	13,172	37,030	1,183			483	700
2070	100,231	4,423,369	20,553	13,732	37,777	1,208			483	725
2071	101,770	4,536,447	20,740	14,293	38,525	1,233			483	750
2072	103,308	4,651,233	20,927	14,854	39,272	1,258			483	775
2073	104,846	4,767,729	21,113	15,414	40,020	1,283			483	800
2074	106,384	4,885,933	21,300	15,975	40,767	1,308			483	825
2075	107,923	5,005,847	21,487	16,035	41,515	1,333			483	850
2076	109,461	5,127,470	21,674	16,596	42,262	1,358			483	875
2077	110,999	5,250,802	21,861	17,157	43,010	1,383			483	900
2078	112,537	5,375,844	22,048	17,717	43,757	1,408			483	925
2079	114,076	5,502,594	22,235	18,278	44,505	1,433			483	950
2080	115,614	5,631,054	22,422	18,839	45,252	1,458			483	975
2081	117,152	5,761,223	22,608	19,399	46,000	1,483			483	1,000
2082	118,690	5,893,101	22,795	19,960	46,747	1,508			483	1,025
2083	120,229	6,026,688	22,982	20,520	47,495	1,533			483	1,050
2084	121,767	6,161,985	23,169	21,081	48,242	1,558			483	1,075
2085	123,305	6,298,990	23,356	21,142	48,990	1,583			483	1,100
2086	124,843	6,437,705	23,543	21,702	49,737	1,608			483	1,125
2087	122,428	6,573,736	23,917	22,076	50,485	1,633			458	1,175
2088	120,013	6,707,084	24,290	22,450	51,232	1,658			433	1,225
2089	117,598	6,837,748	24,664	22,824	51,980	1,683			408	1,275
2090	115,182	6,965,728	25,038	23,197	52,727	1,708			383	1,325
2091	112,767	7,091,025	25,412	23,571	53,475	1,733			358	1,375
2092	110,352	7,213,638	25,785	23,945	54,222	1,758			333	1,425

(RAR)

(IR)

Last of historical SNF generated before 2025 is taken out of power cooled storage

Gen III+ start to decommission at a rate of 25 per year starting in 2086. Gen IV increase to 50 new stations connected to compensate. From this point onwards, all new reactors are Gen IV only

Table P4.3. Scenario E – Generation IV reactors

Year	Annual mining and mineral processing of Uranium to meet reactor requirements (tonnes)	Cumulative sum mined from resources at 90% mining efficiency from 2016 (tonnes)	UOX pelletization of converted UF6 (tonnes)	Required supply of unprocessed SNF from cooled storage to be used directly in Gen IV TWR reactors (tonnes)	Rod/assembly fabrication (UOX+MOX+SNF) (tonnes)	Number of nuclear power stations (number)	Number of Generation II Nuclear Power Plants (number)	Number of Generation III Nuclear Power Plants (number)	Number of Generation III+ Nuclear Power Plants (number)	Number of Generation IV TWR Nuclear Power Plants (number)
2093	107,937	7,333,567	26,159	24,319	54,970	1,783			308	1,475
2094	105,521	7,450,813	26,533	24,692	55,717	1,808			283	1,525
2095	103,106	7,565,375	26,907	24,566	56,465	1,833			258	1,575
2096	100,691	(IR) 7,677,254	27,280	24,940	57,212	1,858			233	1,625
2097	98,276	7,786,449	27,654	25,314	57,960	1,883			208	1,675
2098	95,860	7,892,960	28,028	25,687	58,707	1,908			183	1,725
2099	93,445	7,996,788	28,402	26,061	59,455	1,933			158	1,775
2100	91,030	8,097,932	28,775	26,435	60,202	1,958			133	1,825
2101	88,615	8,196,393	29,149	26,809	60,950	1,983			108	1,875
2102	86,199	8,292,170	29,523	27,182	61,697	2,008			83	1,925
2103	83,784	8,385,263	29,897	27,556	62,445	2,033			58	1,975
2104	81,369	8,475,673	30,270	27,930	63,192	2,058			33	2,025
2105	78,954	8,563,399	30,644	27,804	63,940	2,083			8	2,075
2106	80,273	8,652,591	31,018	28,686	65,195	2,125			0	2,125
2107	81,811	8,743,492	31,205	29,246	65,943	2,150				2,150
2108	83,349	(PR) 8,836,102	31,392	29,807	66,690	2,175				2,175
2109	84,887	8,930,421	31,578	30,367	67,438	2,200				2,200
2110	86,426	9,026,450	31,765	30,928	68,185	2,225				2,225
2111	87,964	9,124,187	31,952	31,489	68,933	2,250				2,250
2112	89,502	9,223,634	32,139	32,049	69,680	2,275				2,275
2113	91,040	9,324,790	32,326	32,610	70,428	2,300				2,300
2114	92,579	9,427,655	32,513	33,171	71,175	2,325				2,325
2115	94,117	9,532,230	32,700	33,231	71,923	2,350				2,350
2116	95,655	9,638,513	32,887	33,792	72,670	2,375				2,375
2117	97,193	9,746,506	33,073	34,352	73,418	2,400				2,400
2118	98,732	9,856,208	33,260	34,913	74,165	2,425				2,425
2119	100,270	9,967,619	33,447	35,474	74,913	2,450				2,450
2120	101,808	10,080,739	33,634	36,034	75,660	2,475				2,475
2121	103,346	10,195,568	33,821	36,595	76,408	2,500				2,500
2122	104,885	10,312,107	34,008	37,156	77,155	2,525				2,525
2123	106,423	10,430,354	34,195	37,716	77,903	2,550				2,550
2124	107,961	10,550,311	34,382	38,277	78,650	2,575				2,575
2125	109,499	(SR) 10,671,977	34,568	38,337	79,398	2,600				2,600
2126	111,038	10,795,352	34,755	38,898	80,145	2,625				2,625
2127	112,576	10,920,437	34,942	39,459	80,893	2,650				2,650
2128	114,114	11,047,230	35,129	40,019	81,640	2,675				2,675
2129	115,652	11,175,733	35,316	40,580	82,388	2,700				2,700
2130	117,191	11,305,945	35,503	41,141	83,135	2,725				2,725
2131	118,729	11,437,866	35,690	41,701	83,883	2,750				2,750
2132	120,267	11,571,496	35,877	42,262	84,630	2,775				2,775
2133	121,805	11,706,835	36,063	42,822	85,378	2,800				2,800
2134	123,344	11,843,884	36,250	43,383	86,125	2,825				2,825

Table P4.4. Scenario E – Generation IV reactors

Year	Annual mining and mineral processing of Uranium to meet reactor requirements (tonnes)	Cumulative sum mined from resources at 90% mining efficiency from 2016 (tonnes)	UOX pelletization of converted UF6 (tonnes)	Required supply of unprocessed SNF from cooled storage to be used directly in Gen IV TWR reactors (tonnes)	Rod/assembly fabrication (UOX+MOX+SNF) (tonnes)	Number of nuclear power stations (number)	Number of Generation II Nuclear Power Plants (number)	Number of Generation III Nuclear Power Plants (number)	Number of Generation III+ Nuclear Power Plants (number)	Number of Generation IV TWR Nuclear Power Plants (number)
2135	124,882	11,982,641	36,437	43,444	86,873	2,850				2,850
2136	126,420	12,123,108	36,624	44,004	87,620	2,875				2,875
2137	127,958	12,265,284	36,811	44,565	88,368	2,900				2,900
2138	129,497	12,409,169	36,998	45,126	89,115	2,925				2,925
2139	131,035	12,554,764	37,185	45,686	89,863	2,950				2,950
2140	132,573	12,702,067	37,372	46,247	90,610	2,975				2,975
2141	134,111	12,851,080	37,558	46,807	91,358	3,000				3,000
2142	135,650	13,001,802	37,745	47,368	92,105	3,025				3,025
2143	137,188	13,154,233	37,932	47,929	92,853	3,050				3,050
2144	138,726	13,308,373	38,119	48,489	93,600	3,075				3,075
2145	140,264	(SR) 13,464,222	38,306	48,550	94,348	3,100				3,100
2146	141,803	13,621,781	38,493	49,111	95,095	3,125				3,125
2147	143,341	13,781,048	38,680	49,671	95,843	3,150				3,150
2148	144,879	13,942,025	38,867	50,232	96,590	3,175				3,175
2149	146,417	14,104,711	39,053	50,792	97,338	3,200				3,200
2150	147,956	14,269,106	39,240	51,353	98,085	3,225				3,225
2151	149,494	14,435,211	39,427	51,914	98,833	3,250				3,250
2152	151,032	14,603,024	39,614	52,474	99,580	3,275				3,275
2153	152,570	14,772,547	39,801	53,035	100,328	3,300				3,300
2154	154,109	14,943,779	39,988	53,596	101,075	3,325				3,325
2155	155,647	15,116,720	40,175	53,656	101,823	3,350				3,350
2156	157,185	15,291,370	40,362	54,217	102,570	3,375				3,375
2157	158,723	15,467,729	40,548	54,777	103,318	3,400				3,400
2158	160,262	15,645,798	40,735	55,338	104,065	3,425				3,425
2159	161,800	15,825,575	40,922	55,899	104,813	3,450				3,450
2160	163,338	16,007,062	41,109	56,459	105,560	3,475				3,475
2161	164,876	16,190,258	41,296	57,020	106,308	3,500				3,500
2162	166,415	16,375,163	41,483	57,581	107,055	3,525				3,525
2163	167,953	16,561,778	41,670	58,141	107,803	3,550				3,550
2164	169,491	16,750,101	41,857	58,702	108,550	3,575				3,575
2165	171,029	16,940,134	42,043	58,762	109,298	3,600				3,600
2166	172,568	(UR) 17,131,876	42,230	59,323	110,045	3,625				3,625
2167	174,106	17,325,327	42,417	59,884	110,793	3,650				3,650
2168	175,644	17,520,487	42,604	60,444	111,540	3,675				3,675
2169	177,182	17,717,356	42,791	61,005	112,288	3,700				3,700
2170	178,721	17,915,935	42,978	61,566	113,035	3,725				3,725
2171	180,259	18,116,222	43,165	62,126	113,783	3,750				3,750
2172	181,797	18,318,219	43,352	62,687	114,530	3,775				3,775
2173	183,335	18,521,925	43,538	63,247	115,278	3,800				3,800
2174	184,874	18,727,340	43,725	63,808	116,025	3,825				3,825
2175	186,412	18,934,465	43,912	63,869	116,773	3,850				3,850
2176	187,950	19,143,298	44,099	64,429	117,520	3,875				3,875

Table P4.5. Scenario E – Generation IV reactors

Year	Annual mining and mineral processing of Uranium to meet reactor requirements (tonnes)	Cumulative sum mined from resources at 90% mining efficiency from 2016 (tonnes)	UOX pelletization of converted UF6 (tonnes)	Required supply of unprocessed SNF from cooled storage to be used directly in Gen IV TWR reactors (tonnes)	Rod/assembly fabrication (UOX+MOX+SNF) (tonnes)	Number of nuclear power stations (number)	Number of Generation II Nuclear Power Plants (number)	Number of Generation III Nuclear Power Plants (number)	Number of Generation III+ Nuclear Power Plants (number)	Number of Generation IV TWR Nuclear Power Plants (number)
2177	189,488	19,353,841	44,286	64,990	118,268	3,900				3,900
2178	191,027	19,566,093	44,473	65,551	119,015	3,925				3,925
2179	192,565	19,780,054	44,660	66,111	119,763	3,950				3,950
2180	194,103	19,995,724	44,847	66,672	120,510	3,975				3,975
2181	195,641	20,213,103	45,033	67,232	121,258	4,000				4,000
2182	197,180	20,432,192	45,220	67,793	122,005	4,025				4,025
2183	198,718	20,652,989	45,407	68,354	122,753	4,050				4,050
2184	200,256	20,875,496	45,594	68,914	123,500	4,075				4,075
2185	201,794	(UR) 21,099,712	45,781	68,975	124,248	4,100				4,100
2186	203,333	21,325,637	45,968	69,536	124,995	4,125				4,125
2187	204,871	21,553,272	46,155	70,096	125,743	4,150				4,150
2188	206,409	21,782,615	46,342	70,657	126,490	4,175				4,175
2189	207,947	22,013,668	46,528	71,217	127,238	4,200				4,200
2190	209,486	22,246,430	46,715	71,778	127,985	4,225				4,225
2191	211,024	22,480,901	46,902	72,339	128,733	4,250				4,250
2192	212,562	22,717,081	47,089	72,899	129,480	4,275				4,275
2193	214,100	22,954,970	47,276	73,460	130,228	4,300				4,300
2194	215,639	23,194,569	47,463	74,021	130,975	4,325				4,325
2195	217,177	23,435,876	47,650	74,581	131,723	4,350				4,350
2196	218,715	23,678,893	47,837	75,142	132,470	4,375				4,375
2197										
2198										
2199										
2200										
2201										
2202										
2203										
2204										
2205										
2206										
2207										

Table P4.6. Scenario E – Generation IV reactors

Year	Electrical power generated by global nuclear fleet (TWh)	Annual mass of Spent Nuclear Fuel generated and put in powered underwater cooled storage (tonnes)	Annual mass of Spent Nuclear Fuel taken out of powered underwater cooled storage (tonnes)	Total mass of Spent Nuclear Fuel (SNF) in power cooled storage pools for 10 year cycle (tonnes)	Annual mass of Spent Nuclear Fuel put into long term storage, adjusting for SNF fuel tasked for fuel recycling (tonnes)	Fabrication of MOX fuel (tonnes)	Total Stockpile mass of SNF to be disposed of (tonnes)	Stable waste disposal of SNF (LLW) (tonnes)	Long term storage of SNF in near surface depth facilities (depth 30m) (VLLW) (tonnes)	Long term storage of SNF in intermediate depth facilities (depth 90-300m) (ILW) (tonnes)	Long term storage of SNF in deep underground geological repository facilities (depth 500-1000m) (HLW) (tonnes)
2010		12,000		172,200		1,597	73,800	51,033	21,513	1,203	44
2011		12,000		184,200		1,162	73,800	51,033	21,513	1,203	44
2012		12,000		196,200		1,200	73,800	51,033	21,513	1,203	44
2013	2,367	12,000		208,200		992	73,800	51,033	21,513	1,203	44
2014	2,432	12,000		220,200		1,072	73,800	51,033	21,513	1,203	44
2015	2,451	12,000		232,200		997	73,800	51,033	21,513	1,203	44
2016	2,474	12,000		244,200		992	73,800	51,033	21,513	1,203	44
2017	2,499	12,000		256,200		992	73,800	51,033	21,513	1,203	44
2018	2,525	12,000		268,200		992	73,800	51,033	21,513	1,203	44
2019	2,550	12,000		280,200		992	73,800	51,033	21,513	1,203	44
2020	2,576	12,000		292,200		992	73,800	51,033	21,513	1,203	44
2021	2,602	12,000		304,200		992	73,800	51,033	21,513	1,203	44
2022	2,602	12,000		316,200		992	73,800	51,033	21,513	1,203	44
2023	2,602	12,000		328,200		992	73,800	51,033	21,513	1,203	44
2024	2,602	12,000		340,200		992	73,800	51,033	21,513	1,203	44
2025	2,679	12,051	22,000	329,259		992	95,800	66,246	27,926	1,562	57
2026	2,858	12,371	22,000	319,629		1,492	117,800	81,459	34,339	1,920	71
2027	3,037	12,691	22,000	310,320		1,492	139,800	96,672	40,752	2,279	84
2028	3,216	13,011	22,000	301,330		1,492	161,800	111,885	47,165	2,637	97
2029	3,395	13,331	22,000	292,661		1,492	183,800	127,098	53,578	2,996	110
2030	3,585	13,680	22,536	283,805	22,000	1,492	205,800	142,311	59,991	3,355	123
2031	3,786	14,060	22,700	275,165	22,000	1,492	214,570	148,375	62,547	3,497	129
2032	3,965	14,380	22,865	266,681	22,000	1,492	223,340	154,440	65,104	3,640	134
2033	4,144	14,700	23,029	258,352	22,000	1,492	232,110	160,504	67,660	3,783	139
2034	4,323	15,020	23,193	250,179	22,000	1,492	240,880	166,569	70,217	3,926	145
2035	4,502	15,340	22,908	242,611	22,051	1,992	249,701	172,668	72,788	4,070	150
2036	4,681	15,660	23,393	234,878	22,371	1,992	258,841	178,989	75,452	4,219	155
2037	4,860	15,980	23,877	226,981	22,691	1,992	268,302	185,531	78,210	4,373	161
2038	5,038	16,300	24,362	218,920	23,011	1,992	278,082	192,294	81,061	4,533	167
2039	5,217	16,620	24,846	210,694	23,331	1,992	288,183	199,278	84,005	4,697	173
2040	5,396	16,940	25,361	202,274	23,680	1,992	298,633	206,505	87,052	4,868	179
2041	5,575	17,260	25,905	193,629	24,060	1,992	309,463	213,994	90,209	5,044	186
2042	5,754	17,580	26,389	184,820	24,380	1,992	320,613	221,704	93,459	5,226	192
2043	5,933	17,900	26,874	175,846	24,700	1,992	332,084	229,636	96,802	5,413	199
2044	6,109	18,219	27,358	166,708	25,020	1,992	343,874	237,789	100,239	5,605	206
2045	6,221	18,518	27,402	157,823	25,340	2,492	355,984	246,163	103,769	5,803	214
2046	6,333	18,817	27,947	148,694	25,660	2,492	368,414	254,758	107,393	6,005	221
2047	6,445	19,116	28,491	139,319	25,980	2,492	381,164	263,575	111,109	6,213	229
2048	6,558	19,415	29,035	129,700	26,300	2,492	394,235	272,613	114,919	6,426	237
2049	6,670	19,714	29,579	119,835	26,620	2,492	407,625	281,873	118,823	6,644	245
2050	6,950	20,462	30,460	109,836	26,940	2,492	421,335	291,353	122,819	6,868	253

Historical Data

Start of fleet expansion. Gen III+ only at 25 new systems per year.

Gen IV reactors commissioned for the first time. 10 Gen IV reactors (1400 Mwe capacity) connected to the grid each year (accounting for decommissioning schedule for Gen II and Gen III+)

Last of Gen II reactors decommissioned

25 extra 1400 MWe Gen VI reactors connected the grid each year

Table P4.7. Scenario E – Generation IV reactors

Year	Electrical power generated by global nuclear fleet (TWh)	Annual mass of Spent Nuclear Fuel generated and put in powered underwater cooled storage (tonnes)	Annual mass of Spent Nuclear Fuel taken out of powered underwater cooled storage (tonnes)	Total mass of Spent Nuclear Fuel (SNF) in power cooled storage pools for 10 year cycle (tonnes)	Annual mass of Spent Nuclear Fuel put into long term storage, adjusting for SNF fuel tasked for fuel recycling (tonnes)	Fabrication of MOX fuel (tonnes)	Total Stockpile mass of SNF to be disposed of (tonnes)	Stable waste disposal of SNF (LLW) (tonnes)	Long term storage of SNF in near surface depth facilities (depth 30m) (VLLW) (tonnes)	Long term storage of SNF in intermediate depth facilities (depth 90-300m) (ILW) (tonnes)	Long term storage of SNF in deep underground geological repository facilities (depth 500-1000m) (HLW) (tonnes)
2051	7,231	21,209	31,341	99,705	27,260	2,492	435,365	301,055	126,909	7,096	261
2052	7,511	21,957	32,221	89,440	27,580	2,492	449,716	310,978	131,092	7,330	270
2053	7,792	22,704	33,102	79,043	27,900	2,492	464,386	321,123	135,368	7,569	279
2054	8,072	23,452	33,982	68,513	28,219	2,492	479,375	331,488	139,738	7,814	288
2055	8,353	24,199	34,341	58,371	28,518	2,992	494,663	342,060	144,194	8,063	297
2056	8,634	24,947	35,201	48,117	28,817	2,992	510,251	352,838	148,738	8,317	306
2057	8,914	25,694	36,060	37,751	29,116	2,992	526,137	363,824	153,369	8,576	316
2058	9,195	26,442	36,920	27,273	29,415	2,992	542,322	375,016	158,087	8,840	325
2059	9,475	27,189	27,780	18,617	19,714	2,992	548,806	379,500	159,977	8,946	329
2060	9,756	27,937	20,462	17,466	11,836	2,992	547,412	378,535	159,571	8,923	328
2061	10,036	28,684	21,209	15,754	12,023	2,992	546,205	377,700	159,219	8,903	328
2062	10,317	29,432	21,957	13,482	12,209	2,992	545,184	376,995	158,921	8,887	327
2063	10,597	30,179	22,704	10,649	12,396	2,992	544,350	376,418	158,678	8,873	327
2064	10,878	30,927	23,452	7,255	12,583	2,992	543,704	375,971	158,490	8,862	326
2065	11,158	31,674	24,199	14,730	13,270	3,492	543,744	375,999	158,501	8,863	326
2066	11,439	32,422	24,947	22,205	13,457	3,492	543,971	376,156	158,567	8,867	326
2067	11,720	33,169	25,694	29,680	13,644	3,492	544,385	376,442	158,688	8,873	327
2068	12,000	33,917	26,442	37,155	13,831	3,492	544,985	376,857	158,863	8,883	327
2069	12,281	34,664	27,189	44,630	14,018	3,492	545,773	377,402	159,093	8,896	327
2070	12,561	35,412	27,937	52,105	14,204	3,492	546,747	378,076	159,377	8,912	328
2071	12,842	36,159	28,684	59,580	14,391	3,492	547,909	378,879	159,715	8,931	329
2072	13,122	36,907	29,432	67,055	14,578	3,492	549,257	379,811	160,108	8,953	330
2073	13,403	37,654	30,179	74,530	14,765	3,492	550,792	380,873	160,556	8,978	330
2074	13,683	38,402	30,927	82,005	14,952	3,492	552,514	382,063	161,058	9,006	332
2075	13,964	39,149	31,674	89,480	15,639	3,992	554,923	383,729	161,760	9,045	333
2076	14,244	39,897	32,422	96,955	15,826	3,992	557,519	385,524	162,517	9,088	335
2077	14,525	40,644	33,169	104,430	16,013	3,992	560,301	387,448	163,328	9,133	336
2078	14,805	41,392	33,917	111,905	16,199	3,992	563,271	389,502	164,193	9,181	338
2079	15,086	42,139	34,664	119,380	16,386	3,992	566,427	391,684	165,113	9,233	340
2080	15,367	42,887	35,412	126,855	16,573	3,992	569,770	393,996	166,088	9,287	342
2081	15,647	43,634	36,159	134,330	16,760	3,992	573,300	396,437	167,117	9,345	344
2082	15,928	44,382	36,907	141,805	16,947	3,992	577,017	399,007	168,201	9,405	346
2083	16,208	45,129	37,654	149,280	17,134	3,992	580,921	401,707	169,338	9,469	349
2084	16,489	45,877	38,402	156,755	17,321	3,992	585,012	404,536	170,531	9,536	351
2085	16,769	46,624	39,149	164,230	18,008	4,492	589,789	407,839	171,924	9,614	354
2086	17,050	47,372	39,897	171,705	18,194	4,492	594,754	411,272	173,371	9,694	357
2087	17,330	48,119	40,644	179,180	18,568	4,492	600,092	414,964	174,927	9,782	360
2088	17,611	48,867	41,392	186,655	18,942	4,492	605,804	418,913	176,592	9,875	363
2089	17,891	49,614	42,139	194,130	19,316	4,492	611,890	423,122	178,366	9,974	367
2090	18,172	50,362	42,887	201,605	19,689	4,492	618,349	427,588	180,249	10,079	371
2091	18,452	51,109	43,634	209,080	20,063	4,492	625,182	432,314	182,241	10,190	375
2092	18,733	51,857	44,382	216,555	20,437	4,492	632,389	437,297	184,342	10,308	379

Last of historical SNF generated before 2025 is taken out of power cooled storage (2058)

Gen III+ start to decommission at a rate of 25 per year starting in 2086. Gen IV increase to 50 new stations connected to compensate. From this point onwards, all new reactors are Gen IV only (2086)

Table P4.8. Scenario E – Generation IV reactors

Year	Electrical power generated by global nuclear fleet (TWh)	Annual mass of Spent Nuclear Fuel generated and put in powered underwater cooled storage (tonnes)	Annual mass of Spent Nuclear Fuel taken out of powered underwater cooled storage (tonnes)	Total mass of Spent Nuclear Fuel (SNF) in power cooled storage pools for 10 year cycle (tonnes)	Annual mass of Spent Nuclear Fuel put into long term storage, adjusting for SNF fuel tasked for fuel recycling (tonnes)	Fabrication of MOX fuel (tonnes)	Total Stockpile mass of SNF to be disposed of (tonnes)	Stable waste disposal of SNF (LLW) (tonnes)	Long term storage of SNF in near surface depth facilities (depth 30m) (VLLW) (tonnes)	Long term storage of SNF in intermediate depth facilities (depth 90-300m) (ILW) (tonnes)	Long term storage of SNF in deep underground geological repository facilities (depth 500-1000m) (HLW) (tonnes)
2093	19,014	52,604	45,129	224,030	20,811	4,492	639,970	442,539	186,551	10,432	384
2094	19,294	53,352	45,877	231,505	21,184	4,492	647,925	448,040	188,870	10,561	389
2095	19,575	54,099	46,624	238,980	22,058	4,992	656,753	454,145	191,443	10,705	394
2096	19,855	54,847	47,372	246,455	22,432	4,992	665,955	460,508	194,126	10,855	400
2097	20,136	55,594	48,119	253,930	22,806	4,992	675,530	467,129	196,917	11,011	405
2098	20,416	56,342	48,867	261,405	23,179	4,992	685,480	474,009	199,817	11,173	411
2099	20,697	57,089	49,614	268,880	23,553	4,992	695,803	481,148	202,827	11,342	417
2100	20,977	57,837	50,362	276,355	23,927	4,992	706,500	488,545	205,945	11,516	424
2101	21,258	58,584	51,109	283,830	24,301	4992	717,571	496,200	209,172	11,696	431
2102	21,538	59,332	51,857	291,305	24,674	4992	729,015	504,114	212,508	11,883	437
2103	21,819	60,079	52,604	298,780	25,048	4992	740,834	512,286	215,953	12,076	445
2104	22,099	60,827	53,352	306,255	25,422	4992	753,026	520,717	219,507	12,274	452
2105	22,380	61,574	54,099	313,730	26,296	5492	766,091	529,752	223,316	12,487	460
2106	22,851	62,830	54,847	321,714	26,161	5492	779,022	538,694	227,085	12,698	467
2107	23,132	63,578	55,594	329,697	26,348	5492	792,140	547,765	230,909	12,912	475
2108	23,412	64,325	56,342	337,680	26,535	5492	805,445	556,965	234,787	13,129	483
2109	23,693	65,073	57,089	345,663	26,722	5492	818,937	566,295	238,720	13,349	491
2110	23,973	65,820	57,837	353,647	26,909	5492	832,616	575,754	242,708	13,572	500
2111	24,254	66,568	58,584	361,630	27,096	5492	846,481	585,342	246,749	13,798	508
2112	24,535	67,315	59,332	369,613	27,282	5492	860,534	595,059	250,846	14,027	516
2113	24,815	68,063	60,079	377,597	27,469	5492	874,773	604,906	254,996	14,259	525
2114	25,096	68,810	60,827	385,580	27,656	5492	889,199	614,881	259,202	14,494	534
2115	25,376	69,558	61,574	393,563	28,343	5992	904,312	625,332	263,607	14,740	543
2116	25,657	70,305	62,830	401,038	29,038	5992	920,120	636,263	268,215	14,998	552
2117	25,937	71,053	63,578	408,513	29,225	5992	936,116	647,324	272,878	15,259	562
2118	26,218	71,800	64,325	415,988	29,412	5992	952,298	658,514	277,595	15,522	571
2119	26,498	72,548	65,073	423,463	29,599	5992	968,666	669,833	282,366	15,789	581
2120	26,779	73,295	65,820	430,938	29,786	5992	985,222	681,281	287,192	16,059	591
2121	27,059	74,043	66,568	438,413	29,973	5992	1,001,965	692,859	292,073	16,332	601
2122	27,340	74,790	67,315	445,888	30,159	5992	1,018,894	704,565	297,008	16,608	611
2123	27,621	75,538	68,063	453,363	30,346	5992	1,036,011	716,401	301,997	16,887	622
2124	27,901	76,285	68,810	460,838	30,533	5992	1,053,314	728,366	307,041	17,169	632
2125	28,182	77,033	69,558	468,313	31,220	6492	1,071,304	740,807	312,285	17,462	643
2126	28,462	77,780	70,305	475,788	31,407	6492	1,089,481	753,376	317,584	17,759	654
2127	28,743	78,528	71,053	483,263	31,594	6492	1,107,845	766,075	322,937	18,058	665
2128	29,023	79,275	71,800	490,738	31,781	6492	1,126,395	778,902	328,344	18,360	676
2129	29,304	80,023	72,548	498,213	31,968	6492	1,145,133	791,859	333,806	18,666	687
2130	29,584	80,770	73,295	505,688	32,154	6492	1,164,057	804,946	339,323	18,974	698
2131	29,865	81,518	74,043	513,163	32,341	6492	1,183,169	818,161	344,894	19,286	710
2132	30,145	82,265	74,790	520,638	32,528	6492	1,202,467	831,506	350,519	19,600	721
2133	30,426	83,013	75,538	528,113	32,715	6492	1,221,952	844,980	356,199	19,918	733
2134	30,706	83,760	76,285	535,588	32,902	6492	1,241,624	858,583	361,933	20,238	745

Table P4.9. Scenario E – Generation IV reactors

Year	Electrical power generated by global nuclear fleet (TWh)	Annual mass of Spent Nuclear Fuel generated and put in powered underwater cooled storage (tonnes)	Annual mass of Spent Nuclear Fuel taken out of powered underwater cooled storage (tonnes)	Total mass of Spent Nuclear Fuel (SNF) in power cooled storage pools for 10 year cycle (tonnes)	Annual mass of Spent Nuclear Fuel put into long term storage, adjusting for SNF fuel tasked for fuel recycling (tonnes)	Fabrication of MOX fuel (tonnes)	Total Stockpile mass of SNF to be disposed of (tonnes)	Stable waste disposal of SNF (LLW) (tonnes)	Long term storage of SNF in near surface depth facilities (depth 30m) (VLLW) (tonnes)	Long term storage of SNF in intermediate depth facilities (depth 90-300m) (ILW) (tonnes)	Long term storage of SNF in deep underground geological repository facilities (depth 500-1000m) (HLW) (tonnes)
2135	30,987	84,508	77,033	543,063	33,589	6992	1,261,983	872,661	367,868	20,570	757
2136	31,268	85,255	77,780	550,538	33,776	6992	1,282,529	886,869	373,857	20,905	770
2137	31,548	86,003	78,528	558,013	33,963	6992	1,303,261	901,205	379,901	21,243	782
2138	31,829	86,750	79,275	565,488	34,149	6992	1,324,181	915,671	385,999	21,584	795
2139	32,109	87,498	80,023	572,963	34,336	6992	1,345,287	930,266	392,151	21,928	807
2140	32,390	88,245	80,770	580,438	34,523	6992	1,366,580	944,990	398,358	22,275	820
2141	32,670	88,993	81,518	587,913	34,710	6992	1,388,060	959,844	404,620	22,625	833
2142	32,951	89,740	82,265	595,388	34,897	6992	1,409,727	974,826	410,936	22,979	846
2143	33,231	90,488	83,013	602,863	35,084	6992	1,431,581	989,938	417,306	23,335	859
2144	33,512	91,235	83,760	610,338	35,271	6992	1,453,622	1,005,180	423,731	23,694	872
2145	33,792	91,983	84,508	617,813	35,958	7492	1,476,349	1,020,896	430,356	24,064	886
2146	34,073	92,730	85,255	625,288	36,144	7492	1,499,264	1,036,741	437,035	24,438	900
2147	34,353	93,478	86,003	632,763	36,331	7492	1,522,365	1,052,716	443,769	24,815	913
2148	34,634	94,225	86,750	640,238	36,518	7492	1,545,653	1,068,819	450,558	25,194	927
2149	34,915	94,973	87,498	647,713	36,705	7492	1,569,129	1,085,052	457,401	25,577	941
2150	35,195	95,720	88,245	655,188	36,892	7492	1,592,791	1,101,415	464,298	25,962	956
2151	35,476	96,468	88,993	662,663	37,079	7492	1,616,639	1,117,906	471,250	26,351	970
2152	35,756	97,215	89,740	670,138	37,266	7492	1,640,675	1,134,527	478,257	26,743	984
2153	36,037	97,963	90,488	677,613	37,453	7492	1,664,898	1,151,277	485,318	27,138	999
2154	36,317	98,710	91,235	685,088	37,639	7492	1,689,307	1,168,156	492,433	27,536	1,014
2155	36,598	99,458	91,983	692,563	38,326	7992	1,714,404	1,185,510	499,749	27,945	1,029
2156	36,878	100,205	92,730	700,038	38,513	7992	1,739,687	1,202,993	507,119	28,357	1,044
2157	37,159	100,953	93,478	707,513	38,700	7992	1,765,157	1,220,606	514,543	28,772	1,059
2158	37,439	101,700	94,225	714,988	38,887	7992	1,790,814	1,238,348	522,022	29,190	1,074
2159	37,720	102,448	94,973	722,463	39,074	7992	1,816,658	1,256,219	529,556	29,612	1,090
2160	38,000	103,195	95,720	729,938	39,261	7992	1,842,688	1,274,219	537,144	30,036	1,106
2161	38,281	103,943	96,468	737,413	39,448	7992	1,868,906	1,292,348	544,786	30,463	1,121
2162	38,562	104,690	97,215	744,888	39,634	7992	1,895,310	1,310,607	552,483	30,894	1,137
2163	38,842	105,438	97,963	752,363	39,821	7992	1,921,902	1,328,995	560,234	31,327	1,153
2164	39,123	106,185	98,710	759,838	40,008	7992	1,948,680	1,347,512	568,040	31,763	1,169
2165	39,403	106,933	99,458	767,313	40,695	8492	1,976,145	1,366,504	576,046	32,211	1,186
2166	39,684	107,680	100,205	774,788	40,882	8492	2,003,797	1,385,626	584,107	32,662	1,202
2167	39,964	108,428	100,953	782,263	41,069	8492	2,031,636	1,404,876	592,222	33,116	1,219
2168	40,245	109,175	101,700	789,738	41,256	8492	2,059,662	1,424,256	600,391	33,572	1,236
2169	40,525	109,923	102,448	797,213	41,443	8492	2,087,874	1,443,765	608,615	34,032	1,253
2170	40,806	110,670	103,195	804,688	41,629	8492	2,116,274	1,463,403	616,894	34,495	1,270
2171	41,086	111,418	103,943	812,163	41,816	8492	2,144,860	1,483,171	625,227	34,961	1,287
2172	41,367	112,165	104,690	819,638	42,003	8492	2,173,633	1,503,067	633,614	35,430	1,304
2173	41,648	112,913	105,438	827,113	42,190	8492	2,202,593	1,523,093	642,056	35,902	1,322
2174	41,928	113,660	106,185	834,588	42,377	8492	2,231,740	1,543,248	650,552	36,377	1,339
2175	42,209	114,408	106,933	842,063	43,064	8992	2,261,574	1,563,879	659,249	36,864	1,357
2176	42,489	115,155	107,680	849,538	43,251	8992	2,291,595	1,584,638	668,000	37,353	1,375

Table P4.10. Scenario E – Generation IV reactors

Year	Electrical power generated by global nuclear fleet	Annual mass of Spent Nuclear Fuel generated and put in powered underwater cooled storage	Annual mass of Spent Nuclear Fuel taken out of powered underwater cooled storage	Total mass of Spent Nuclear Fuel (SNF) in power cooled storage pools for 10 year cycle	Annual mass of Spent Nuclear Fuel put into long term storage, adjusting for SNF fuel tasked for fuel recycling	Fabrication of MOX fuel	Total Stockpile mass of SNF to be disposed of	Stable waste disposal of SNF (LLW)	Long term storage of SNF in near surface depth facilities (depth 30m) (VLLW)	Long term storage of SNF in intermediate depth facilities (depth 90-300m) (ILW)	Long term storage of SNF in deep underground geological repository facilities (depth 500-1000m) (HLW)
	(TWh)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)
2177	42,770	115,903	108,428	857,013	43,438	8992	2,321,802	1,605,526	676,805	37,845	1,393
2178	43,050	116,650	109,175	864,488	43,624	8992	2,352,197	1,626,544	685,665	38,341	1,411
2179	43,331	117,398	109,923	871,963	43,811	8992	2,382,778	1,647,691	694,580	38,839	1,430
2180	43,611	118,145	110,670	879,438	43,998	8992	2,413,546	1,668,967	703,549	39,341	1,448
2181	43,892	118,893	111,418	886,913	44,185	8992	2,444,502	1,690,373	712,572	39,845	1,467
2182	44,172	119,640	112,165	894,388	44,372	8992	2,475,644	1,711,907	721,650	40,353	1,485
2183	44,453	120,388	112,913	901,863	44,559	8992	2,506,972	1,733,571	730,782	40,864	1,504
2184	44,733	121,135	113,660	909,338	44,746	8992	2,538,488	1,755,365	739,969	41,377	1,523
2185	45,014	121,883	114,408	916,813	45,433	9492	2,570,691	1,777,633	749,356	41,902	1,542
2186	45,295	122,630	115,155	924,288	45,619	9492	2,603,080	1,800,030	758,798	42,430	1,562
2187	45,575	123,378	115,903	931,763	45,806	9492	2,635,656	1,822,556	768,294	42,961	1,581
2188	45,856	124,125	116,650	939,238	45,993	9492	2,668,420	1,845,212	777,844	43,495	1,601
2189	46,136	124,873	117,398	946,713	46,180	9492	2,701,370	1,867,997	787,449	44,032	1,621
2190	46,417	125,620	118,145	954,188	46,367	9492	2,734,507	1,890,911	797,109	44,572	1,641
2191	46,697	126,368	118,893	961,663	46,554	9492	2,767,831	1,913,955	806,823	45,116	1,661
2192	46,978	127,115	119,640	969,138	46,741	9492	2,801,341	1,937,128	816,591	45,662	1,681
2193	47,258	127,863	120,388	976,613	46,928	9492	2,835,039	1,960,429	826,414	46,211	1,701
2194	47,539	128,610	121,135	984,088	47,114	9492	2,868,923	1,983,861	836,291	46,763	1,721
2195	47,819	129,358	121,883	991,563	47,301	9492	2,902,995	2,007,421	846,223	47,319	1,742
2196	48,100	130,105	122,630	999,038	47,488	9492	2,937,253	2,031,110	856,209	47,877	1,762
2197			123,378	904,038			3,060,631	2,116,426	892,174	49,888	1,836
2198			124,125	809,038			3,184,756	2,202,258	928,356	51,912	1,911
2199			124,873	714,038			3,309,628	2,288,608	964,757	53,947	1,986
2200			125,620	619,038			3,435,248	2,375,474	1,001,375	55,995	2,061
2201			126,368	524,038			3,561,616	2,462,857	1,038,211	58,054	2,137
2202			127,115	429,038			3,688,731	2,550,757	1,075,265	60,126	2,213
2203			127,863	334,038			3,816,593	2,639,174	1,112,537	62,210	2,290
2204			128,610	239,038			3,945,203	2,728,108	1,150,027	64,307	2,367
2205			129,358	144,038			4,074,561	2,817,559	1,187,735	66,415	2,445
2206			130,105	130,105			4,204,666	2,907,527	1,225,660	68,536	2,523
2207			0	0							

46 APPENDIX Q – BIOPLASTICS PROPERTIES & DATA

This appendix is a compilation of useful statistics for only some of the bioplastics being manufactured, which could substitute petrochemical manufactured plastics.

Starch Plastics

Table Q.1 Overview of starch use for food and non-food purposes in Europe in 2007 (Shen et al 2009)

Sector	Consumption		
	10^6 tonnes	(%) total	% (of non-food, non-fuel)
Food/Feed, Total *	5.6	50%	-
Confectionary & drinks	2.9	26%	-
Processed food	2.6	23%	-
feed	0.1	1%	-
Non-food (without starch for ethanol used as fuel, Total *	3.7	33%	100%
Corrugating & paper making	2.6	23%	70%
Pharmaceutical & chemcials	0.7	6%	19%
Other non-food	0.4	4%	11%
Fuel ethanol **	1.9	17%	-
Total	11.2	100%	-

* Data source AFF (2009)

** Estimate done in (Shen et al 2009)

Table Q.2. Properties and uses of various chemical modified corn starch (Shen et al 2009)

Type	Distinguished properties	Common commercial non-food use
Acid-modified	Decreased hot-paste viscosity compared to unmodifed starches	Textile sizing agents; as binding materials in cardboard making
Cross-linkeded	Reduced peak viscosity, increased paste stability	Ingredients in antiperspirants and textile printing paste; as oil-well drilling muds, printing ink, charcoal briquette binders, fiberglass sizing, and textile sizing.
Acetylated (ester)	Excellent paste clarity and stability, good freeze - thaw stability; hydrophobic for high degree of substitution starch acetate	Low degree of substitution:Warp sizing in textile; forming sizes, and surface sizes in paper making. High degree of subsitution: thermoplastic molding and in films as plasticizer.
Phosphate, monoesters (ester)	Reduced gelatinization temperature, reduced retrogradation	Wet-end additives in paper making; sizes in textile (polyester) and thickeners in textile printing inks.
Hydroxypropyl (ester)	Increased paste clarity, reduced retrogradation, good freeze - thaw stability	Surface sizing and wet ends in paper making; low DS starch ethers are used as warp sizing in textiles.

Table Q.3. Properties of selected starch plastics (Source: Shen et al 2009)

Type of Plastics	Partially fermented starch	TPS	Starch Blends						For Comparison
Product name and type	Solanyl ® BP [1]	Bioplast TPS® [1]	Mater-Bi ® Y101U [2]	Mater-Bi ® ZF03U/A [2]	Bioplast GF106 [1]	Bioplast GF105/30 [3]	BIOPAR ® [1, 4]	Cereplast Hybrid resin [5]	
Polymer	Starch	Starch	Starch - cellulose acetate	Starch - PCL	Starch - copolymer	Starch - copolymer	Starch - copolymer	Starch - PP	LDPE [6]
Resin grade	Injection moulding		Injection moulding	Film	Film	Film	Film	Injection moulding - PP	Film
Melt flow rate (g / 10 min)			8	4.7	1 - 6	5 - 9	2 - 7	3 - 6	
Density (g/cm^3)	1.29	1.3 - 1.5	1.34	1.23	1.2 - 1.3	1.21	1.26 - 1.29	1.04	0.92
Tensile strength at yield (MPa)	24		26	31	20 - 35	38 (TD) 44 (MD)	20 - 30	16.6	20 - 25
Elongation at yield (%)			27	900	500 - 900	400 - 500	300 - 1200	9.5	400 - 700
Flexural Modulus (MPa)	1730		1700	185			25 - 600	965	
HDT (^{0}C)								60	
VICAT Softening point (^{0}C)	52.9								
Melting Point (^{0}C)				64					110
Biodegradable (Yes/No)	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No
Bio-ba/Partially/Fully)	Fully	Fully	Fully	Partially	Partially	Partially	Partially	No	No

[1] Widdecke et al 2008, [2] Degli Innocenti 2008, [3] Biotec 2003, [4] BIOP 2008, [5] Cereplast 2008, [6] Schmitz & Janocha 2002

Cellulosic Polymers

Table Q.4. Major areas of applications in which the individual product groups of cellulose ethers are used (Shen et al 2009, Theilking & Schmidt 2006)

Carboxymethyl cellulose (CMC)	Methyl cellulose (MC), hydroxyalkyl methyl cellulose (HMC)	Hydroxyethyl cellulose (HEC)	Hydroxypropyl cellulose (HPC)
Paper	Tile adhesives	Latex paints	Adhesives
Detergents	Plaster/renders	Adhesives	Ceramics
Drilling for oil and gas	Pharma/cosmetics	Buildings materials	Cosmetics
Pharma	Joint compounds	Cosmetics	Encapsulation
Cosmetics	Wallpaper paste	Drilling for oil and gas	Food
Textile industry	Polymerisation	Agriculture	Household goods
Food	Food	paper	Printing inks
Coatings	Latex paints	Synthetic resins	Polymerisation
Encapsulation	Cement extrusion	Textile industry	Films

Table Q.5. Mechanical, thermal and water retention of selected staple fibres (Shen et al 2009)

Fibre name	Trade name	Density (g/cm^3)	Tenacity [a] (wet) (cN/tex)	Tenacity [a] (dry) (cN/tex)	Water retention (%)	Melting poin (^0C)
Cotton		1.5 - 1.54 [1)]	26 - 40 [2)]	24 - 36	38 - 45 [3)]	n/a
Viscose	Lenzing Viscose	1.52 - 1.54 [1)]	10 - 13 [2)]	24 - 26	90 - 100 [3)]	n/a
Modal	Lenzing Modal	1.52 - 1.54 [1)]	19 -21 [2)]	34 - 36	60 - 65 [3)]	n/a
Lyocell	Tencel	1.50 [1)]	34 - 36 [2)]	40 - 42	60 - 70 [3)]	n/a [b]
Cellulose acetate	Arnel, Celco, Dicel	1.29 - 1.32 [1)]	10 -15 [1)]	20 - 30 [1)]	n/a	255 [1)]
PET [1)]	Dacron	1.36 - 1.41	30 - 55	28 - 55	03-May	250 - 260
PP [1)]	Herculon	0.9 - 0.92	25 - 60	25 - 60	0	160 - 175
PLA [4)]	Ingeo	1.25	n/a [b]	32 - 36	n/a [b]	170

Notes: 1) Schultze-Gebhardt & Herlinger 2002, 2) Abu-Rous & Schuster 2006, 3) Lenzing AG 2006, 4) NatureWorks LLC 2006

[a] Tenacity is expressed realtive to the fineness (1 tex = 1 gram per 1000 metres). Numbers for tenacity are based on both fiber fineness (tex) and cross-sectional area of the sample.

[b] n/a = data not available or not applicable

Table Q.6. Mechanical, thermal, and permeability properties of selected films (Schmitz & Janocha 2002)

Property	Units	Cellulose (uncoated)	Cellulose acetate [a]	LDPE [c]	HDPE [c]	OPP [c]
Thickness	µm	12 - 45	12 - 350	25 - 200	50 - 1000	4 - 80
Density	g/cm^3	1.45	1.3	0.92	0.95	0.91
Modulus of elasticity						
logitudinal	N/mm^2	5 300	1 500	170	900	2 000
lateral	N/mm^2	2 800	1 500	170	900	4 000
Melting point	^0C	n/a[b]	n/a[b]	110	130	165
Permeability						
water vapour	$g/m^2/d$	very high	350	2.5	1	1.5
oxygen [d]	$cm^3/m^2/d/bar$	10	1 500	4 000	1 600	600
CO_2 [d]	$cm^3/m^2/d/bar$	100	10 000	16 000	7 000	1 800
nitrogen [e]	$cm^3/m^2/d/bar$	12	300	1 300	400	140

[a] cellulose acetate film containing plasticiser

[b] n/a = not applicable

[c] LDPE = low density polyethylene; HDPE = high density polyethylene; OPP = oriented polypropylene

[d] Film thickness = 40 µm, 23 ^0C

[e] Film thickness = 200 µm

Polylactic acid (PLA)

Table Q.7. Properties of NatureWorks® PLA polymers (NatureWorks LLC, 2008)

Used in the Application	Sheet Extrusion	Injecton Moulding	Oriented Film		Blow Moulded Bottles	
Polymer type	2002D polymer	3015D resin	4032D film	4042D film	7000D Bottle	7032D Bottle
Density (g/cm^3)	1.24 [b]	1.25 [b]	1.24 [c]	1.24 [c]	1.24 [b]	1.24 [b]
Melt flow rate, (g/10 min) (210 ^{0}C/2.16 kg) [d]	5 - 7	10 - 25	- [m]	-	5 - 15	5 - 15
Colour	Transp.	Transp.	-	-	-	-
Haze [e]	-	-	2.1%	2.1%	-	-
Gloss, 20^0 [e]	-	-	90	90	-	-
T_g (^{0}C)	-	55 - 65 [f]	-	135 [g]	55 - 60 [f]	55 - 60 [f]
T_m (^{0}C)	Amorphous no T_m	150 - 165 [g]	160 [e]	150 [e]	145 - 155 [g]	160 [g]
Tensile strength @ break (Mpa)	53 [h]	48 [i]	103 (MD) [h] 144 (TD) [h]	110 (MD) [h] 144 (TD) [h]	-	-
Tensile Modulus (GPa)	3.5 [h]	-	3.4 (MD) [h] 3.8 (TD) [h]	3.3 (MD) [h] 3.9 (TD) [h]	-	-
Tensile Elongation (%)	6.0 [h]	2.5 [i]	180 (MD) [h] 100 (TD) [h]	160 (MD) [h] 100 (TD) [h]	-	-
Flexural Strength (Mpa)	-	83 [j]	-	-	-	-
Flexural Modulus (Mpa)	-	3828 [j]	-	-	-	-
Transmission Rates	-					
O_2 (cc-mil/m^2 /24h atm)	-	-	550 [k]	550 [k]	-	550 [k]
CO_2 (cc-mil/m^2 /24h atm)	-	-	3000 [k]	3000 [k]	-	3000 [k]
Water vapour (g-mil/m^2/24h atm)	-	-	325 [k]	325 [k]	-	325 [k]

[a] Refer to NatureWorks® PLA processing guide (sheet extrusion, injection moulding, oriented film extrusion & blow moulding); [b] Testing method: ASTM D792; [c] Testing method: ASTM1505; [d] Testing method: ASTM D1238; [e] Testing method: ASTM 1003; [f] Testing method: ASTM D3417; [g] Testing method: ASTM D3418; [h] Testing method: ASTM D882; **MD** means polymer orientation in machine direction; **TD** means polymer orientation in transverse direction; [i] Testing method: ASTM D638; [j] Testing method: ASTM D790; [k] Testing method: ASTM D1434; [l] Testing method: ASTM E96; [m] data not available, not reported or not applicable.

Table Q.8. Thermal properties of amorphous versus crystalline and stereocomplex PLA (with courtesy to PURAC 2008)

Property	Amorphous PLA	Crystalline PLA	Stereocomplex PLA (50/50)
T_g (^{0}C)	55 - 60	55 - 60	60 - 70
T_m (^{0}C)	-	160 - 170	200 - 240
HDT (@0.45 MPa, ^{0}C)	55 - 60	100 - 150	160 - 200

47 APPENDIX R – U.S. MANUFACTURING ENERGY FOOTPRINT

This appendix is a compilation of the energy consumption requirements for the United States manufacturing sector. These flowsheets were released by the U.S. Department of Energy in 2018, using 2014 data (U.S. Department of Energy 2014).

- All Manufacturing
- Alumina and Aluminum
- Cement
- Chemicals
- Computers, Electronics and Electrical Equipment
- Fabricated Metals
- Food and Beverage
- Forest Products
- Foundries
- Glass
- Iron and Steel
- Machinery
- Petroleum Refining
- Plastics
- Textiles
- Transportation Equipment

Each footprint presents data at two levels of detail. The first page provides a high-level view of supply and end use (primary energy use), while the second page shows details of how energy is distributed to onsite end uses. The analyses are based on manufacturing energy consumption data from EIA's Manufacturing Energy Consumption Survey (MECS) data for 2014, along with referenced energy loss and emission factors, and input from industry and subject matter experts.

Footprints show aggregate data for each sector, including:

- Electricity and steam generated offsite and transferred to the facility, as well as electricity and steam generated onsite
- Fuel, electricity, and steam consumed by major end uses in a manufacturing facility
- Offsite and onsite energy losses due to the generation, transmission, and distribution, and end use consumption of energy (some losses are unrecoverable)
- GHG emissions released during the combustion of fuel

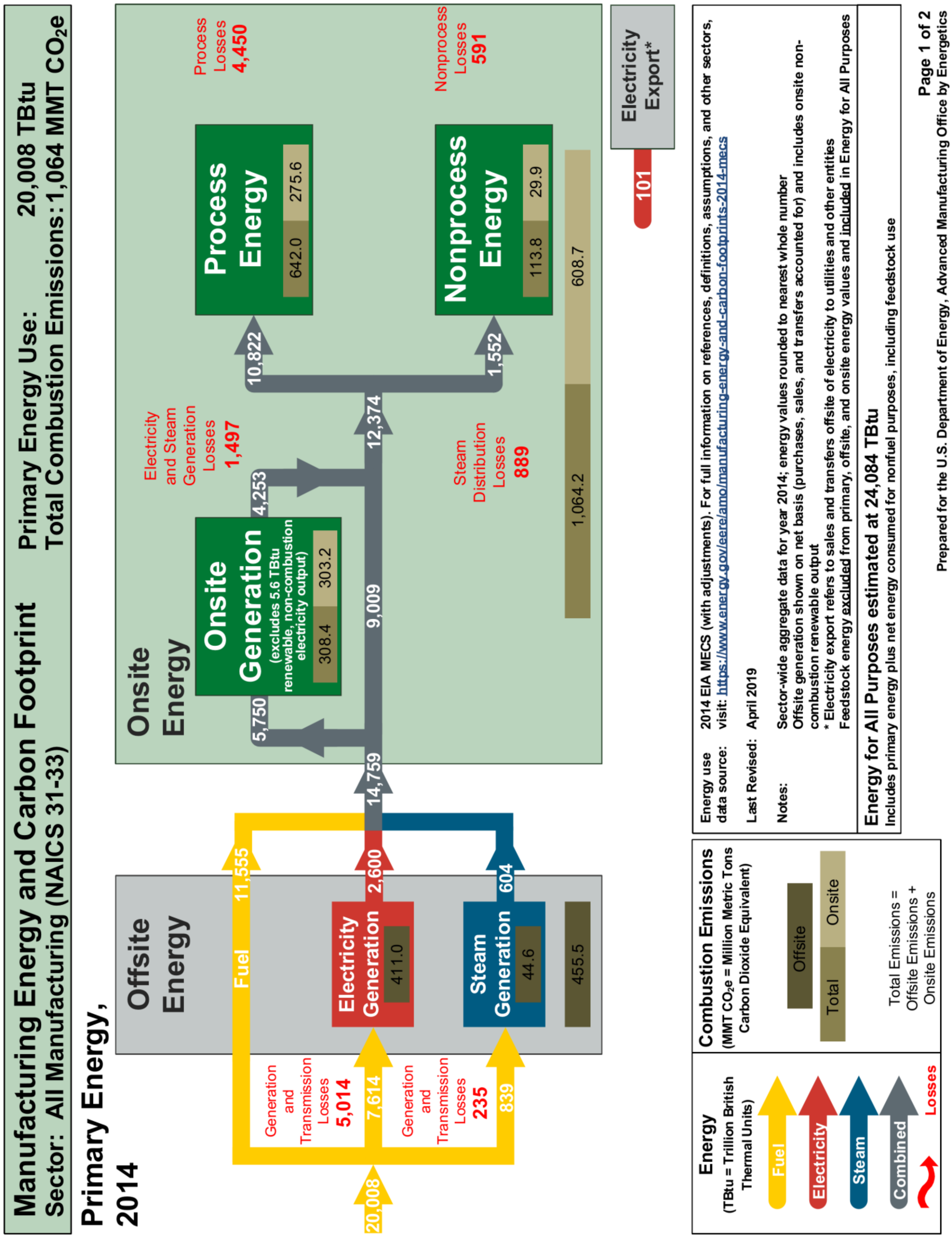


Figure R1. Manufacturing energy Onsite energy use of all manufacturing in the US, combines the footprints of 94% of manufacturing energy used for: Alumina and aluminum, cement, chemicals, computers, electronics, electrical equipment, fabricated metals, food and beverage, forest products, foundries, glass, iron and steel, machinery, petroleum refining, plastics, textiles, transportation equipment. Part 1 (US DoE 2014) (Copyright License: https://www.energy.gov/about-us/web-policies)

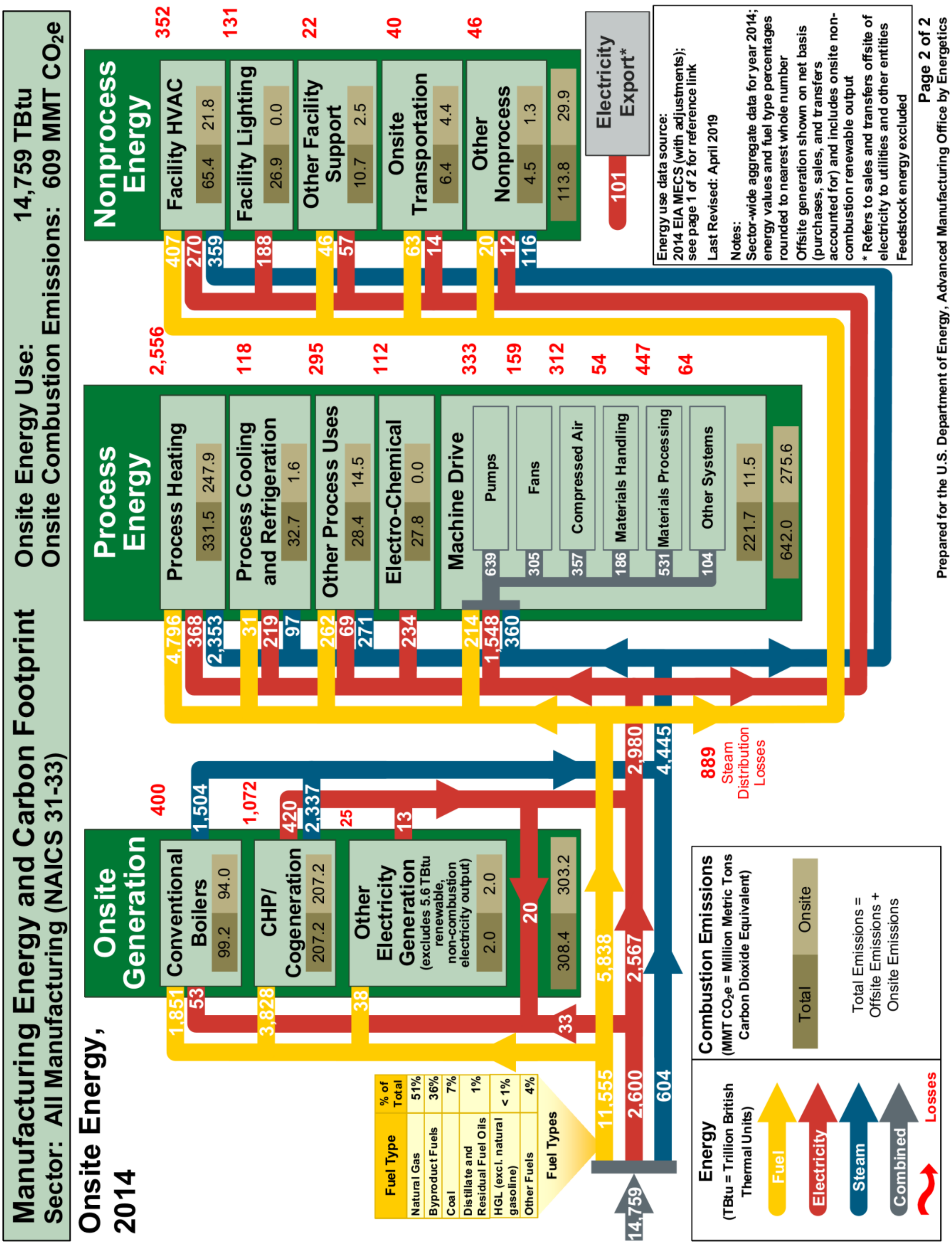


Figure R2. Manufacturing energy Onsite energy use of all manufacturing in the US, combines the footprints of 94% of manufacturing energy used for: Alumina and aluminum, cement, chemicals, computers, electronics, electrical equipment, fabricated metals, food and beverage, forest products, foundries, glass, iron and steel, machinery, petroleum refining, plastics, textiles, transportation equipment. Part 2 (US DoE 2014) (Copyright License: https://www.energy.gov/about-us/web-policies)

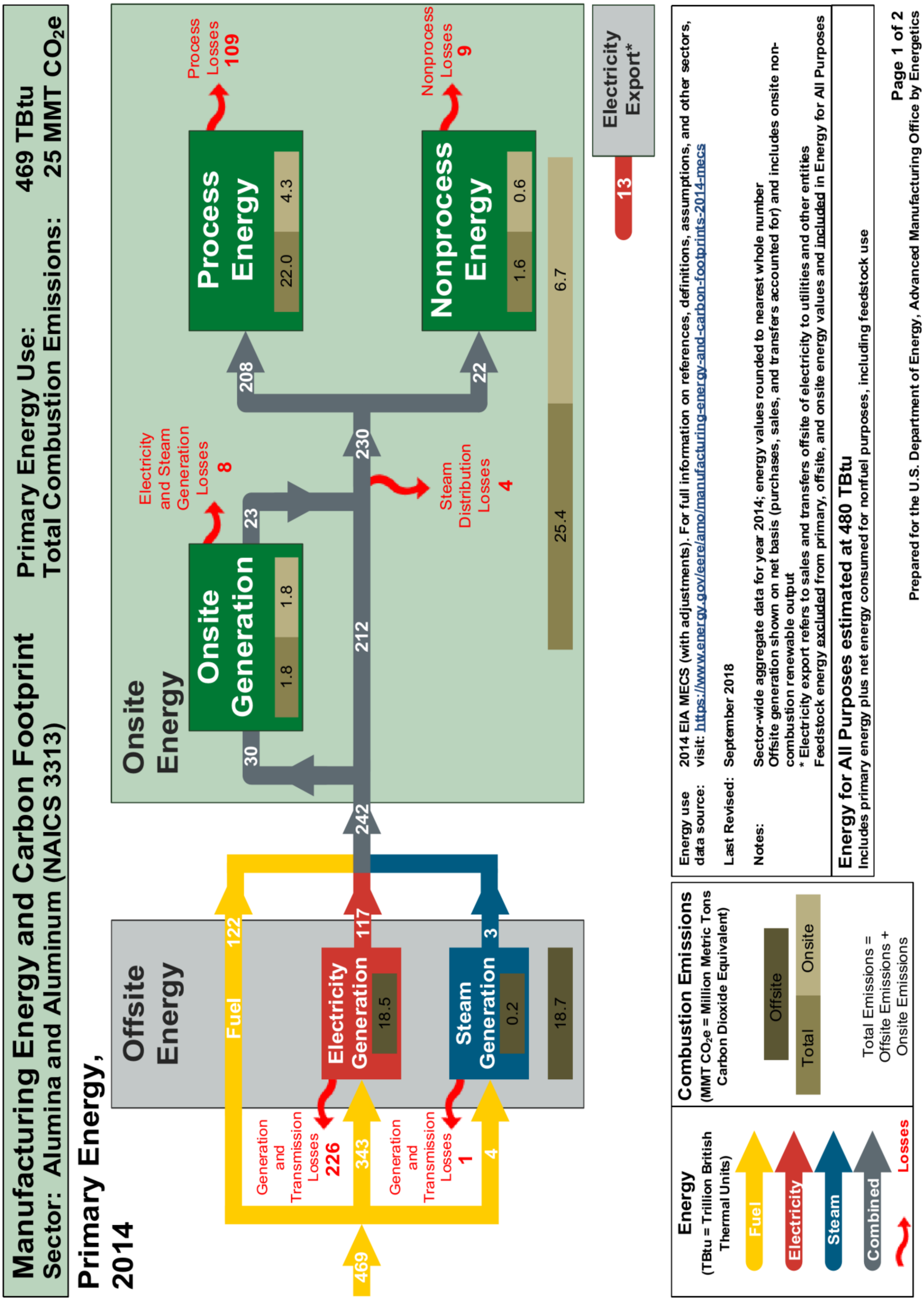


Figure R3. Manufacturing energy – Alumina and Aluminium – Part 1 (US DoE 2014)

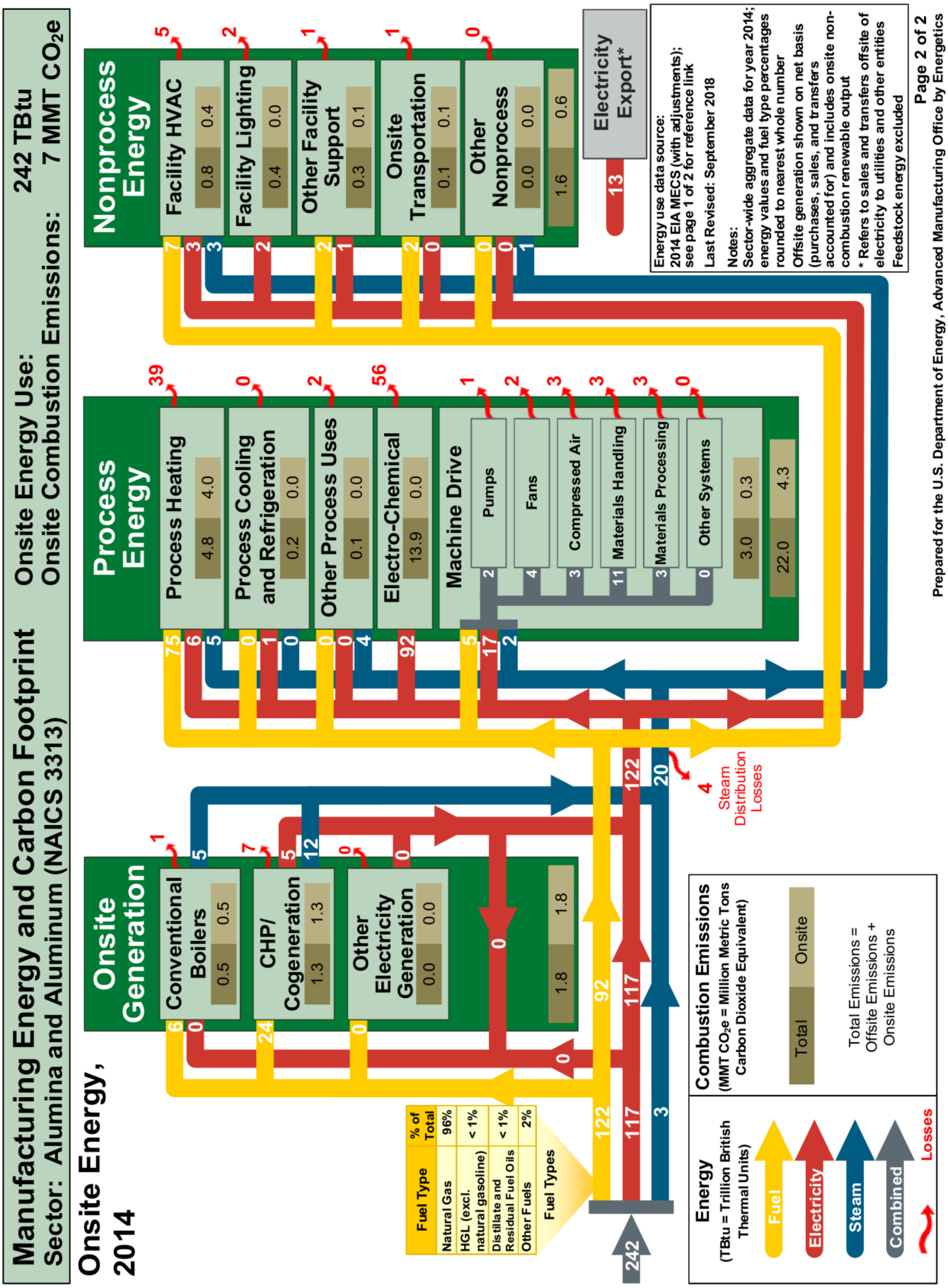


Figure R4. Manufacturing energy – Alumina and Aluminium – Part 2 (US DoE 2014)
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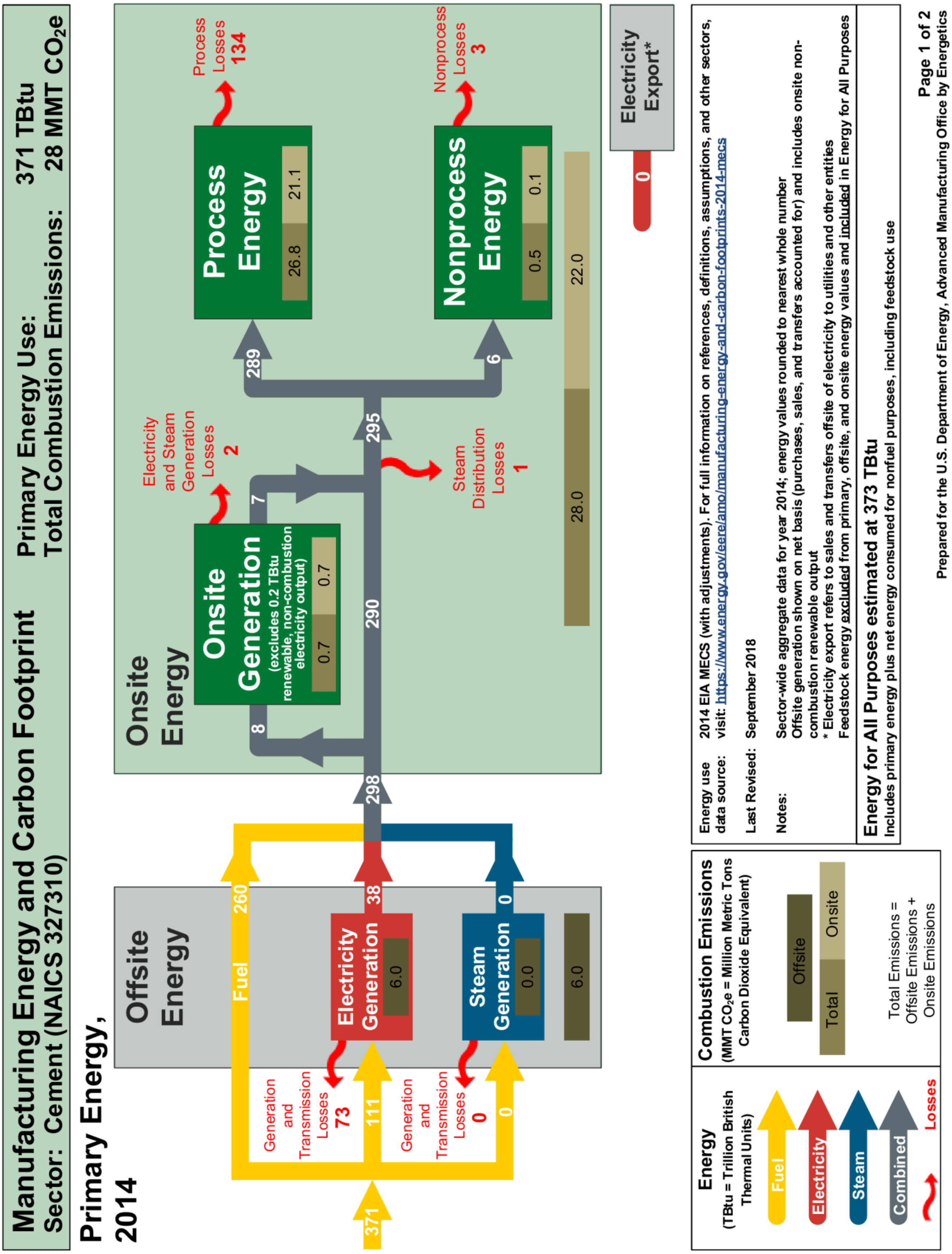

Figure R5. Manufacturing energy – Cement– Part 1 (US DoE 2014)
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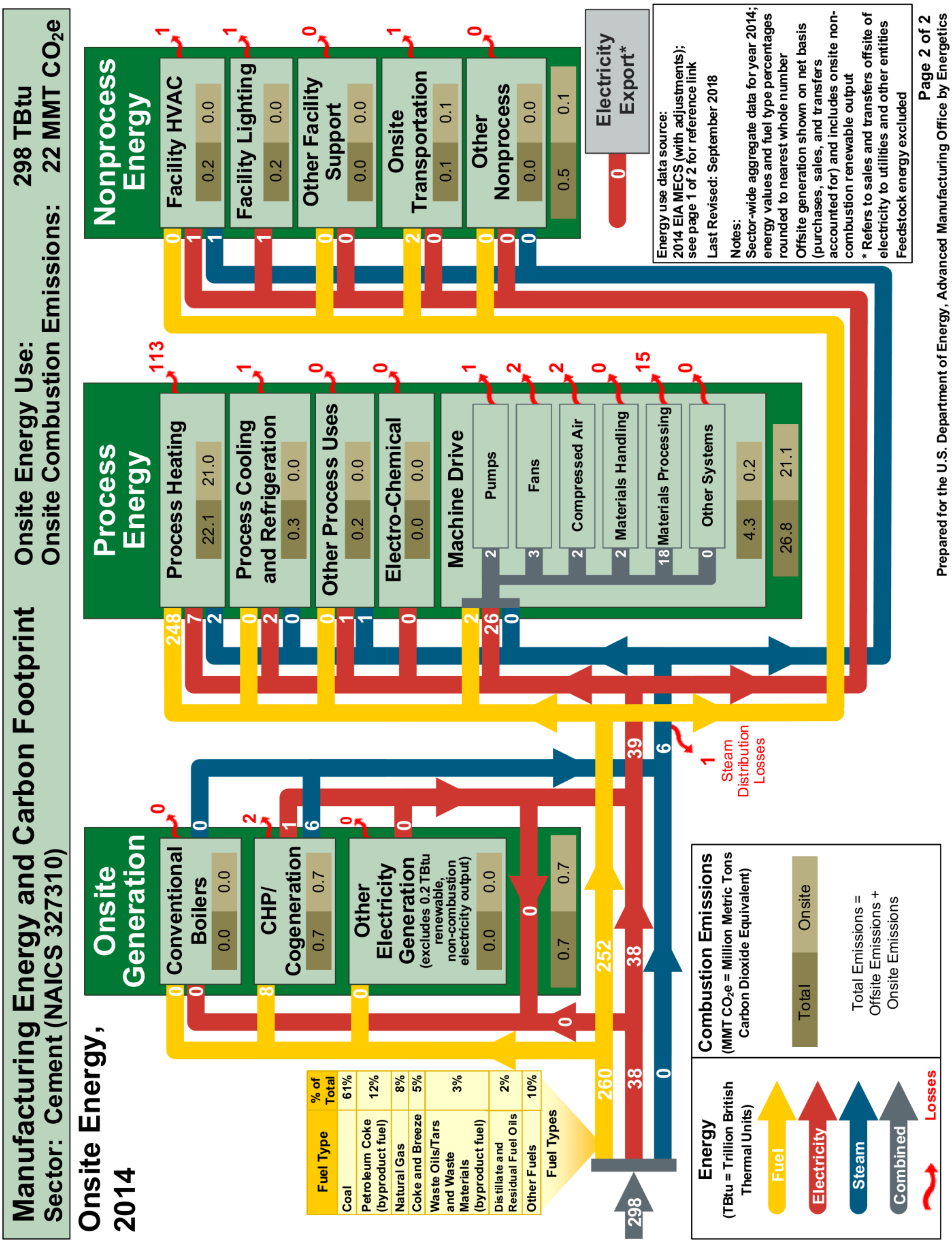

Figure R6. Manufacturing energy – Cement – Part 2 (US DoE 2014)
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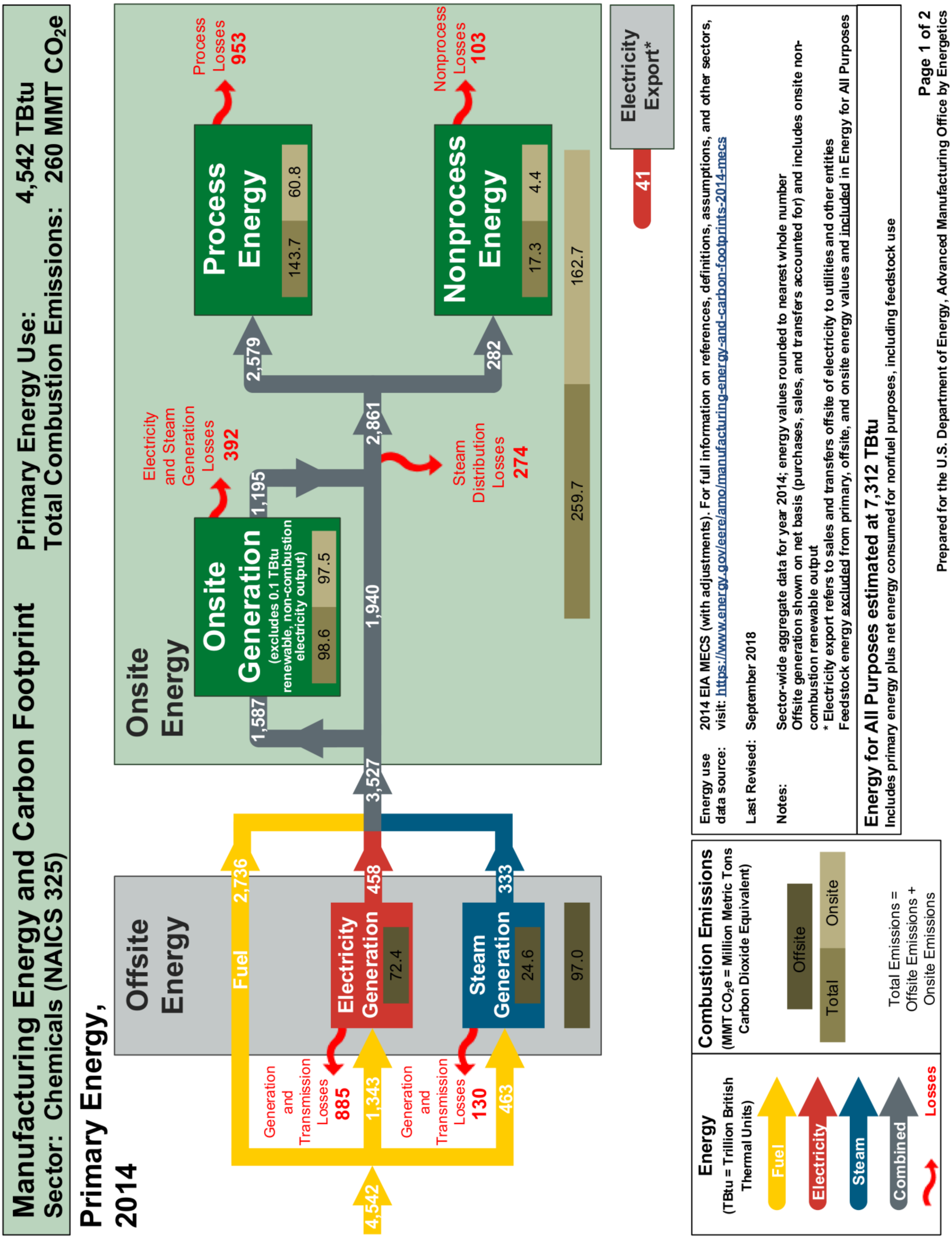

Figure R7. Manufacturing energy – Chemicals – Part 1 (US DoE 2014)
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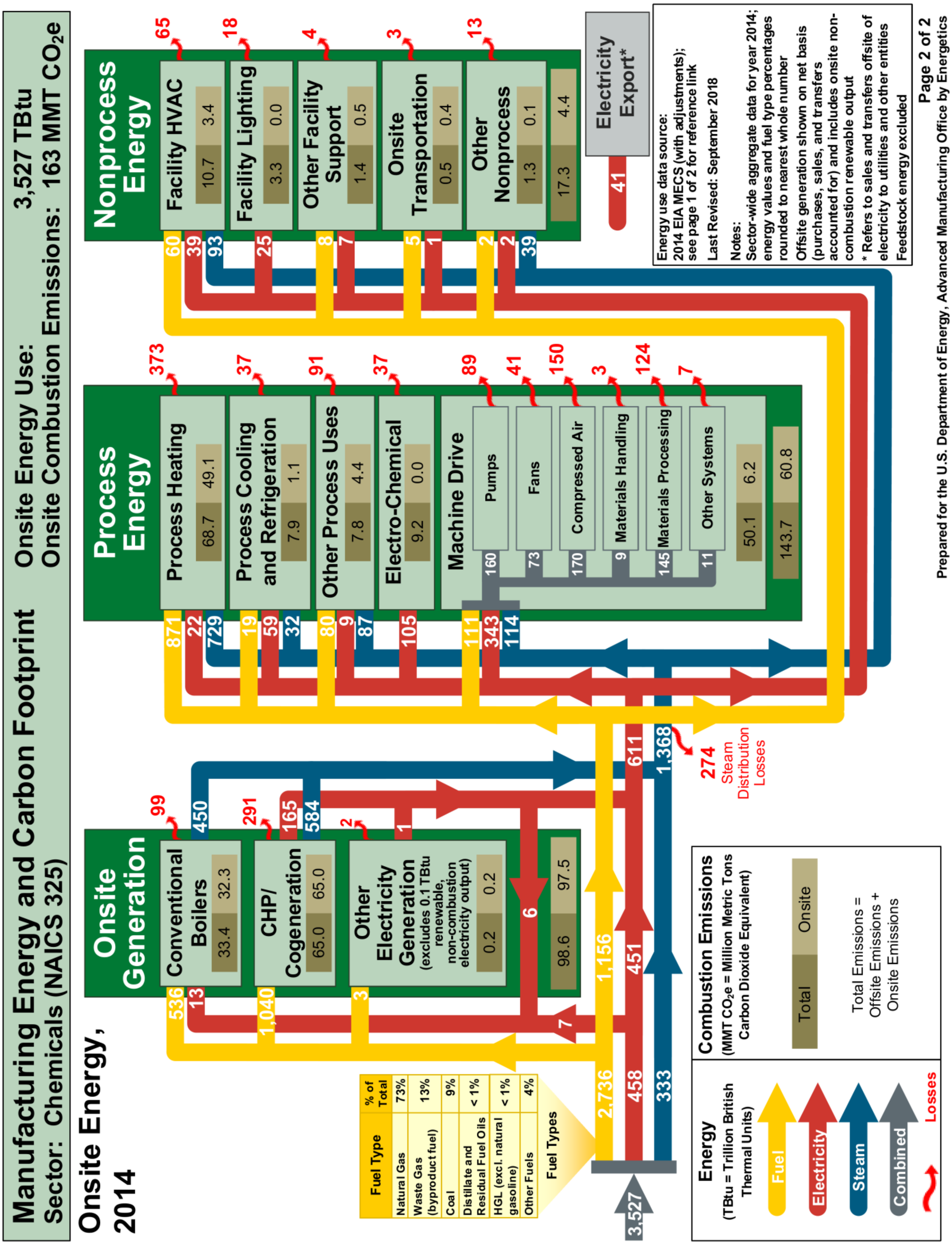

Figure R8. Manufacturing energy – Chemicals – Part 2 (US DoE 2014)
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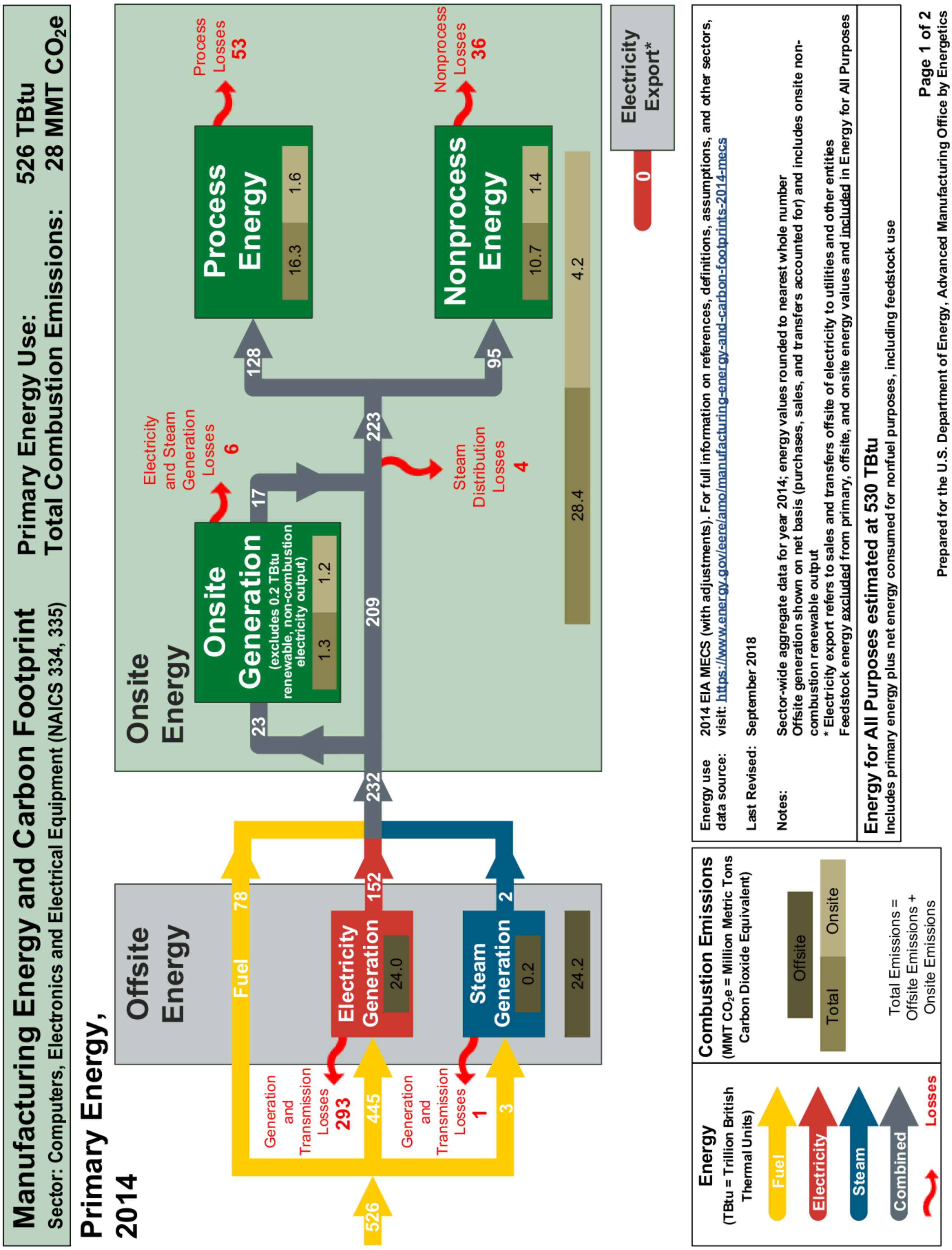

Figure R9. Manufacturing energy – Computers, Electronics and Electrical Equipment– Part 1 (US DoE 2014)
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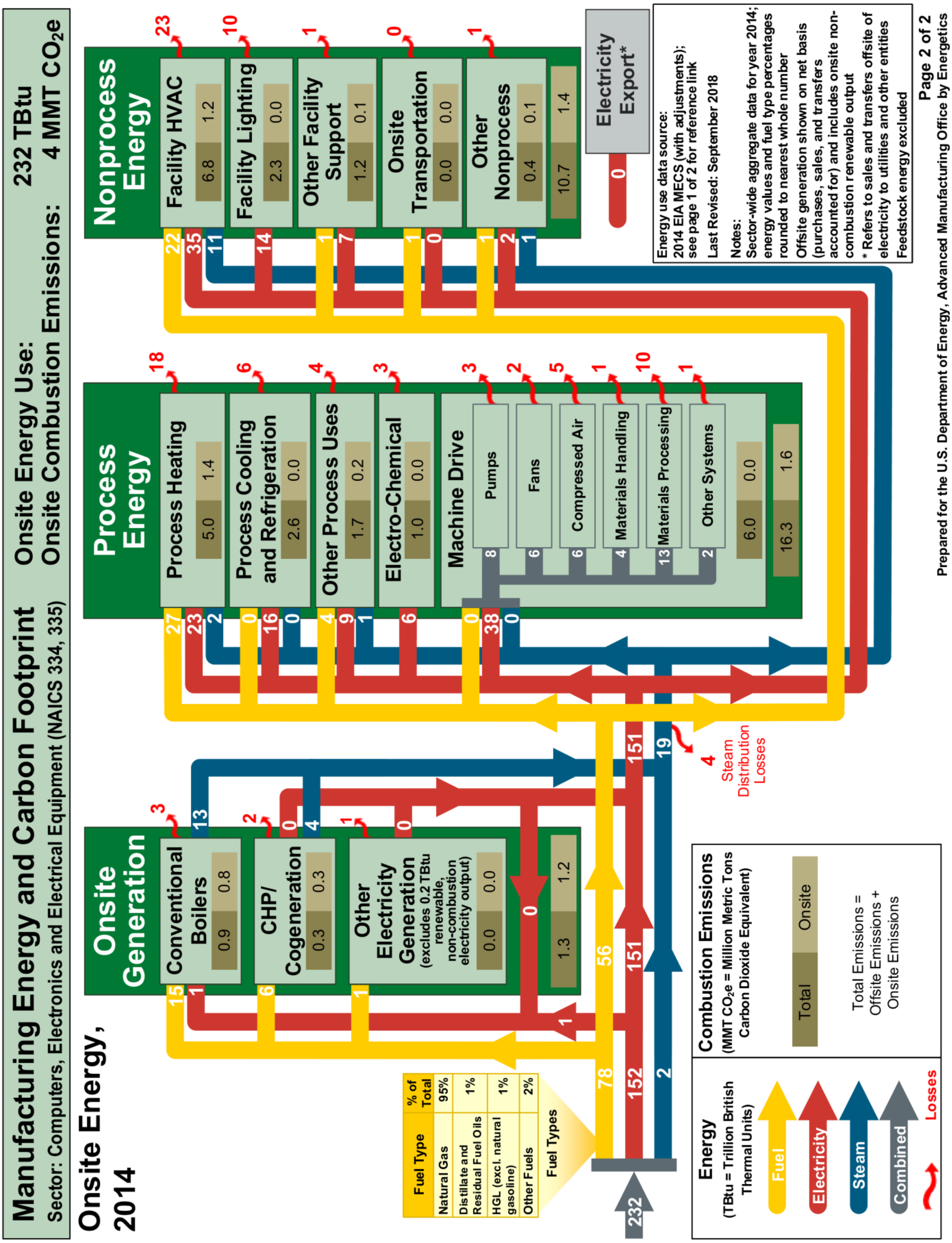

Figure R10. Manufacturing energy – Computers, Electronics and Electrical Equipment– Part 2 (US DoE 2014)
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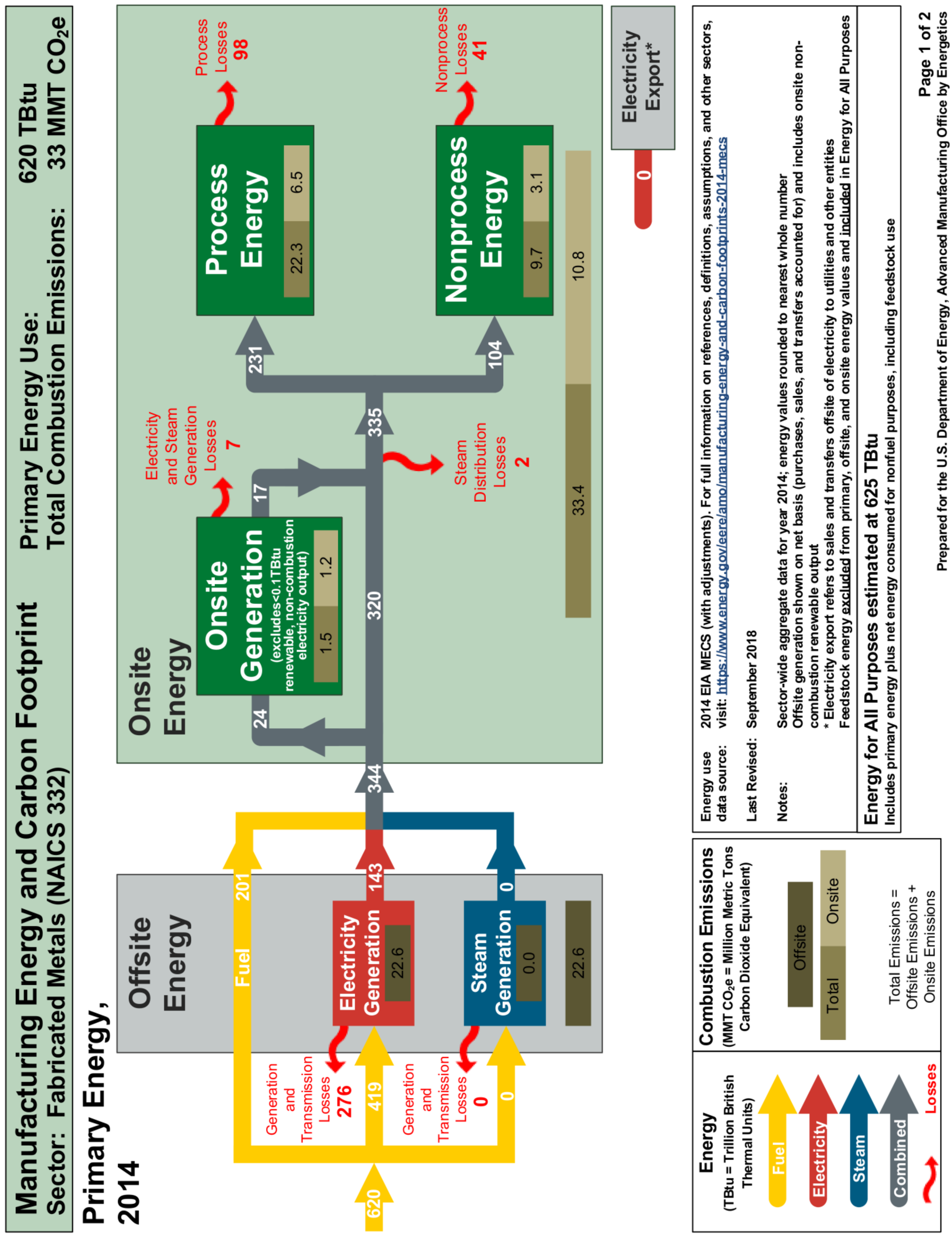

Figure R11. Manufacturing energy – Fabricated Metals – Part 1 (US DoE 2014)
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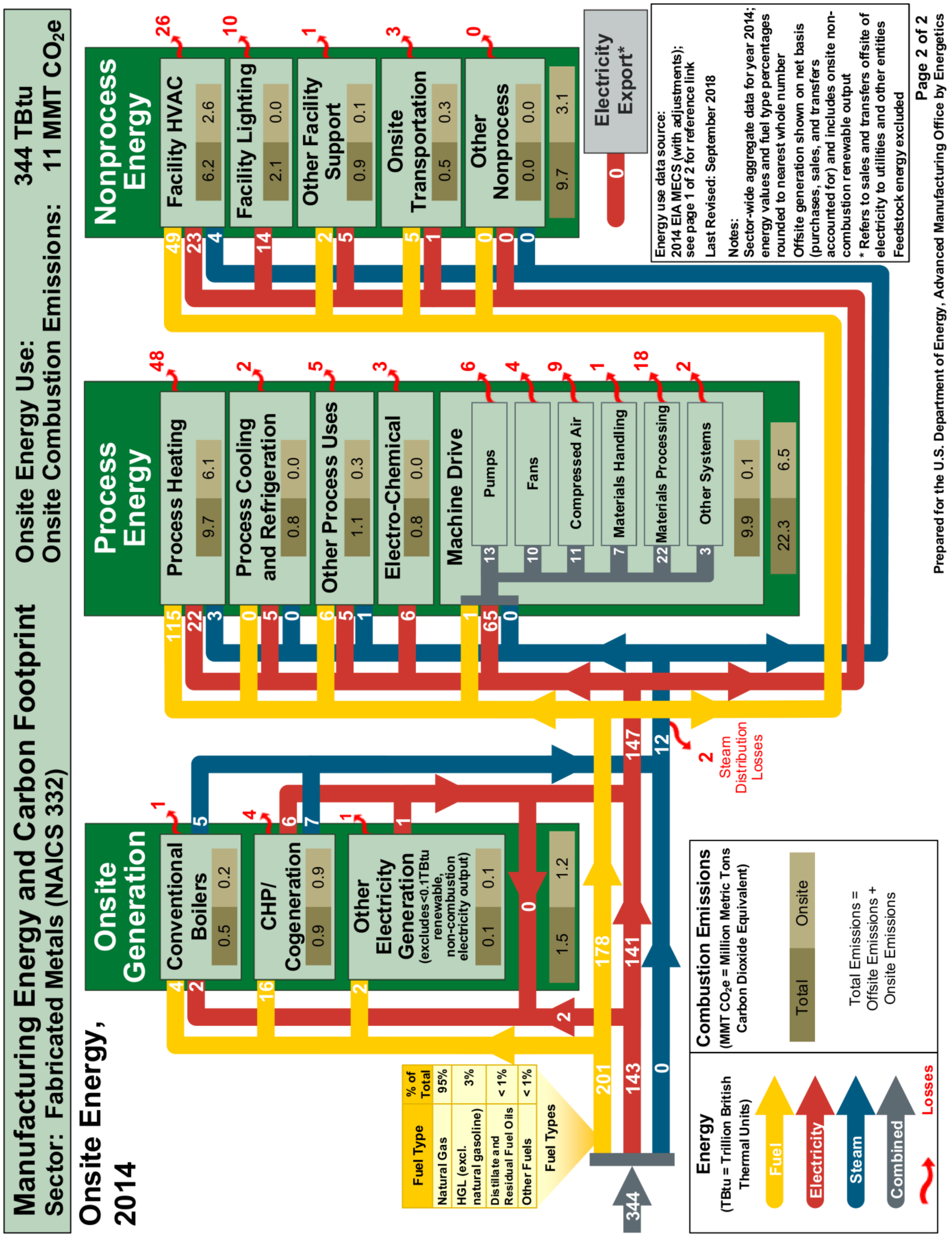

Figure R12. Manufacturing energy – Fabricated Metals – Part 2 (US DoE 2014)
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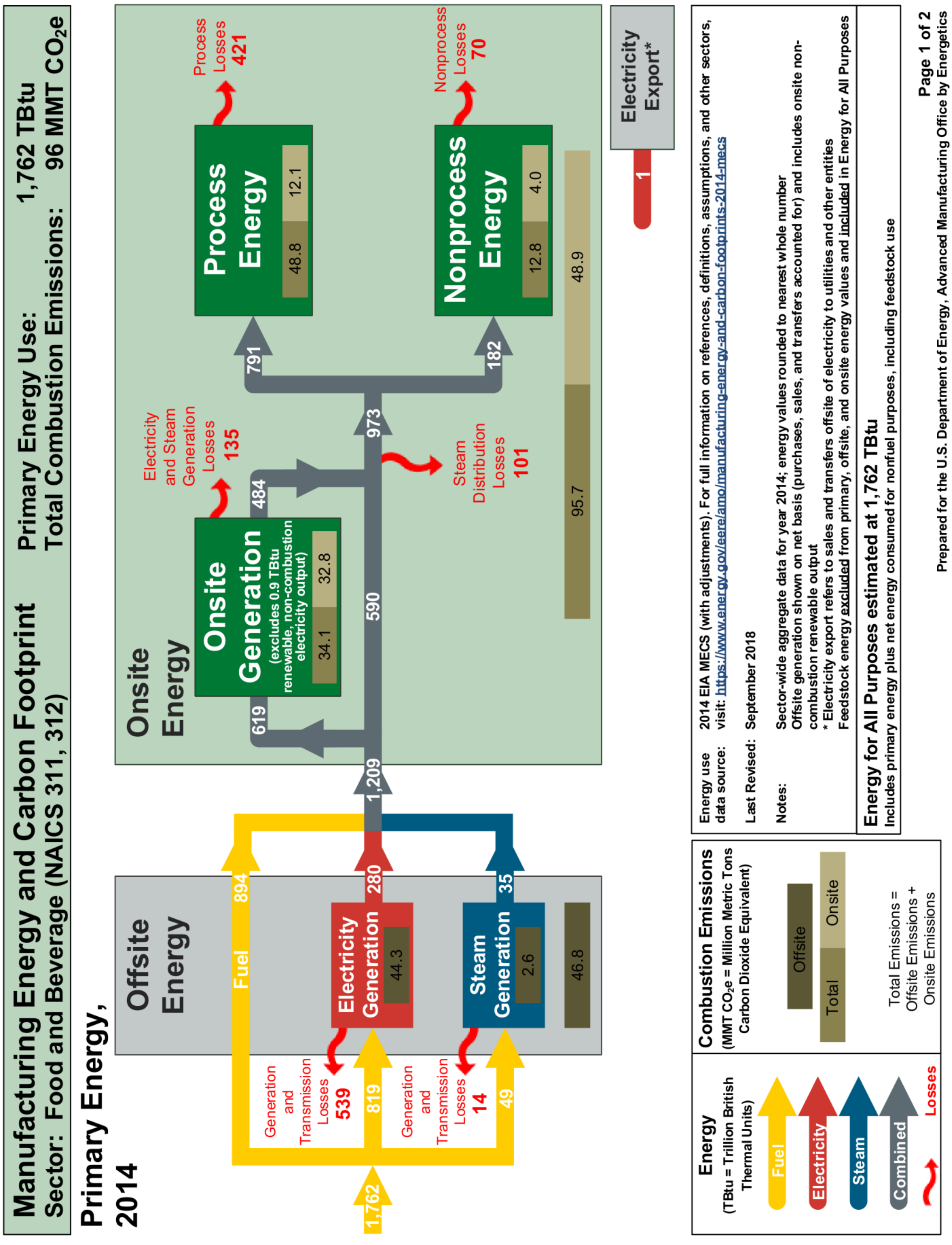

Figure R13. Manufacturing energy – Food & Beverage – Part 1 (US DoE 2014)

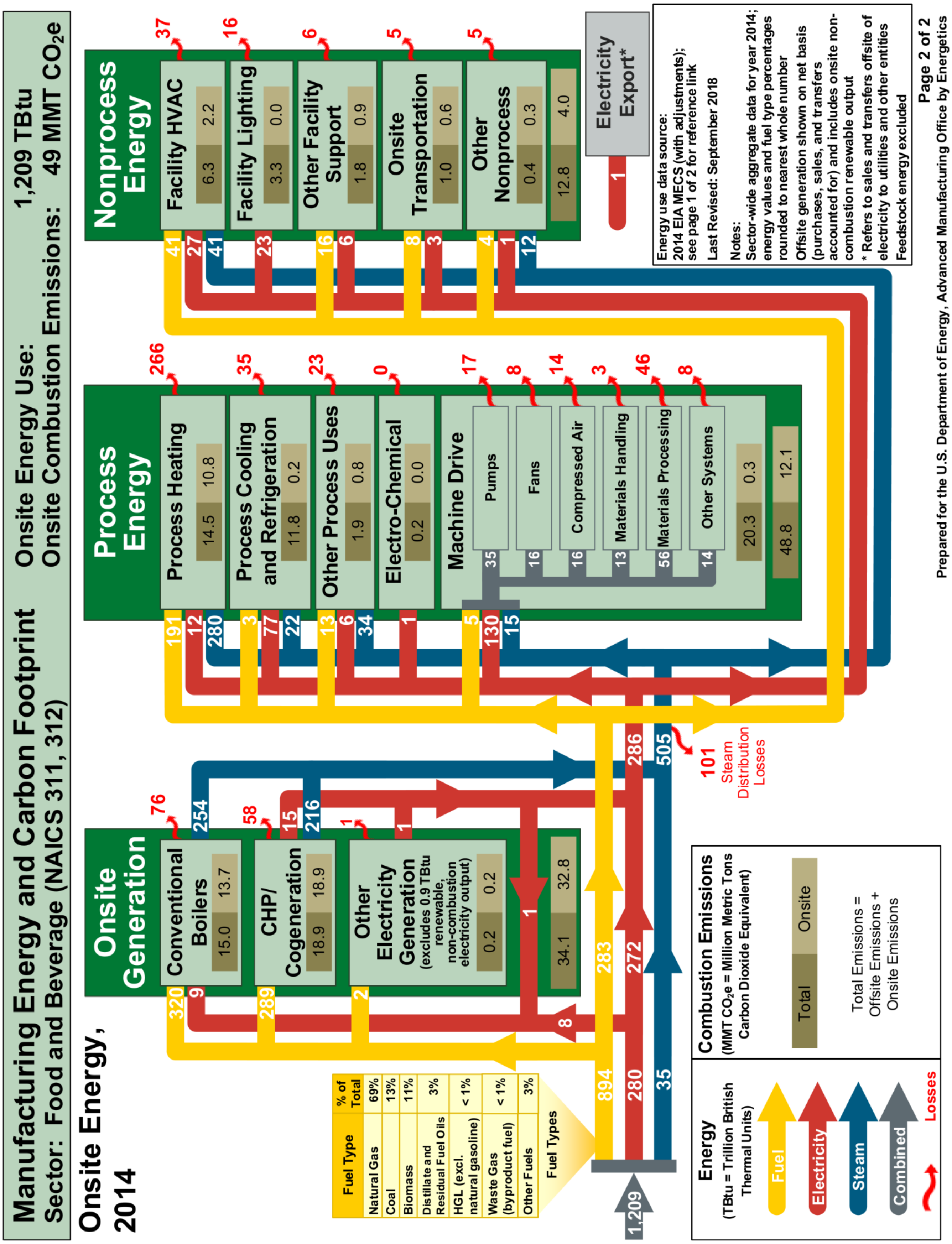

Figure R14. Manufacturing energy – Food & Beverage – Part 2 (US DoE 2014)
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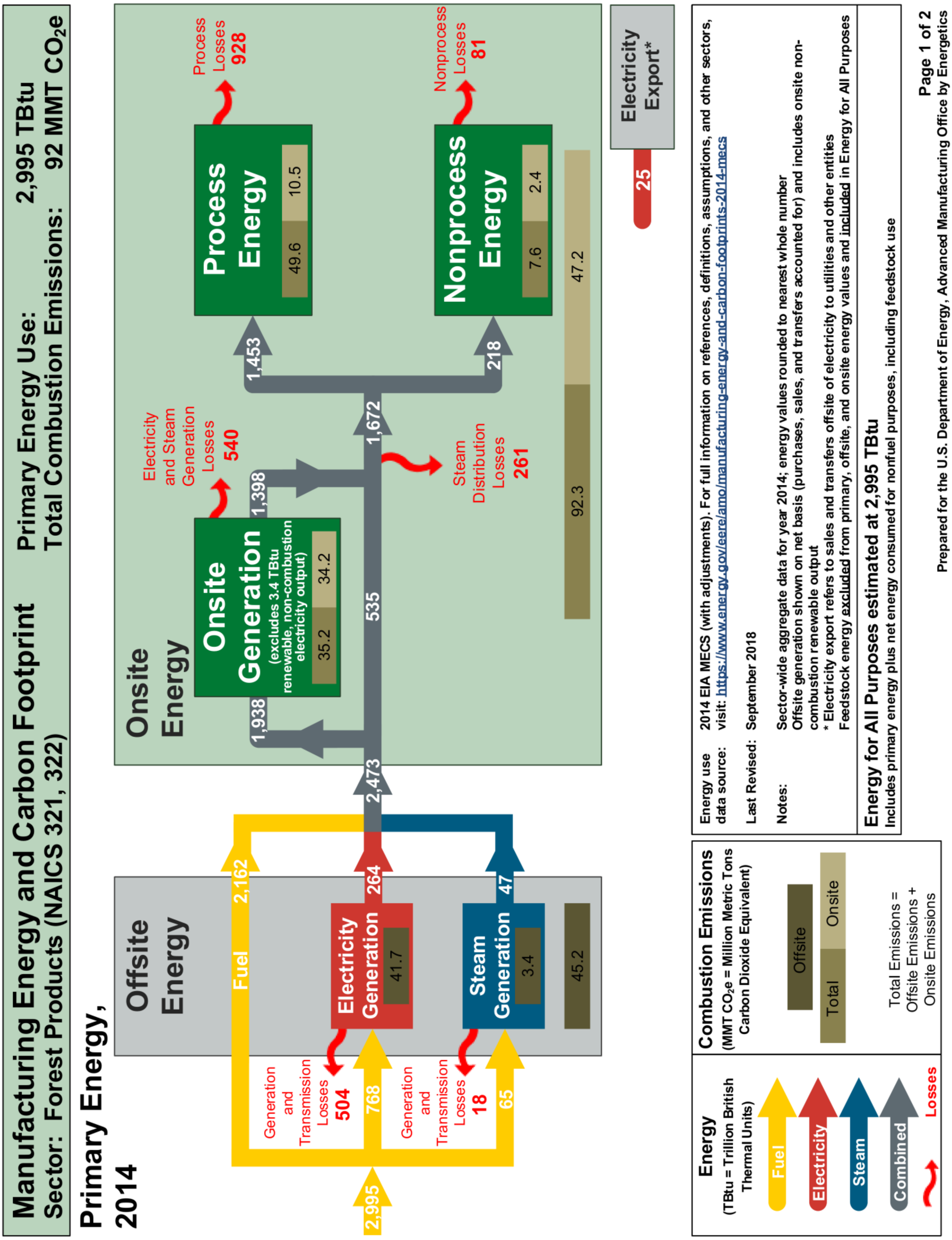

Figure R15. Manufacturing energy – Forest Products – Part 1 (US DoE 2014)
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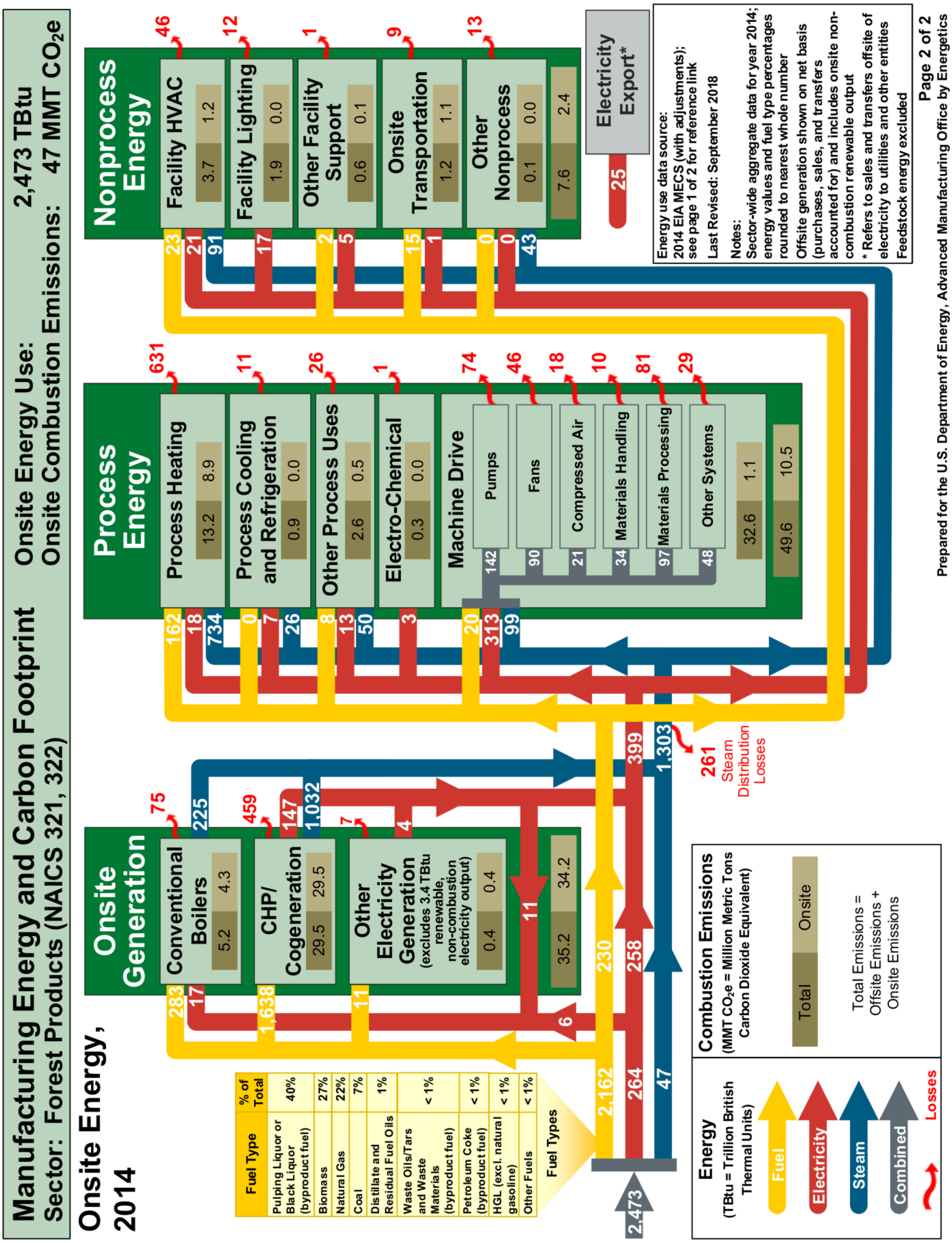

Figure R16. Manufacturing energy – Forest Products – Part 2 (US DoE 2014)
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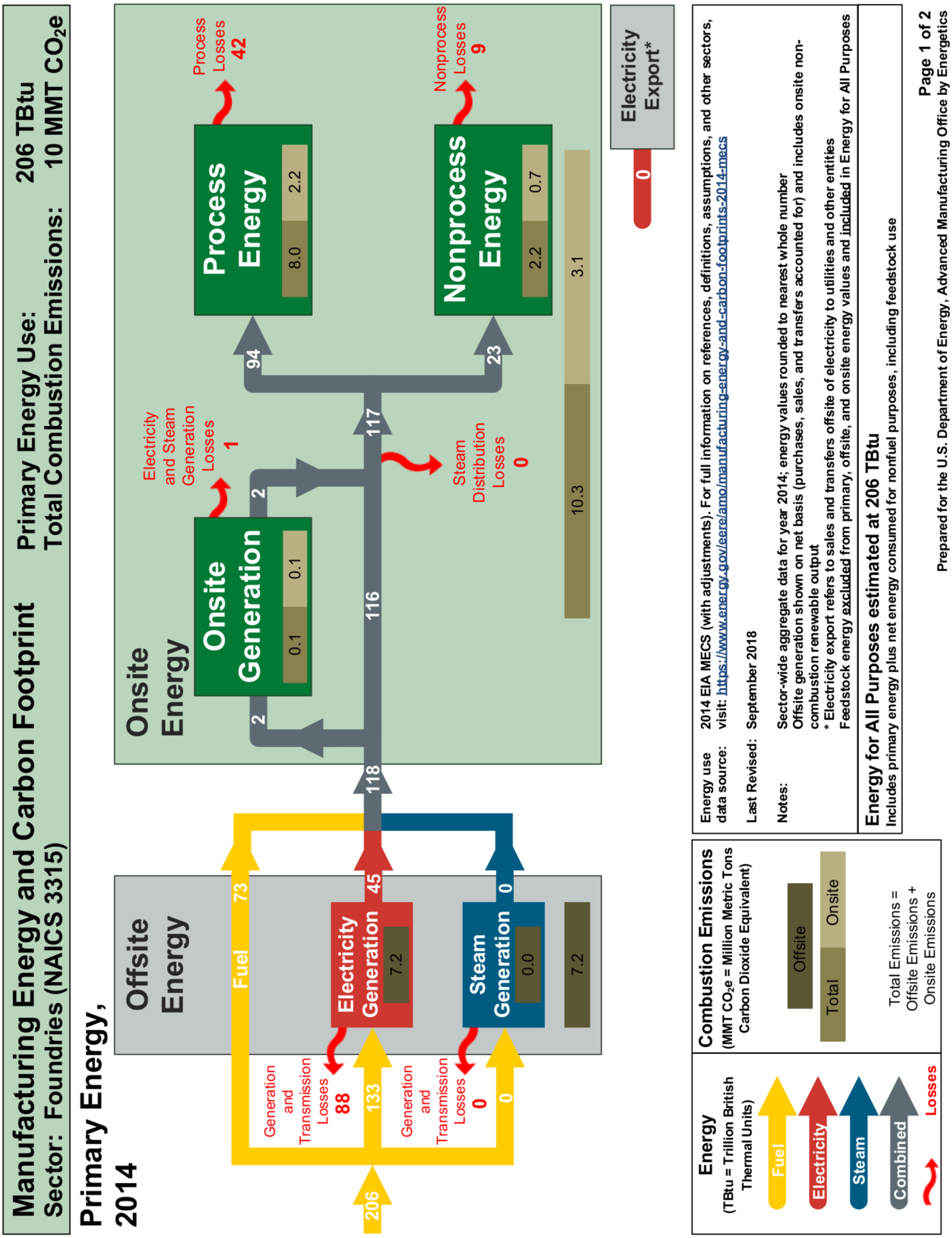

Figure R17. Manufacturing energy – Foundries – Part 1 (US DoE 2014)
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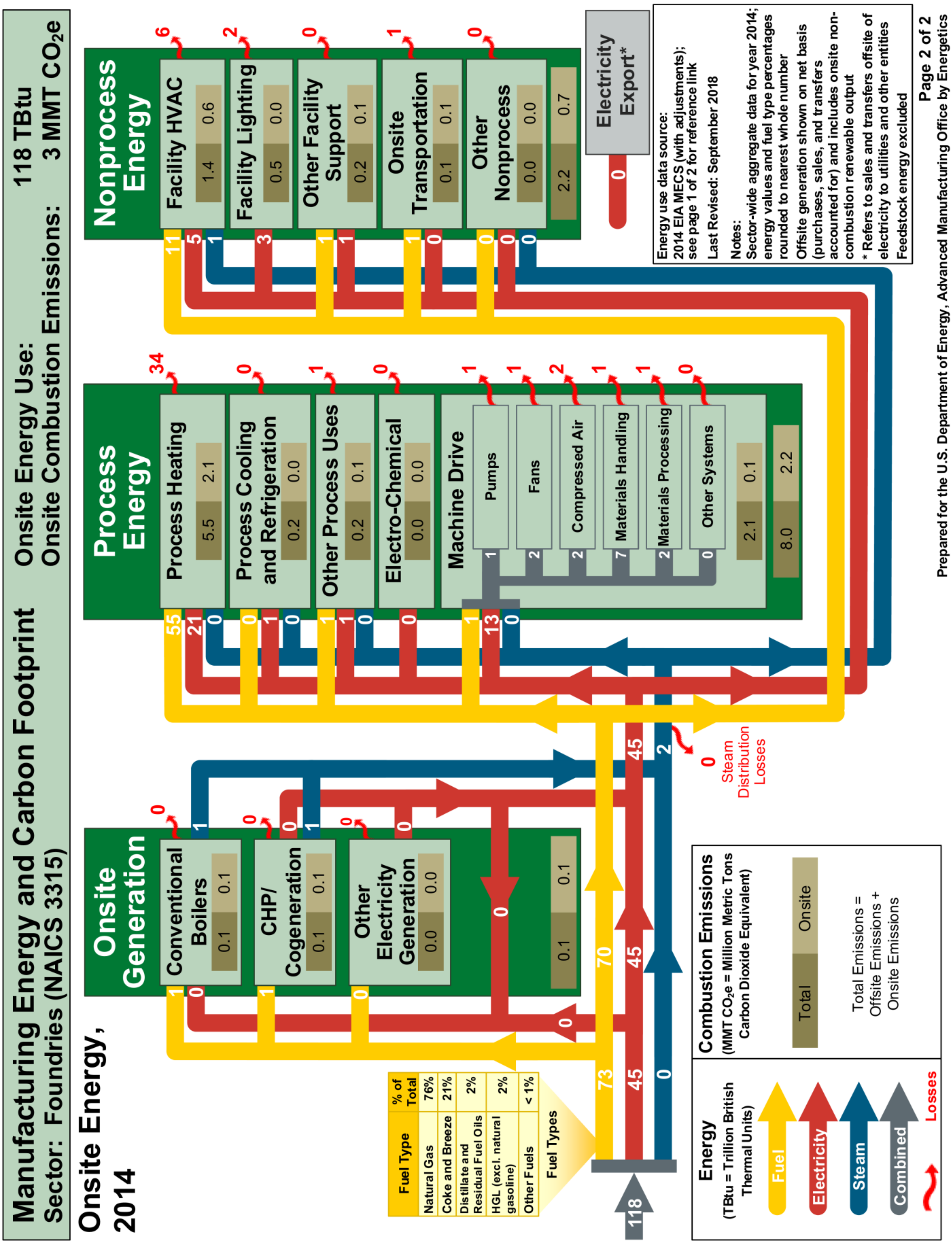

Figure R18. Manufacturing energy – Foundries – Part 2 (US DoE 2014)

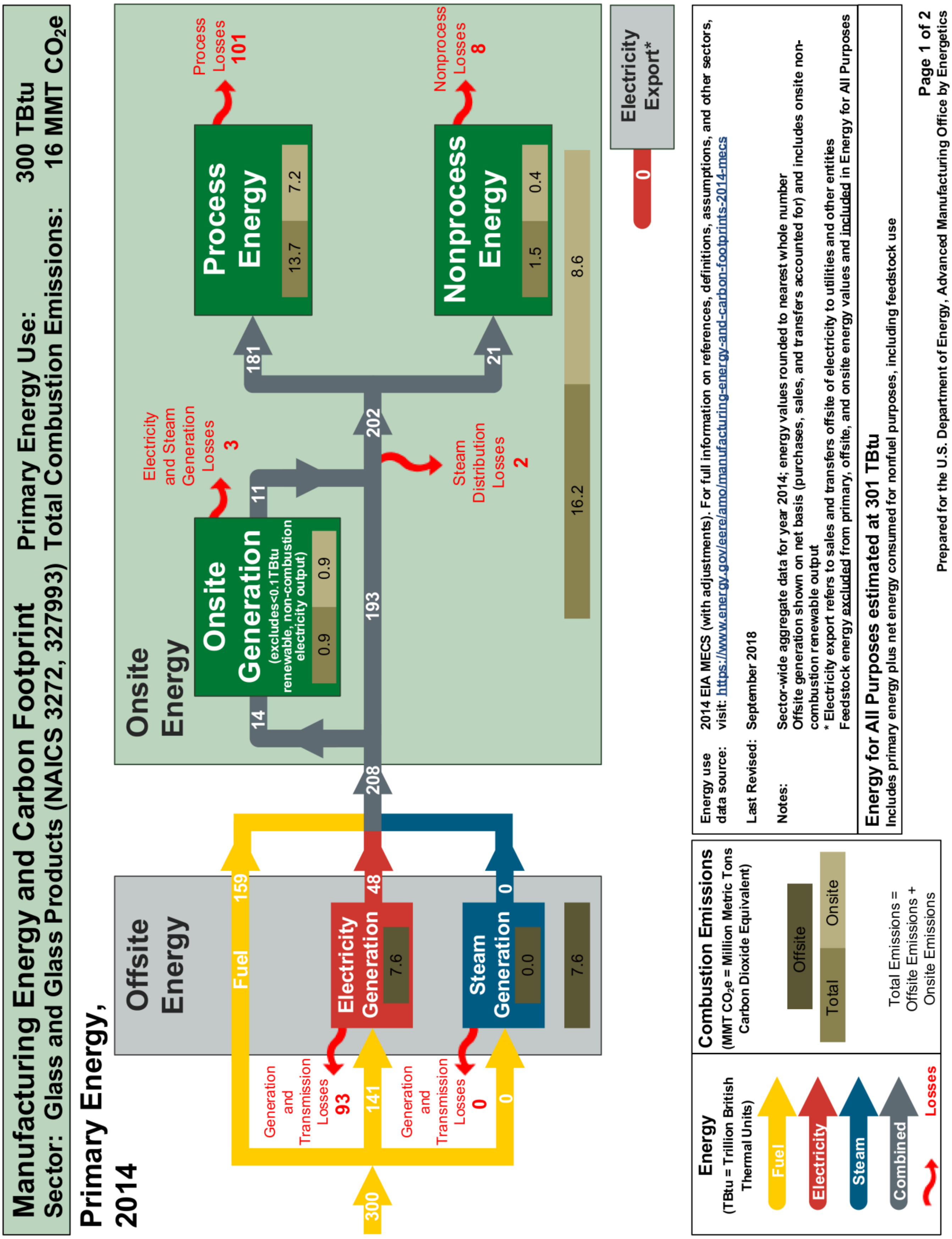

Figure R19. Manufacturing energy – Glass – Part 1 (US DoE 2014)
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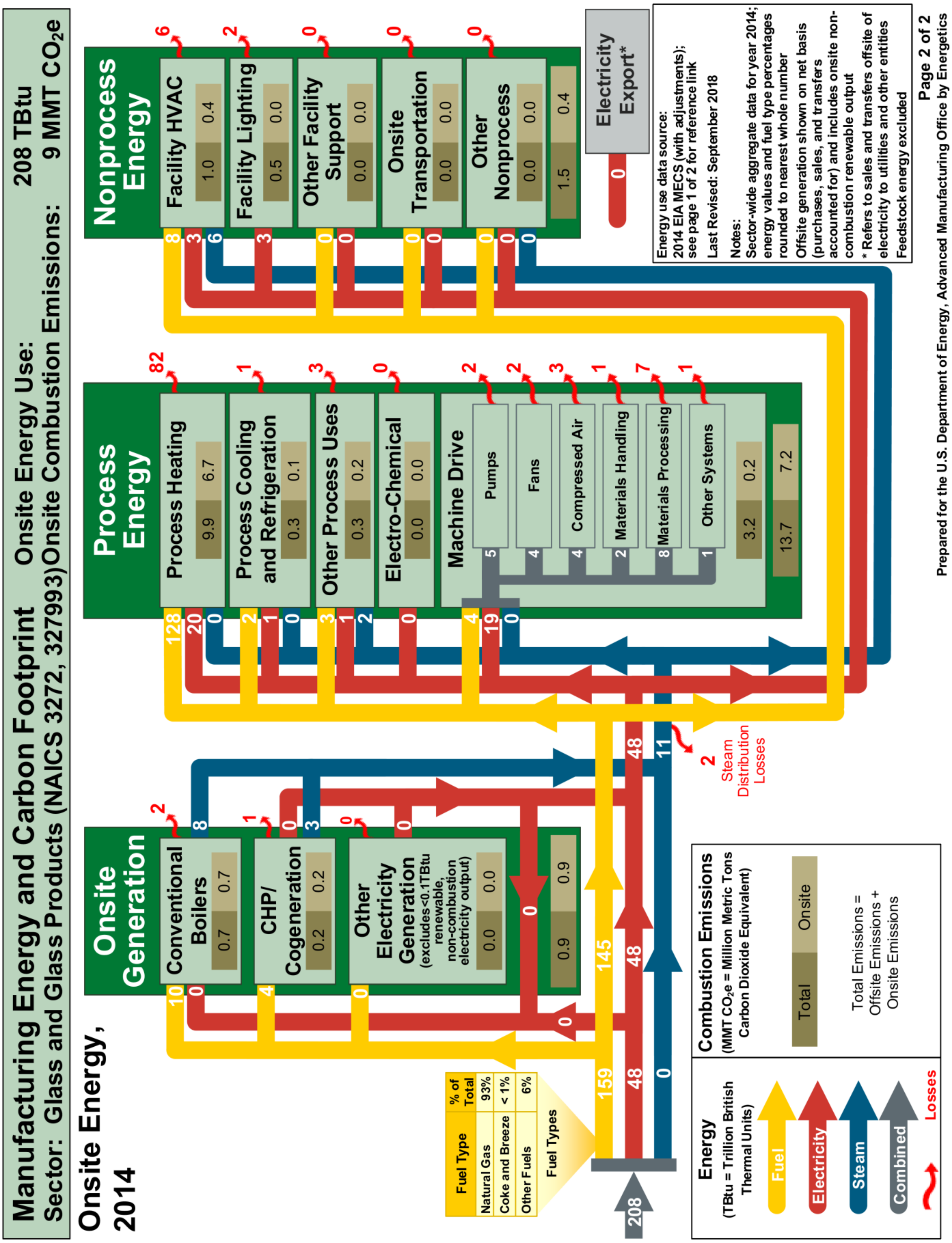

Figure R20. Manufacturing energy – Glass – Part 2 (US DoE 2014)
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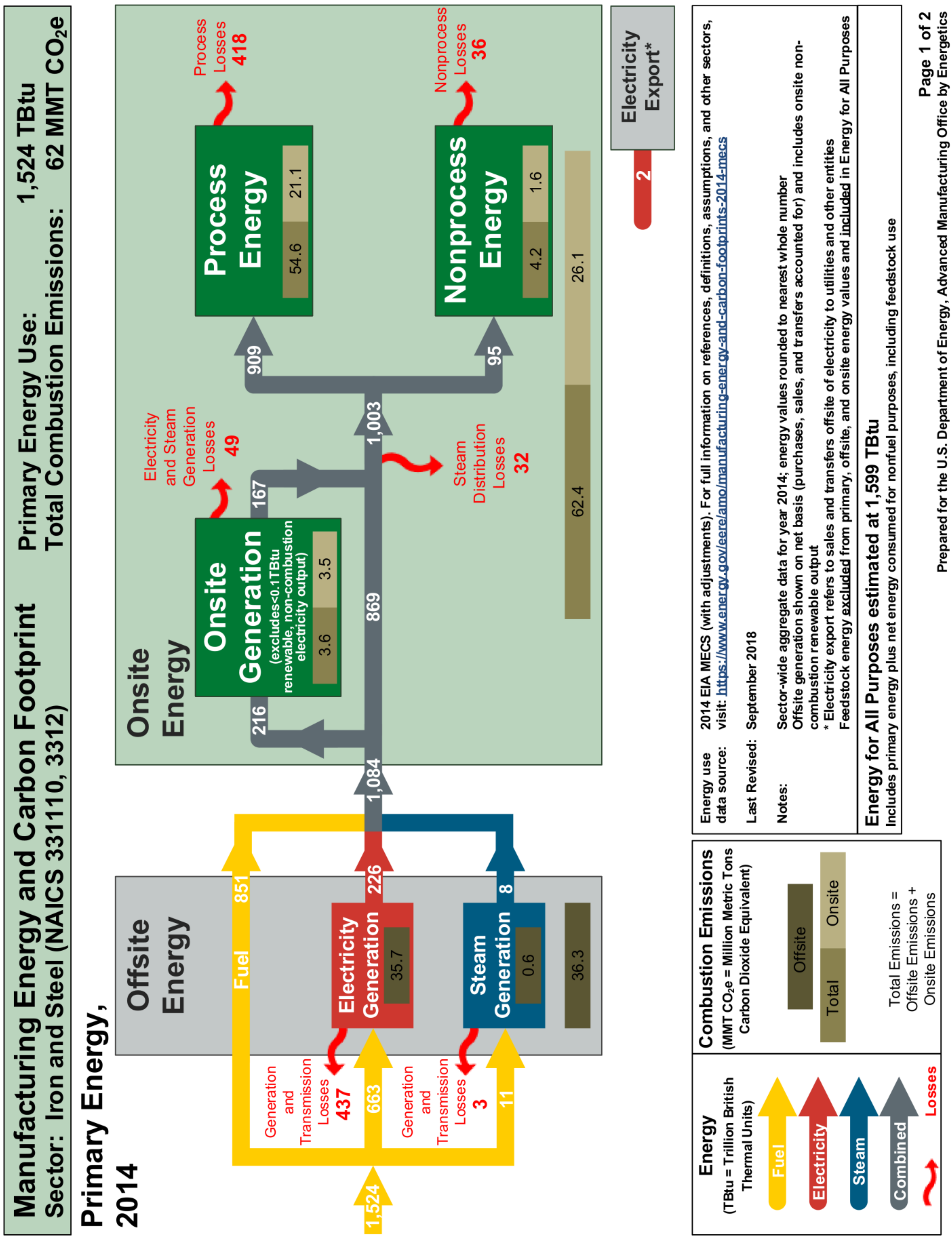

Figure R21. Manufacturing energy – Iron & Steel – Part 1 (US DoE 2014)

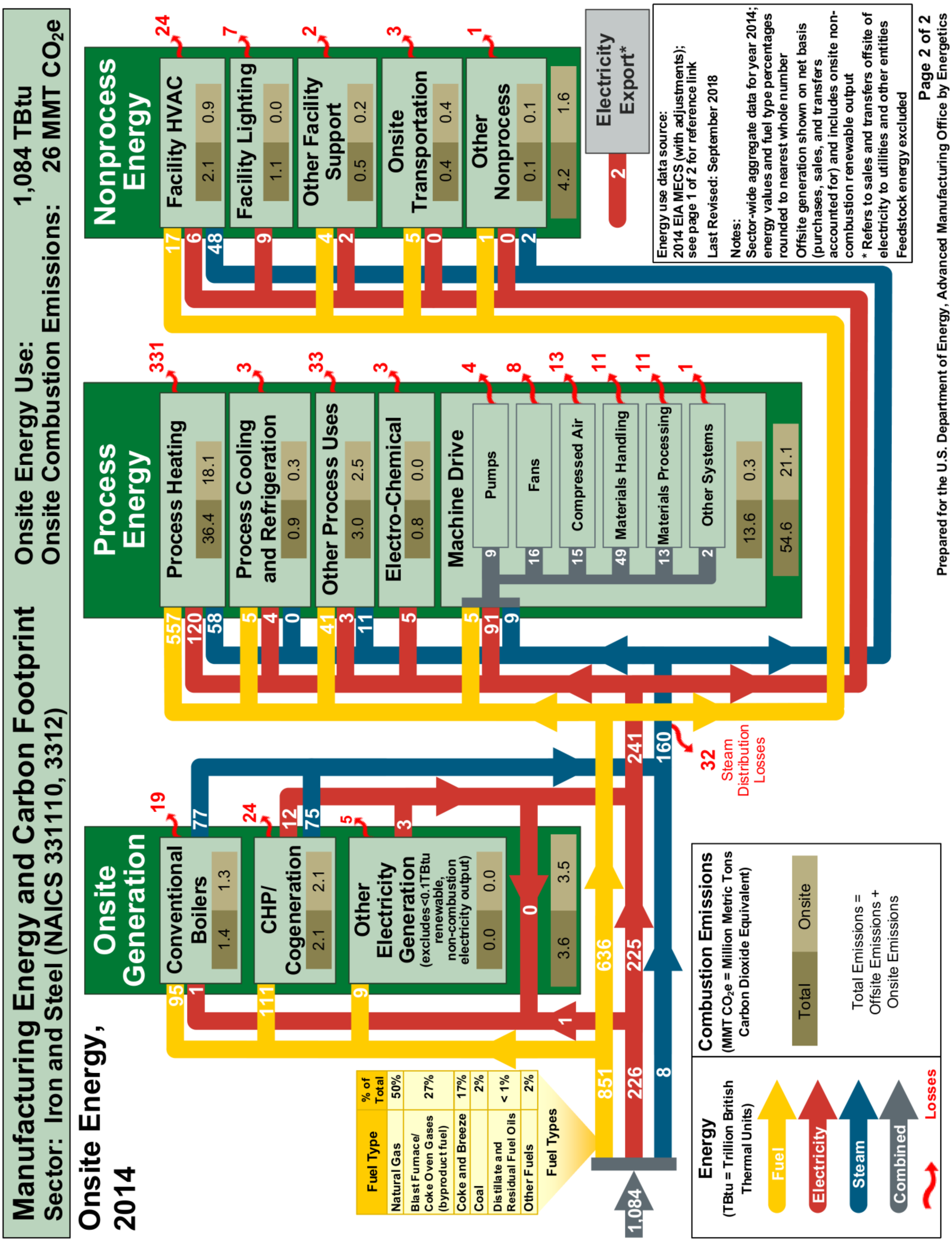

Figure R22. Manufacturing energy – Iron & Steel – Part 2 (US DoE 2014)
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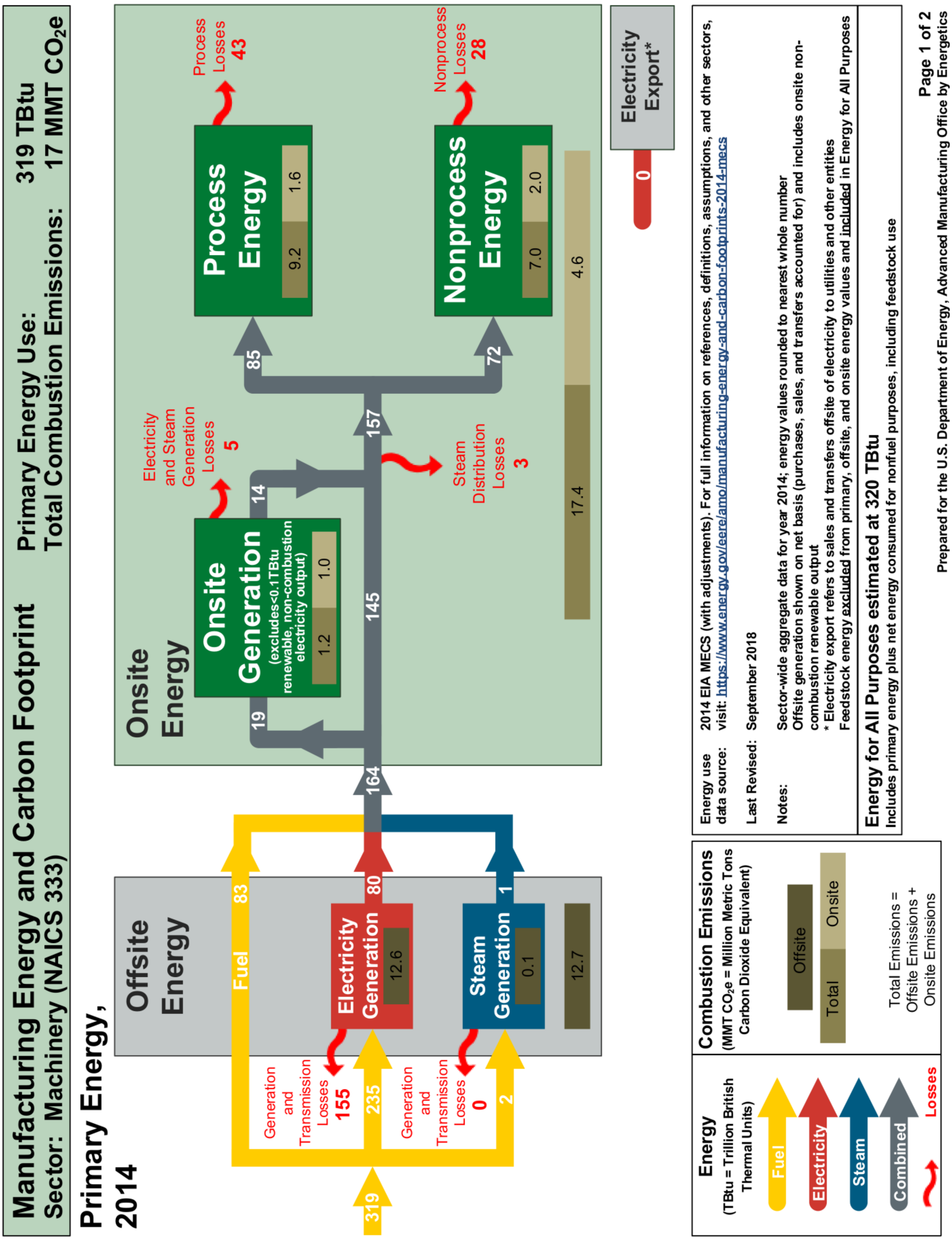

Figure R23. Manufacturing energy – Machinery – Part 1 (US DoE 2014)

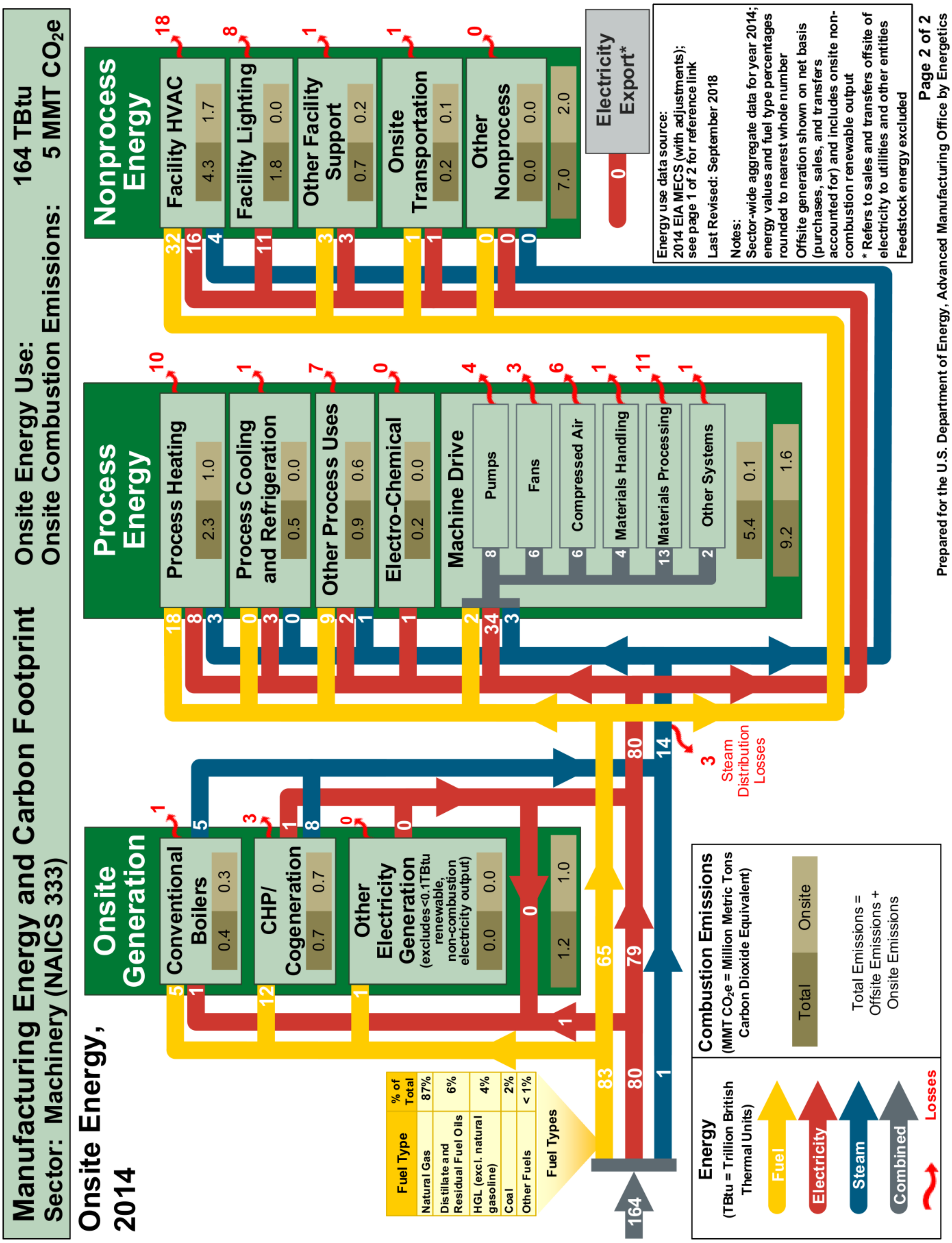

Figure R24. Manufacturing energy – Machinery – Part 2 (US DoE 2014)

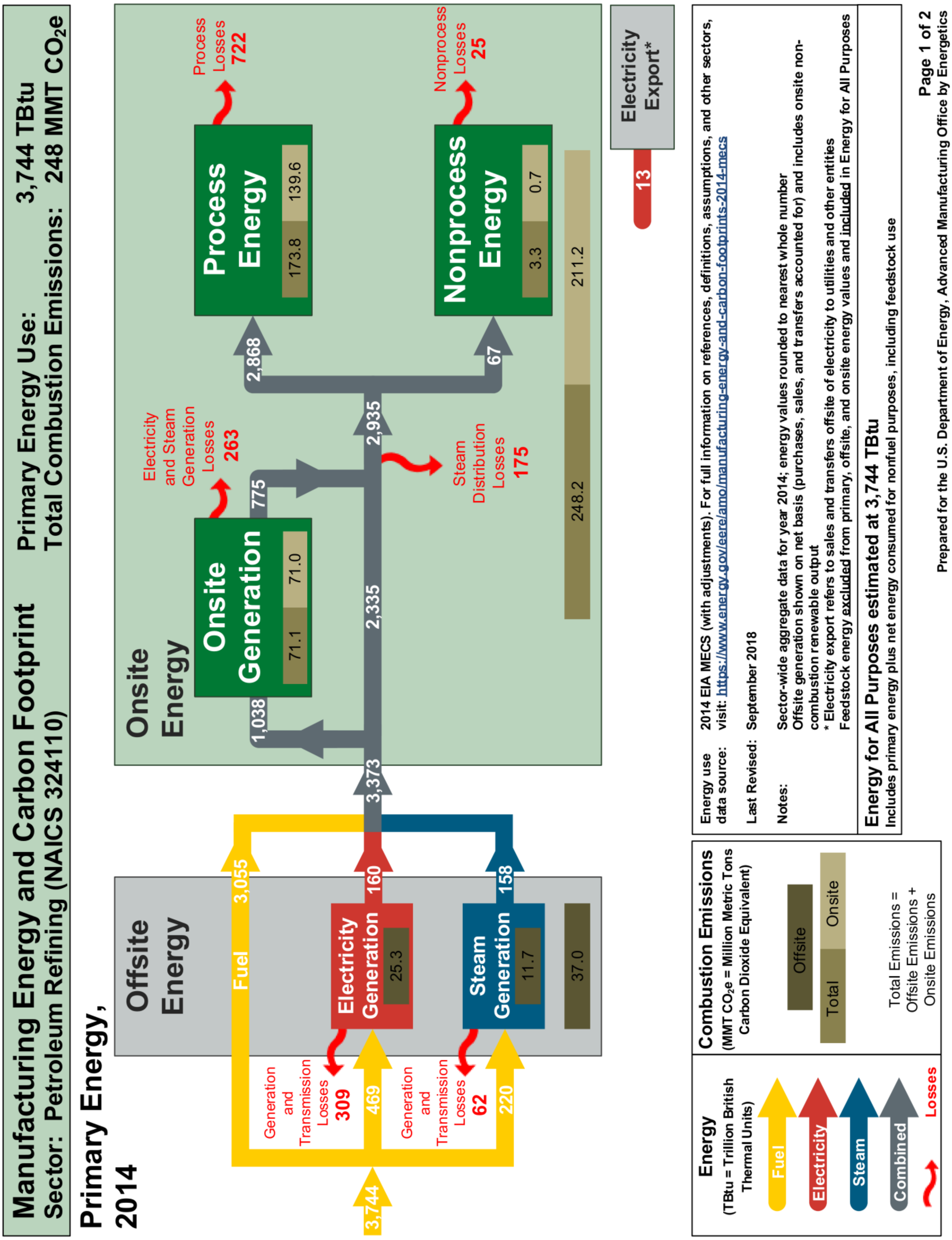

Figure R25. Manufacturing energy – Petroleum Refining – Part 1 (US DoE 2014)
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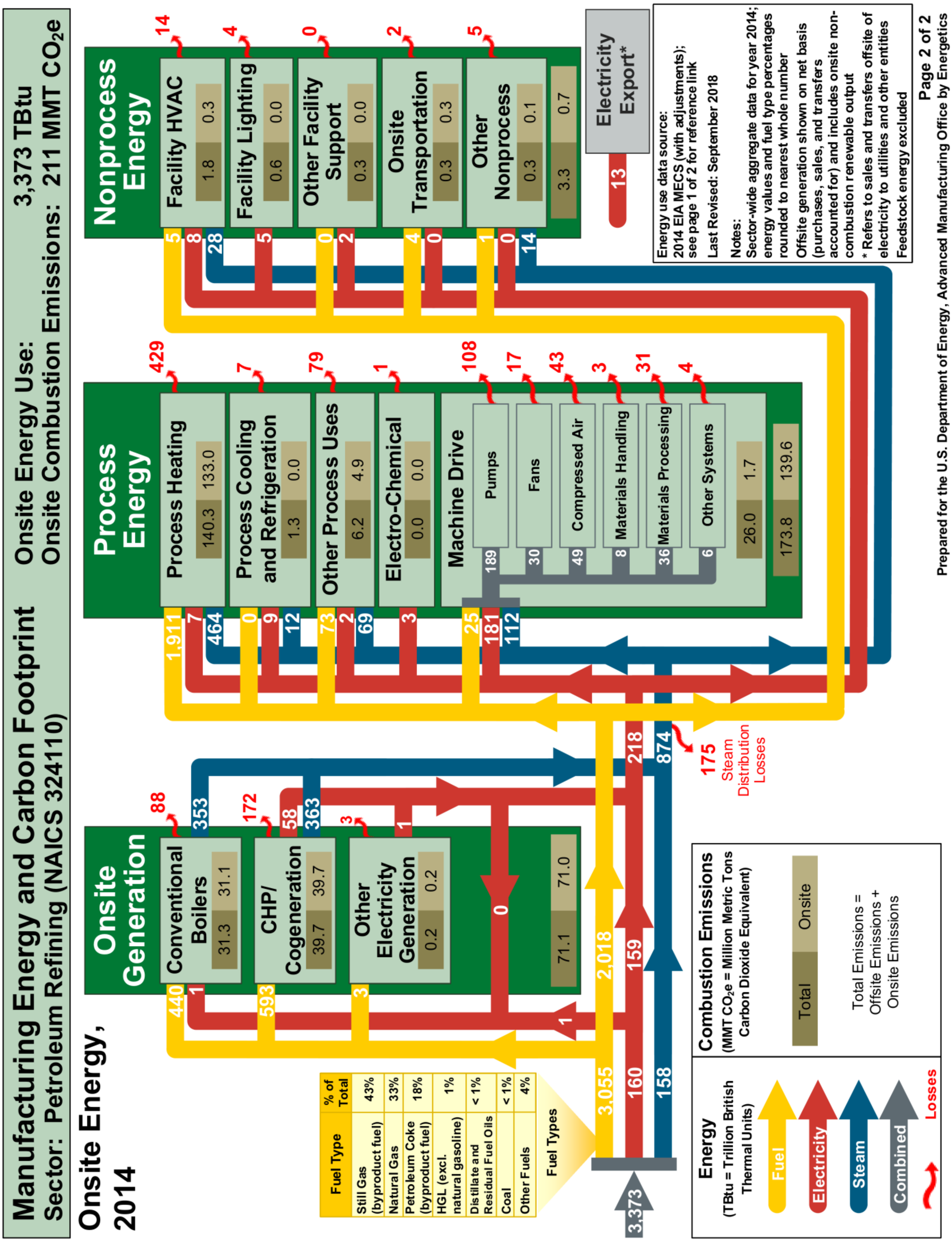

Figure R26. Manufacturing energy – Petroleum Refining – Part 2 (US DoE 2014)

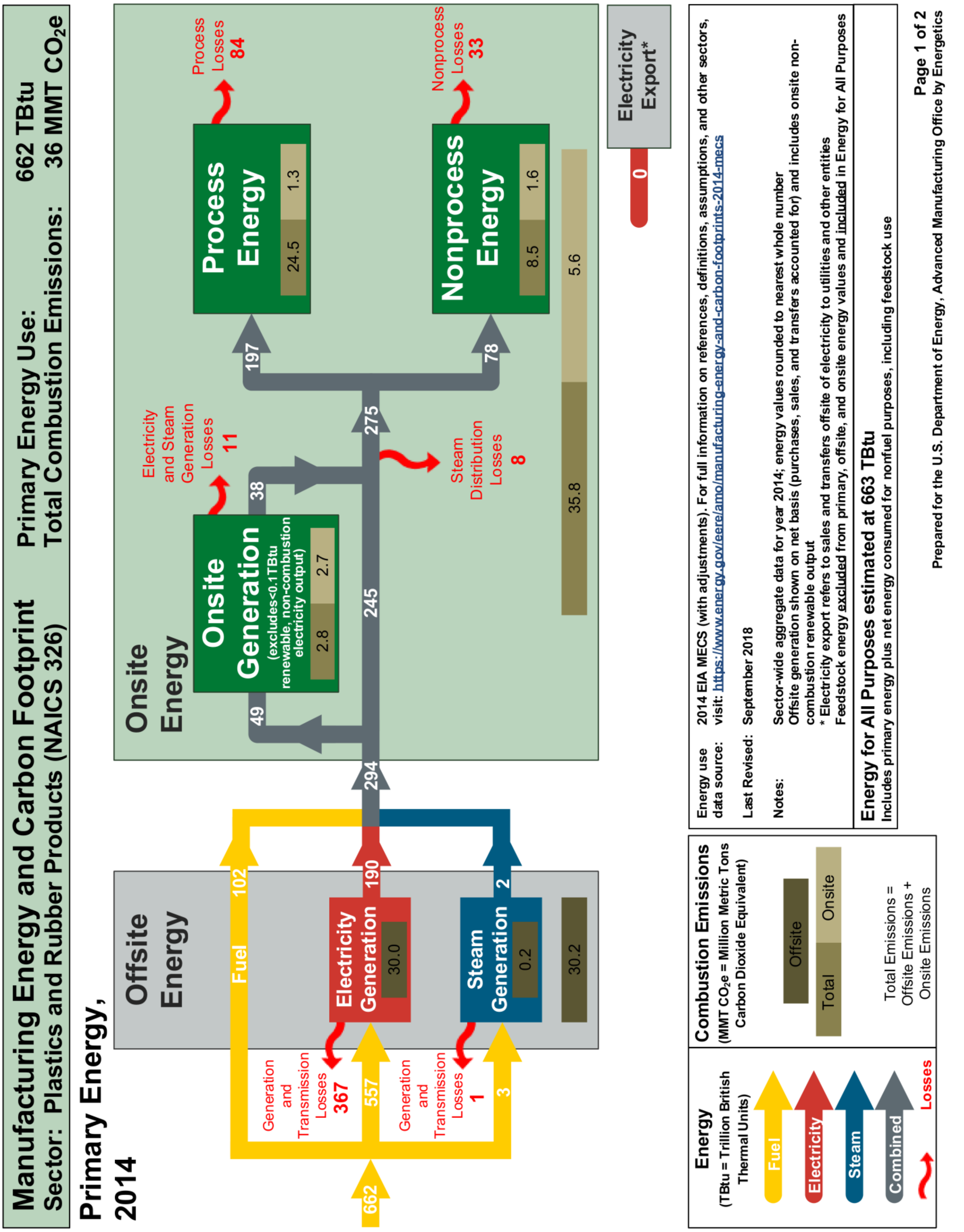

Figure R27. Manufacturing energy – Plastics & Rubber – Part 1 (US DoE 2014)
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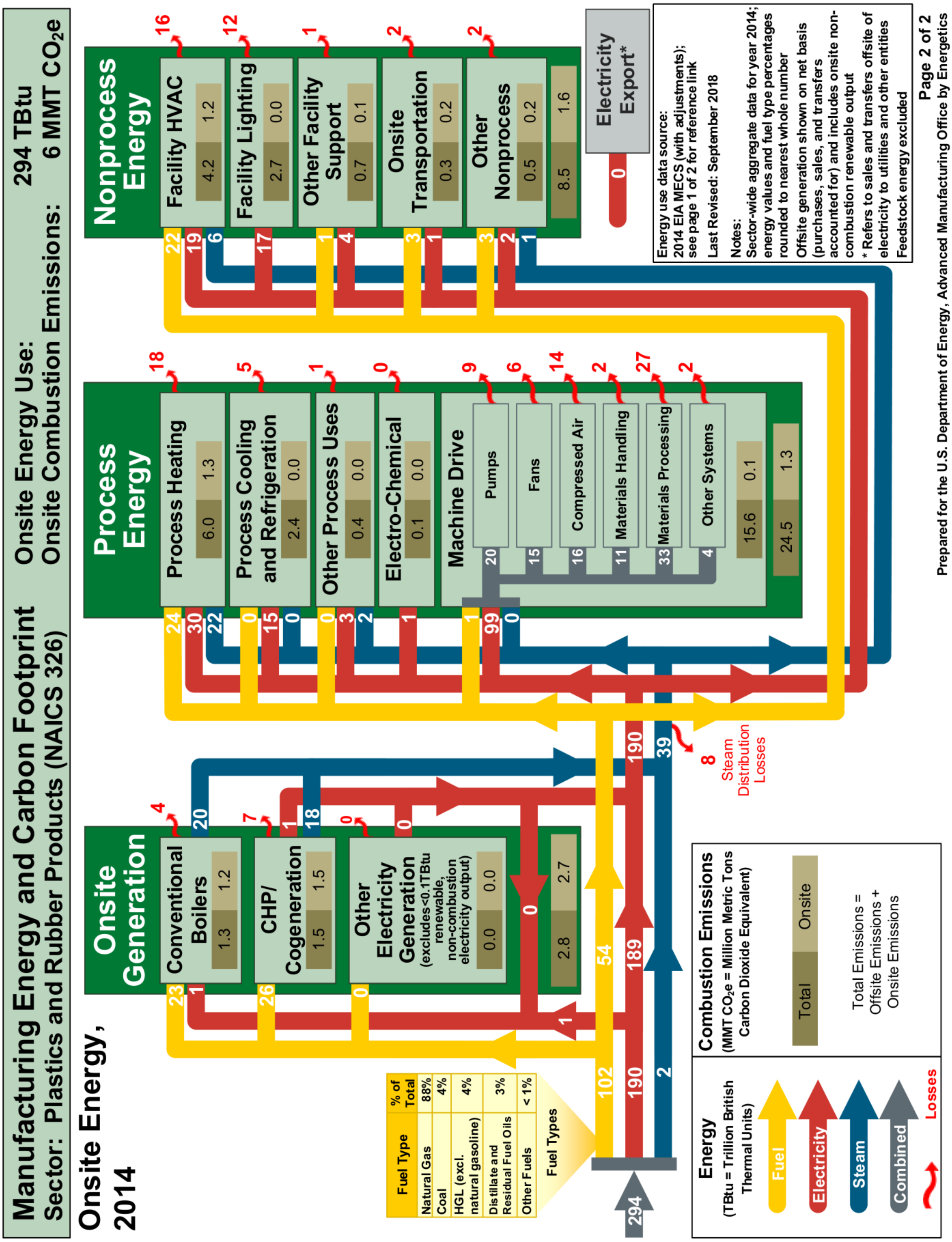

Figure R28. Manufacturing energy – Plastics & Rubber – Part 2 (US DoE 2014)
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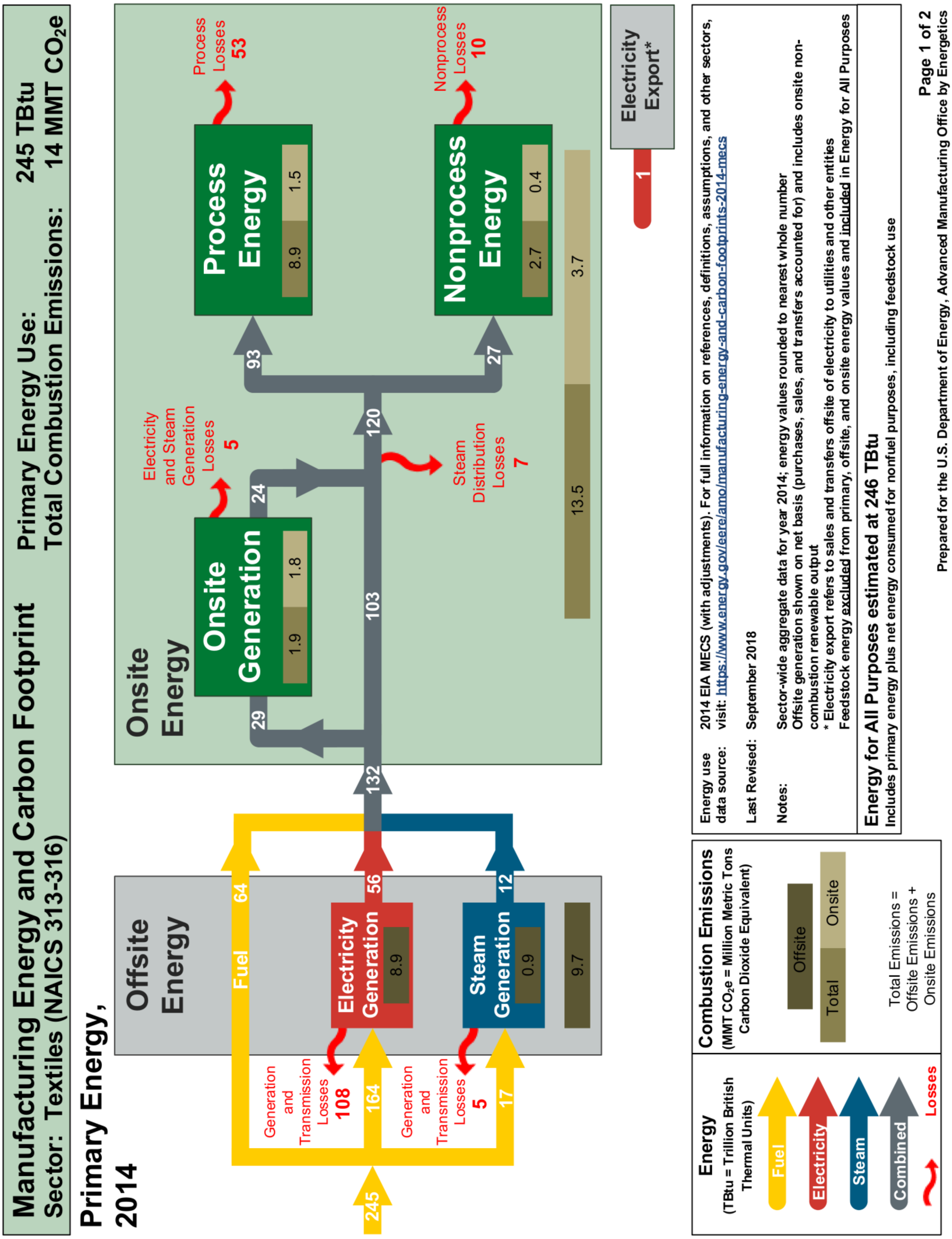

Figure R29. Manufacturing energy – Textiles – Part 1 (US DoE 2014)
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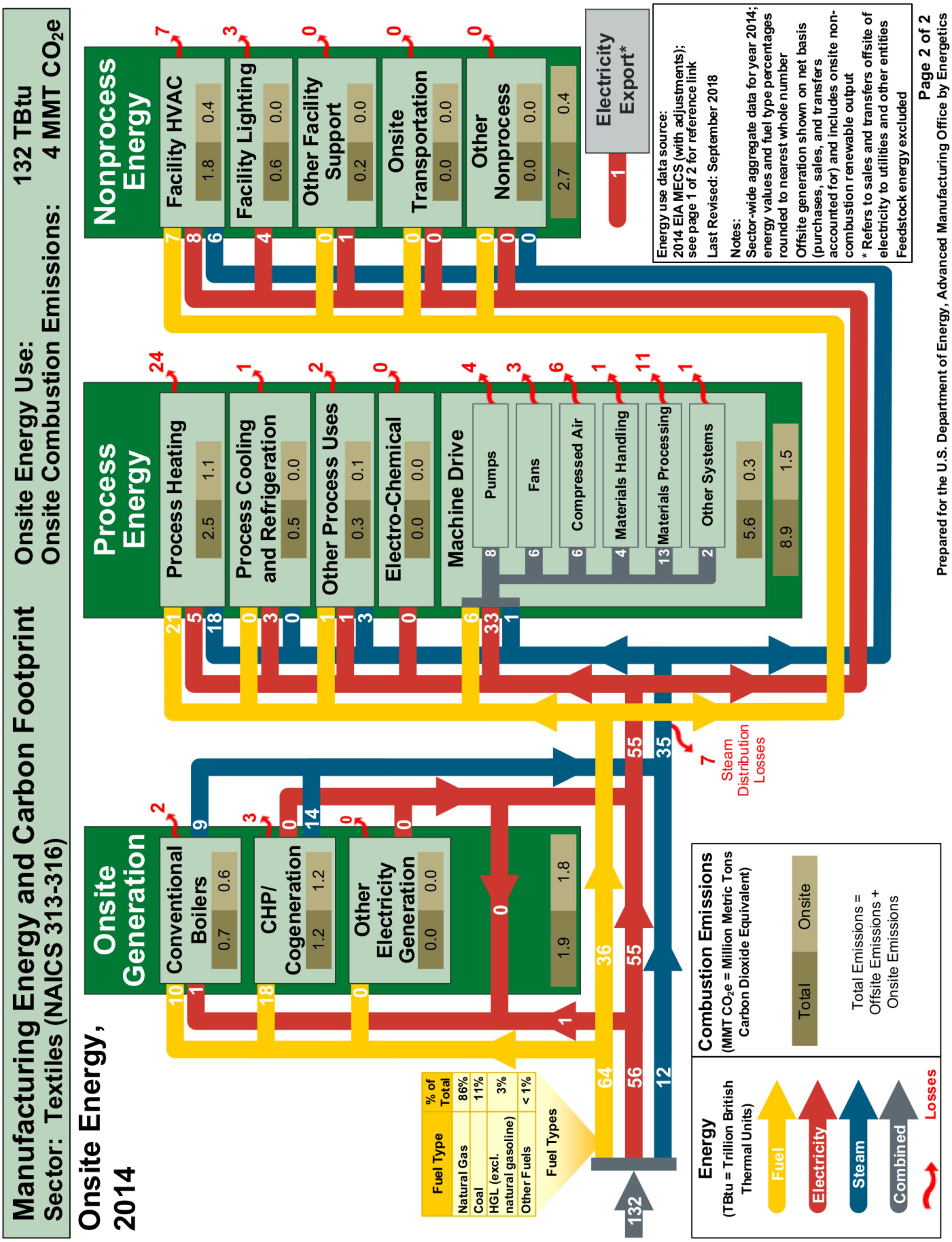

Figure R30. Manufacturing energy – Textiles – Part 2 (US DoE 2014)
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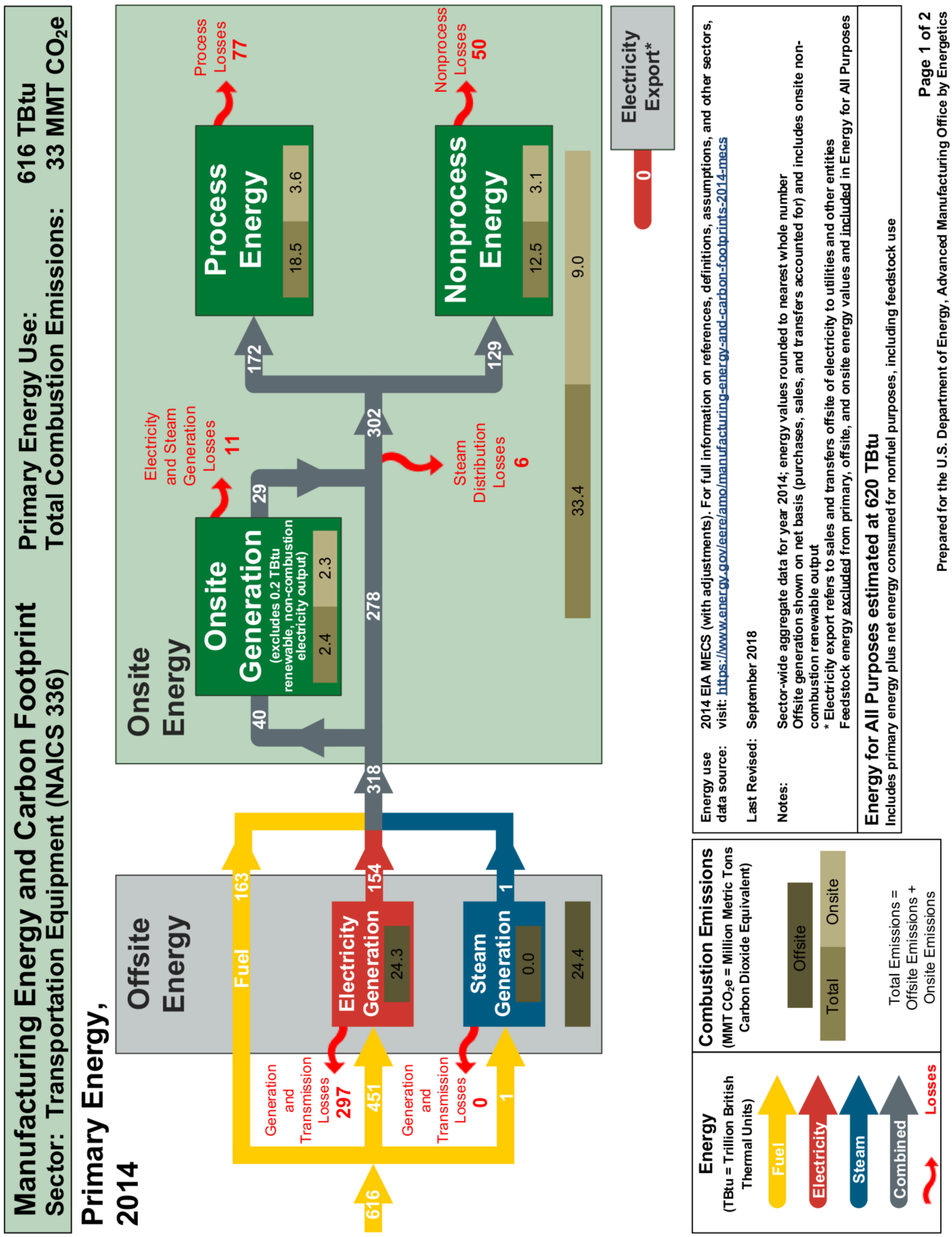

Figure R31. Manufacturing energy – Transportation Equipment – Part 1 (US DoE 2014)

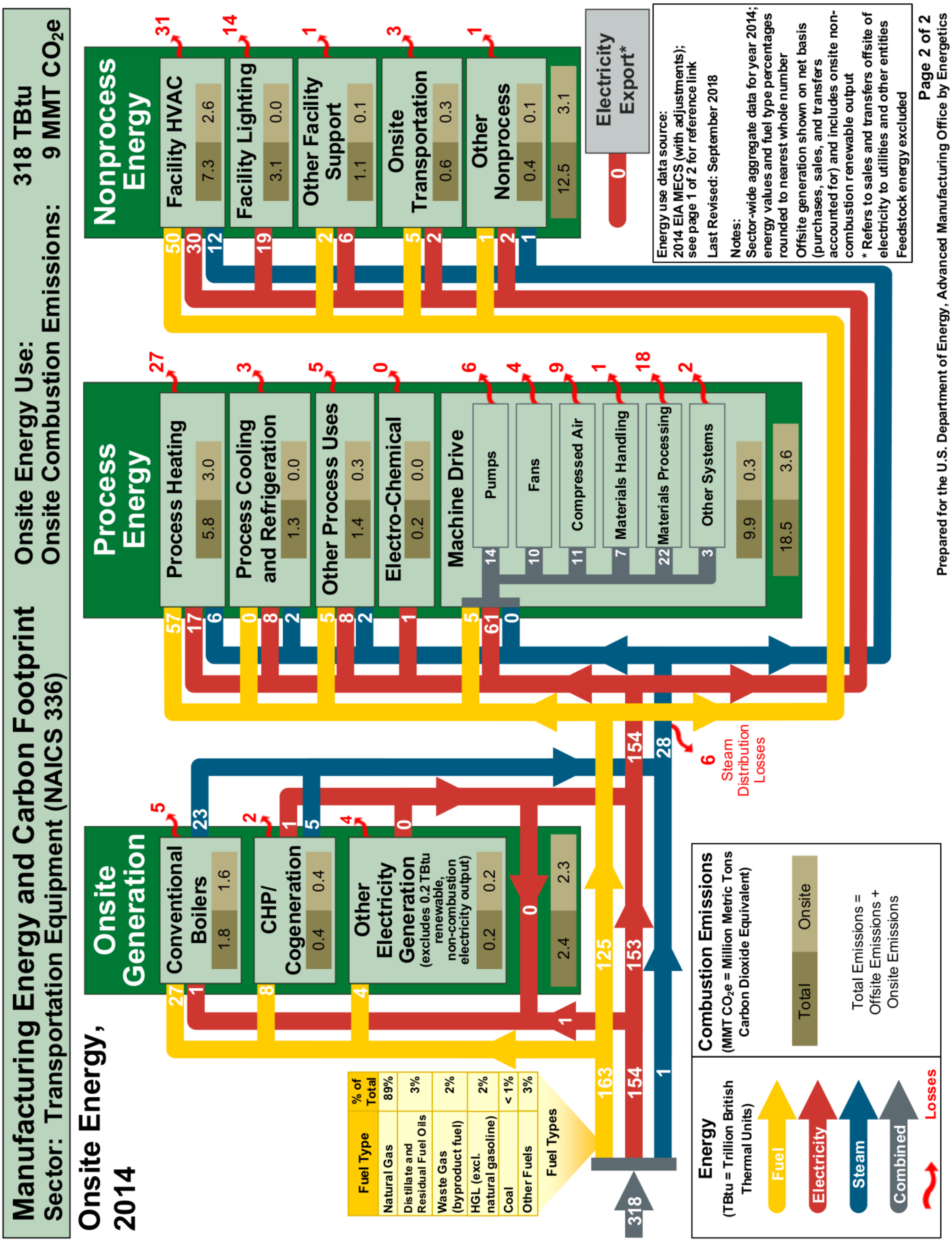

Figure R32. Manufacturing energy – Transportation Equipment – Part 2 (US DoE 2014)

48 APPENDIX S – ENERGY UNITS AND CONVERSIONS

48.1 Energy Units and Conversions

- 1 Joule (J) is the MKS unit of energy, equal to the force of one Newton acting through one meter.
- 1 Watt is the power of a Joule of energy per second
- Power = Current x Voltage (P = I V)
- 1 Watt is the power from a current of 1 Ampere flowing through 1 Volt.
- 1 kilowatt is 1 000 Watts.
- 1 megawatt is 1 000 000 Watts.
- 1 gigawatt is 1 000 000 000 Watts.
- 1 terawatt is 1 000 000 000 000 Watts
- 1 kilowatt-hour is the energy of one kilowatt power flowing for one hour. (E = P t).
- 1 kilowatt-hour (kWh) = 3.6×10^6 J = 3.6 million Joules
- 1 calorie of heat is the amount needed to raise 1 gram of water 1 degree Centigrade.
- 1 calorie (cal) = 4.184 J (The Calories in food ratings are actually kilocalories.)
- A BTU (British Thermal Unit) is the amount of heat necessary to raise one pound of water by 1 degree Farenheit (F).
- 1 British Thermal Unit (BTU) = 1055 J (The Mechanical Equivalent of Heat Relation)
- 1 BTU = 252 cal = 1.055 kJ
- 1 Quad = 1015 BTU (World energy usage is about 300 Quads/year, US is about 100 Quads/year in 1996.)
- 1 therm = 100,000 BTU
- 1,000 kWh = 3.41 million BTU
- 1 US gallon = 3.784 liters

48.2 Power Conversion

- horsepower (hp) = 745.7 watts

48.3 Gas Volume to Energy Conversion

- One thousand cubic feet of gas (Mcf) -> 1.027 million BTU = 1.083 billion J = 301 kWh
- One therm = 100,000 BTU = 105.5 MJ = 29.3 kWh
- Mcf -> 10.27 therms

48.4 Energy Content of Fuels

- Coal 25 million BTU/ton
- Crude Oil 5.6 million BTU/barrel
- Oil 5.78 million BTU/barrel = 1700 kWh / barrel
- Gasoline 5.6 million BTU/barrel (a barrel is 42 gallons) = 1.33 therms / gallon
- Natural gas liquids 4.2 million BTU/barrel
- Natural gas 1030 BTU/cubic foot
- Wood 20 million BTU/cord

Table S1. Scaling labels

SI Unit	Watt-hour (Wh) equivalent
Watt-hour (Wh)	-
Kilowatt-hour (kWh)	One thousand watt-hours (10^3 Wh)
Megawatt-hour (MWh)	One million watt-hours (10^6 Wh)
Gigawatt-hour (GWh)	One billion watt-hours (10^9 Wh)
Terawatt-hour (TWh)	One trillion watt-hours (10^{12} Wh)

48.5 Energy Content of Fuels

Le Systeme international d'Unites officially came into being in October 1960 and has been officially recognized and adopted by nearly all countries, though the amount of actual usage varies considerably. It is based upon 7 principal units, 1 in each of 7 different categories.

Table S2. Standard S.I. units

Category	*Name*	*Abbrev.*
Length	metre	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Temperature	kelvin	K
Amount of substance	mole	mol
Luminous intensity	candela	cd

48.6 Unit of measurement definitions

meter [m]
The meter (also spelt metre) is the basic unit of length. It is the distance light travels, in a vacuum, in 1/299792458th of a second.

kilogram [kg]
The kilogram is the basic unit of mass. It is the mass of an international prototype in the form of a platinum-iridium cylinder kept at Sevres in France. It is now the only basic unit still defined in terms of a material object, and also the only one with a prefix[kilo] already in place.

Liter [l]
The liter is a metric unit of capacity, formerly defined as the volume of one kilogram of water under standard conditions, now equal to 1,000 Cubic centimeters (about 1.75 pints).

second [s]
The second is the basic unit of time. It is the length of time taken for 9192631770 periods of vibration of the caesium-133 atom to occur.

ampere [A]
The ampere is the basic unit of electric current. It is that current which produces a specified force between two parallel wires which are 1 meter apart in a vacuum. It is named after the French physicist Andre Ampere (1775-1836).

kelvin [K]
The kelvin is the basic unit of temperature. It is 1/273.16th of the thermodynamic temperature of the triple point of water. It is named after the Scottish mathematician and physicist William Thomson 1st Lord Kelvin (1824-1907).
mole [mol]
The mole is the basic unit of substance. It is the amount of substance that contains as many elementary units as there are atoms in 0.012 kg of carbon-12.

candela [cd]
The candela is the basic unit of luminous intensity. It is the intensity of a source of light of a specified frequency, which gives a specified amount of power in a given direction.

farad [F]
The farad is the SI unit of the capacitance of an electrical system, that is, its capacity to store electricity. It is a rather large unit as defined and is more often used as a microfarad. It is named after the English chemist and physicist Michael Faraday (1791-1867).

hertz [Hz]
The hertz is the SI unit of the frequency of a periodic phenomenon. One hertz indicates that 1 cycle of the phenomenon occurs every second. For most work much higher frequencies are needed such as the kilohertz [kHz] and megahertz [MHz]. It is named after the German physicist Heinrich Rudolph Hertz (1857-94).

joule [J]
The joule is the SI unit of work or energy. One joule is the amount of work done when an applied force of 1 newton moves through a distance of 1 meter in the direction of the force. It is named after the English physicist James Prescott Joule (1818-89).

newton [N]
The newton is the SI unit of force. One newton is the force required to give a mass of 1 kilogram an acceleration of 1 meter per second per second. It is named after the English mathematician and physicist Sir Isaac Newton (1642-1727).
ohm [Ω]
The ohm is the SI unit of resistance of an electrical conductor. Its symbol, is the capital Greek letter 'omega'. It is named after the German physicist Georg Simon Ohm (1789-1854).

pascal [Pa]
The pascal is the SI unit of pressure. One pascal is the pressure generated by a force of 1 newton acting on an area of 1 square meter. It is a rather small unit as defined and is more often used as a kilopascal [kPa]. It is named after the French mathematician, physicist, and philosopher Blaise Pascal (1623-62).

volt [V]
The volt is the SI unit of electric potential. One volt is the difference of potential between two points of an electrical conductor when a current of 1 ampere flowing between those points dissipates a power of 1 watt. It is named after the Italian physicist Count Alessandro Giuseppe Anastasio Volta (1745-1827).

watt [W]
The watt is used to measure power or the rate of doing work. One watt is a power of 1 joule per second. It is named after the Scottish engineer James Watt (1736-1819).

48.7 CO^2 Pollution of Fossil Fuels

- Pounds of CO^2 per billion BTU of energy::
- Coal 208,000 pounds
- Oil 164,000 pounds
- Natural Gas 117,000 pounds

- Ratios of CO^2 pollution:
    - Oil / Natural Gas = 1.40
    - Coal / Natural Gas = 1.78

- Pounds of CO^2 per 1,000 kWh, at 100% efficiency:
- Coal 709 pounds
- Oil 559 pounds
- Natural Gas 399 pounds

Table S3. Approximate conversion factors (BP Statistical Review of World Energy 2019).

Crude oil*

From	To: tonnes (metric)	kilolitres	barrels	US gallons	tonnes per year
	Multiply by				
Tonnes (metric)	1	1.165	7.33	307.86	–
Kilolitres	0.8581	1	6.2898	264.17	–
Barrels	0.1364	0.159	1	42	–
US gallons	0.00325	0.0038	0.0238	1	–
Barrels per day	–	–	–	–	49.8

*Based on worldwide average gravity.

Products

	To convert: barrels to tonnes	tonnes to barrels	kilolitres to tonnes	tonnes to kilolitres
	Multiply by			
Liquefied petroleum gas (LPG)	0.086	11.60	0.542	1.844
Gasoline	0.120	8.35	0.753	1.328
Kerosene	0.127	7.88	0.798	1.253
Gas oil/diesel	0.134	7.46	0.843	1.186
Residual fuel oil	0.157	6.35	0.991	1.010
Product basket	0.125	7.98	0.788	1.269

Natural gas (NG) and liquefied natural gas (LNG)

From	To: billion cubic metres NG	billion cubic feet NG	million tonnes oil equivalent	million tonnes LNG	trillion British thermal units	million barrels oil equivalent
	Multiply by					
1 billion cubic metres NG	1.000	35.315	0.860	0.735	34.121	5.883
1 billion cubic feet NG	0.028	1.000	0.024	0.021	0.966	0.167
1 million tonnes oil equivalent	1.163	41.071	1.000	0.855	39.683	6.842
1 million tonnes LNG	1.360	48.028	1.169	1.000	46.405	8.001
1 trillion British thermal units	0.029	1.035	0.025	0.022	1.000	0.172
1 million barrels oil equivalent	0.170	6.003	0.146	0.125	5.800	1.000

Units

1 metric tonne	= 2204.62lb = 1.1023 short tons
1 kilolitre	= 6.2898 barrels = 1 cubic metre
1 kilocalorie (kcal)	= 4.1868kJ = 3.968Btu
1 kilojoule (kJ)	= 0.239kcal = 0.948Btu
1 British thermal unit (Btu)	= 0.252kcal = 1.055kJ
1 kilowatt-hour (kWh)	= 860kcal = 3600kJ = 3412Btu

Calorific equivalents

One tonne of oil equivalent equals approximately:

Heat units	10 million kilocalories 42 gigajoules 40 million British thermal units
Solid fuels	1.5 tonnes of hard coal 3 tonnes of lignite and sub-bituminous coal
Gaseous fuels	See Natural gas and liquefied natural gas table
Electricity	12 megawatt-hours

One million tonnes of oil or oil equivalent produces about 4400 gigawatt-hours (= 4.4 terawatt-hours) of electricity in a modern power station.

1 barrel of ethanol = 0.58 barrels of oil equivalent
1 barrel of biodiesel = 0.86 barrels of oil equivalent
1 tonne of ethanol = 0.68 tonnes of oil equivalent
1 tonne of biodiesel = 0.88 tonnes of oil equivalent

Definitions

Statistics published in this review are taken from government sources and published data. No use is made of confidential information obtained by BP in the course of its business.

Country, regions and geographic groupings

Country and geographic groupings are made purely for statistical purposes and are not intended to imply any judgement about political or economic standings.

North America
US (excluding US territories), Canada, Mexico.

South & Central America
Caribbean (including Puerto Rico and US Virgin Islands), Bermuda, Central and South America.

Europe
European members of the OECD plus Albania, Bosnia-Herzegovina, Bulgaria, Croatia, Cyprus, Georgia, Gibraltar, Latvia, Lithuania, Malta, Montenegro, North Macedonia, Romania, Serbia and Ukraine.

Commonwealth of Independent States (CIS)
Armenia, Azerbaijan, Belarus, Kazakhstan, Kyrgyzstan, Moldova, Russian Federation, Tajikistan, Turkmenistan, Uzbekistan.

Middle East
Arabian Peninsula, Iran, Iraq, Israel, Jordan, Lebanon, Syria.

North Africa
Territories on the north coast of Africa from Egypt to Western Sahara.

West Africa
Territories on the west coast of Africa from Mauritania to Angola, including Cape Verde, Chad.

East and Southern Africa
Territories on the east coast of Africa from Sudan to Republic of South Africa. Also Botswana, Madagascar, Malawi, Namibia, Uganda, Zambia, Zimbabwe.

Asia Pacific
Brunei, Cambodia, China†, China Hong Kong SAR*, China Macau SAR*, Indonesia, Japan, Laos, Malaysia, Mongolia, North Korea, Philippines, Singapore, South Asia (Afghanistan, Bangladesh, India, Myanmar, Nepal, Pakistan, Sri Lanka), South Korea, Taiwan, Thailand, Vietnam, Australia, New Zealand, Papua New Guinea, Oceania.

†Mainland China.
*Special Administrative Region.

Australasia
Australia, New Zealand.

OECD members
Europe: Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Luxembourg, Netherlands, Norway, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, UK.
Other member countries: Australia, Canada, Chile, Israel, Japan, Mexico, New Zealand, South Korea, US.

OPEC members
Middle East: Iran, Iraq, Kuwait, Qatar, Saudi Arabia, United Arab Emirates.
North Africa: Algeria, Libya.
West Africa: Angola, Equatorial Guinea, Gabon, Nigeria, Republic of Congo.
South America: Ecuador, Venezuela.

European Union members
Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, UK.

Non-OECD
All countries that are not members of the OECD.

Methodology

Primary energy consumption is reported in net terms. The gross calorific value to net calorific value adjustment is fuel-specific.

The primary energy values of nuclear and hydroelectric power generation, as well as electricity from renewable sources, have been derived by calculating the equivalent amount of fossil fuel required to generate the same volume of electricity in a thermal power station, assuming a conversion efficiency of 38% (the average for OECD thermal power generation).

Fuels used as inputs for conversion technologies (gas-to-liquids, coal-to-liquids and coal-to-gas) are counted as production for the source fuel and the outputs are counted as consumption for the converted fuel.

Percentages
Calculated before rounding of actuals.

Rounding differences
Because of rounding, some totals may not agree exactly with the sum of their component parts.

Tonnes
Metric equivalent of tons.

48.8 Liquid Fuel Measurements and Conversions

Gasoline Petrol
1 gallon = 125,000 Btu – HHV *
1 gallon = 131.9 megajoules – HHV *
1 gallon = 115,400 Btu – LHV *
1 gallon = 121.7 megajoules – LHV *
1 gallon = .002791 metric tons
1 barrel = 5,250,000 Btu – HHV *
1 barrel = 5,539 megajoules – HHV *
1 barrel = 4,846,800 Btu – LHV *
1 barrel = 5,113 megajoules – LHV *
1 barrel = .1172 metric tons
1 liter = 33,025 Btu – HHV *
1 liter = 30,489 Btu – LHV *
1 liter = 34.8 megajoules – HHV *
1 liter = 32.2 megajoules – LHV *
1 metric ton = 8.5 barrels
1 metric ton = 1.351 kiloliters
1 kiloliter = .740 metric tons

Diesel fuel
1 gallon = 138,700 Btu – HHV *
1 gallon = 146.3 megajoules – HHV *
1 gallon = 128,700 Btu – LHV *
1 gallon = 135.8 megajoules – LHV *
1 gallon = .003192 metric tons
1 barrel = 5,825,400 Btu – HHV *
1 barrel = 6,146 megajoules – HHV *
1 barrel = 5,405,400 Btu – LHV *
1 barrel = 5,703 megajoules LHV *
1 barrel = .1341 metric tons
1 metric ton = 7.5 barrels
1 kiloliter = .839 metric tons
1 metric ton = 1.192 kiloliters
1 liter = 36,645 Btu – HHV *
1 liter = 38.7 megajoules – HHV *
1 liter = 34,003 Btu – LHV *
1 liter = 35.9 megajoules – LHV *

Ethanol
1 gallon = 84,600 Btu – HHV *
1 gallon = 89.3 megajoules – HHV *
1 gallon = 75,670 Btu – LHV *
1 gallon = 79.8 megajoules – LHV *
1 barrel = 3,553,200 Btu – HHV *

1 barrel = 3,749 megajoules -- HHV *
1 barrel = 3,178,140 Btu – LHV *
1 barrel = 3,353 megajoules – LHV *
1 liter = 22,351 Btu – HHV *
1 liter = 23.6 megajoules – HHV *
1 liter = 19.992 Btu – LHV *
1 liter = 21.1 megajoules – LHV *
Ethanol average density = .79 grams per milliliter
Ethanol average density = .79 metric tons per cubic meter

Bio-diesel
1 gallon = 126,206 Btu – HHV *
1 gallon = 133.1 megajoules – HHV *
1 gallon = 117,093 Btu – LHV *
1 gallon = 123.5 megajoules – LHV *
1 barrel = 5,300,652 Btu – HHV *
1 barrel = 5,592 megajoules – HHV *
1 barrel = 4,917,906 Btu – LHV *
1 barrel = 5,188 megajoules – LHV *
1 liter = 33,344 Btu – HHV *
1 liter = 35.2 megajoules – HHV *
1 liter = 30,936 Btu – LHV *
1 liter = 32.6 megajoules – LHV *
1 metric ton of biodiesel = 37.8 gigajoules
Bio-diesel average density = .88 grams per milliliter
Bio-diesel average density = .88 metric tons per cubic meter

Residual Fuel
1 gallon = 149,700 Btu – HHV *
1 gallon = 157.9 megajoules – HHV *
1 gallon = 138,400 Btu – LHV *
1 gallon = 146.0 megajoules – LHV *
1 barrel = 6,287,400 Btu – HHV *
1 barrel = 6,633 megajoules – HHV *
1 barrel = 5,812,800 Btu – LHV *
1 barrel = 6,133 megajoules – LHV *
1 liter = 39,551 Btu – HHV *
1 liter = 41.7 megajoules – HHV *
1 liter = 36,565 Btu – LHV *
1 liter = 38.6 megajoules – LHV *

LP Gas (liquefied petroleum gas – propane)
1 gallon = 91,300 Btu – HHV *
1 gallon = 96.3 megajoules – HHV *
1 gallon = 83,500 Btu – LHV *

1 gallon = 88.1 megajoules – LHV *
1 barrel = 3,834,600 Btu – HHV *
1 barrel = 4,046 megajoules – HHV *
1 barrel = 3,507,000 Btu – LHV *
1 barrel = 3,700 megajoules – LHV *
1 liter = 24,121 Btu – HHV *
1 liter = 25.4 megajoules – HHV *
1 liter = 22,061 Btu – LHV *
1 liter = 23.3 megajoules – LHV *
1 barrel = .086 metric tons
1 metric ton = 11.6 barrels
1 kiloliter = .542 metric tons
1 metric ton = 1.844 kiloliters

Methanol
1 gallon = 64,600 Btu – HHV *
1 gallon = 68.2 megajoules – HHV *
1 gallon = 56,560 Btu –LHV *
1 gallon = 59.7 megajoules – LHV *
1 barrel = 2,713,200 Btu – HHV *
1 barrel = 2,862 megajoules – HHV *
1 barrel = 2,375,520 Btu -- LHV *
1 barrel = 2,506 megajoules – LHV *
1 liter = 17,067 Btu – HHV *
1 liter = 18.0 megajoules – HHV *
1 liter = 14,943 Btu – LHV *
1 liter = 15.8 megajoules – LHV *

Butane
1 gallon = 103,000 Btu – HHV *
1 gallon = 108.7 megajoules – HHV *
1 gallon = 93,000 Btu – LHV *
1 gallon = 98.1 megajoules – LHV *
1 barrel = 4,326,000 Btu – HHV *
1 barrel = 4,564 megajoules – HHV *
1 barrel = 3,906,000 Btu -- LHV *
1 barrel = 4,121 megajoules – LHV *
1 liter = 27,213 Btu – HHV *
1 liter = 28.7 megajoules – HHV *
1 liter = 24,571 Btu – LHV *
1 liter = 25.9 megajoules – LHV *

Barrels of petroleum or related products (bbl) measurements and conversions

Crude Oil (based on worldwide average gravity)
1 barrel = 42 gallons
1 drum = 55 gallons
1 metric drum = 52.8 gallon
1 gallon = .0182 drum
1 gallon = .0189 metric drum
1 gallon = 138,100 Btu – HHV *
1 gallon = 145.7 megajoules – HHV *
1 gallon = 131,800 Btu – LHV *
1 gallon = 139.0 megajoules – LHV *
1 gallon = .003247 metric tons
1 gallon = .0038 kiloliters
1 gallon = .0238 barrels
1 barrel = 5,800,200 Btu – HHV *
1 barrel = 6,119 megajoules – HHV *
1 barrel = 5,535,600 Btu – LHV *
1 barrel = 5,840 megajoules – LHV *
1 barrel = .13637 metric tons
1 barrel = .159 kiloliters
1 liter = 36,486 Btu – HHV *
1 liter = 38.5 megajoules – HHV *
1 liter = 34,822 Btu – LHV *
1 liter = 36.7 megajoules – LHV *
1 kiloliter = .8581 metric tons
1 kiloliter = 6.2898 barrels
1 kiloliter = 264.17 gallons
1 kiloliter = 1 cubic meter
1 metric ton = 1.165 kiloliters
1 metric ton = 7.33 barrels
1 metric ton = 307.86 gallons

1 barrel of crude oil = 44.60 gallons of petroleum products

Oil Equivalents

A barrel (metric ton) of oil equivalent is a unit of energy based on the approximate energy released by burning one barrel (metric ton) of crude oil.

1 barrel oil equivalent (bboe) = .1364 metric tons oil equivalent
1 barrel oil equivalent = approximately 1.364 million kilocalories
1 barrel oil equivalent = approximately 5.73 gigajoules
1 barrel oil equivalent = approximately .20 metric tons of hard coal
1 barrel oil equivalent = approximately .41 metric tons of lignite coal
1 barrel oil equivalent = approximately 1.64 metawatt-hours
1 million barrels oil equivalent = .16 billion cubic meters natural gas
1 million barrels oil equivalent = 5.61 billion cubic feet natural gas
1 million barrels oil equivalent = .12 million metric tons of liquefied natural gas

1 million barrels oil equivalent = 5.8 trillion Btus
1 million barrels oil equivalent = .14 million metric tons oil equivalent
1 metric ton oil equivalent (toe) = 7.33 barrels oil equivalent
1 metric ton oil equivalent = approximately 10 million kilocalories
1 metric ton oil equivalent = approximately 42 gigajoules
1 metric ton oil equivalent = approximately 1.5 metric tons of hard coal
1 metric ton oil equivalent = approximately 3 metric tons of lignite coal
1 metric ton oil equivalent = approximately 12 megawatt-hours
1 million metric tons oil equivalent = 1.111 billion cubic meters natural gas
1 million metric tons oil equivalent = 39.2 billion cubic feet natural gas
1 million metric tons oil equivalent = .805 million tons liquefied natural gas
1 million metric tons oil equivalent = 7.33 million barrels oil equivalent

Refined petroleum products
1 metric ton motor gasoline = 8.53 barrels
1 metric ton LP-gas (liquefied petroleum gas) (propane) = 11.6 barrels
1 metric ton natural gas = 10 barrels
1 metric ton NGL (natural gas liquids) = 10.4 barrels

Liquid fuels
1 cubic meter = 6.289 barrels
1 barrel = 159 liters
1 barrel = 42 US gallons
1 U.S. gallon = 231 cubic inches
1 U.S. gallon = .1337 cubic feet
1 U.S. gallon = 3.785 liters
1 U.S. gallon = .8321 imperial gallons
1 U.S. gallon = .0238 barrels
1 U.S. gallon = .003785 cubic meters
1 liter = 61.02 cubic inches
1 liter = .03531 cubic feet
1 liter = .2642 U.S. gallons
1 liter = .22 imperial gallons
1 liter = .00629 barrels
1 liter = .001 cubic meters

Flow Rate
1 barrel per hour = 137.8 cubic feet per day
1 barrel per hour = 49,187 cubic feet per year
1 barrel per hour = 1,008 U.S. gallons per day
1 barrel per hour = 367,920 U.S. gallons per year
1 barrel per hour = 839.3 imperial gallons per day
1 barrel per hour = 306,345 imperial gallons per year
1 barrel per hour = 3,815 liters per day
1 barrel per hour = 1,392,475 liters per year

1 gallon per hour = .5712 barrels per day
1 gallon per hour = 207.92 barrels per year
1 liter per hour = .1510 barrels per day
1 liter per hour = 55.10 barrels per year

48.9 Fuel usage measurements and conversions

1 mile per gallon = .264 miles per liter
1 mile per gallon = .425 kilometers per liter
1 mile per gallon = 235 liters per 100 kilometers
1 mile per gallon = 100 gallons per 100 miles
1 mile per liter = 3.79 miles per gallon
1 mile per liter = 1.609 kilometers per liter
1 mile per liter = 62.15 liters per 100 kilometers
1 kilometer per liter = 2.35 miles per gallon
1 kilometer per liter = .6215 miles per liter
1 kilometer per liter = 100 liters per 100 kilometers
1 kilometer per liter = 42.5 gallons per 100 miles

* Energy contents are expressed as either High (gross) Heating Value (HHV) or Lower (net) Heating Value (LHV). LHV is closest to the actual energy yield in most cases. HHV (including condensation of combustion products) is greater by between 5% (in the case of coal) and 10% (for natural gas), depending mainly on the hydrogen content of the fuel. For most biomass feed-stocks this difference appears to be 6-7%. The appropriateness of using LHV or HHV when comparing fuels, calculating thermal efficiencies, etc. really depends upon the application. For stationary combustion where exhaust gases are cooled before discharging (e.g. power stations), HHV is more appropriate. Where no attempt is made to extract useful work from hot exhaust gases (e.g. motor vehicles), the LHV is more suitable. In practice, many European publications report LHV, whereas North American publications use HHV. (Source: Bioenergy Feedstock Network -- https://bioenergy.ornl.gov/)