Achieving the Paris Climate Agreement Goals

Sven Teske
Editor

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Global and Regional 100% Renewable Energy Scenarios with Non-energy GHG Pathways for +1.5°C and +2°C

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For the next generation.
For my son, Travis.

Climate Model: Foreword

In October of 2018, the Intergovernmental Panel on Climate Change issued its starkest warning yet: we have around 12 years to avoid the worst effects of anthropogenic climate change. The consumption of fossil fuels, the reckless destruction of forests and other natural ecosystems, and the release of powerful greenhouse gases have already caused around 1.0 °C of warming above pre-industrial levels.

Continuing at the current rate, we are likely to reach 1.5 °C by 2030 – and all the evidence suggests that a world beyond 1.5 °C is not one we want to live in.

While making the 2016 documentary film, *Before the Flood*, I witnessed first-hand the impacts of an already-changing climate: the rapid melting of ice in the Arctic Circle, massive bleaching of coral reefs in the Bahamas, and rampant deforestation in Indonesia and the Amazon. Better than ever, we understand the heart-breaking impact of human activity on our natural world. It is estimated, for example, that 60% of animals have been wiped out since 1970.

Higher temperatures and extreme weather events will cause ever more severe harm to biodiversity and ecosystems and even greater species loss and extinction. And when we lose biodiversity, we lose resilience. Currently, natural ecosystems absorb about half of human-caused carbon dioxide emissions. If we continue to degrade the natural world, we could lose completely the Earth's ability to adapt to climate change.

A passion for nature conservation and animal protection has driven much of my foundation's work over the past 20 years. Ultimately, however, the climate crisis is a humanitarian one. If business-as-usual continues, the impact on human beings will be immeasurable. Water supplies will become more insecure. Sea level rise will profoundly impact islands, low-lying coastal areas, and river deltas. Small island communities like those I visited in the South Pacific are already preparing for migration to safer lands. Fatal floods, droughts, hurricanes, and wildfires are the new normal, and happening closer to home. An estimated 41 million Americans live within a 100-year flood zone. Texas saw its third 500-year flood 3 years in a row.

Poor air quality is a public health emergency across the world and now the fourth-highest cause of death – contributing to strokes, heart attacks, and lung cancer – causing public unrest in countries like China and India, where the poorest find themselves at the mercy of pollution from industrial facilities and the burning of biomass. In states like Texas, Colorado, and North Dakota, communities are fighting back against gas drilling operations near playgrounds or soccer fields, where children breathe in poisonous gases.

These health impacts are only part of the story. Climate change, as the US Pentagon notes, is a national security threat. In a 2017 report by the Environmental Justice Foundation, senior US military experts pointed to the likelihood of tens of millions of climate refugees displaced by extreme weather – in a world already struggling with a refugee crisis. We already know that many conflicts are driven by environmental factors and access to natural resources. The truth is that, where ecosystems collapse, societies collapse too.

Politically, there has been a monumental failure to grasp the scale of this problem. Climate scientists still face disinformation campaigns and a press corps that often draws a false equivalence between those who support the scientific consensus for human-caused climate change and those who do not. Surveys suggest that most Americans do not know a scientific consensus exists, and scientists like Michael Mann, who spoke to me for *Before the Flood*, face abuse for exposing the truth. As a result, scientific research programs, critical to better understanding and addressing climate change, are often attacked or defunded.

Nevertheless, in the face of these challenges, some progress is being made. With the growth of the environmental movement, public awareness of the climate crisis has increased significantly. Governments and the private sector are beginning to ramp up their efforts. Renewable energy is booming. And the UN Sustainable Development Goals, ratified by 193 countries, now call for a halt to deforestation and land degradation by 2030. After decades of climate negotiations, the Paris Agreement now calls upon the world's governments to keep warming "well below 2°C" while striving for 1.5°C.

While we are beginning to move in the right direction, the reality is that these efforts are simply not ambitious enough to address the climate crisis at scale. The IPCC warns that to avoid the worst consequences of climate change, we must stay below the 1.5 °C limit. But what does that mean in practical terms?

Determined to find solutions, my foundation supported a 2-year research program led by a team of international climate and energy experts to develop a roadmap for how we can actually stay below this critical climate threshold. The findings, outlined in this book, give cause for optimism. With a transition to 100% renewable energy by mid-century and a major land conservation and restoration effort, it is possible to stay below the 1.5 °C limit with technologies that are available right now. It will be a lot of work, but the costs will be far less than the $5 trillion per year governments currently spend subsidizing the fossil fuel industries responsible for climate change.

The climate model and energy transition pathways compiled in this book offer an exciting, positive, and achievable vision of a better world in which we are no longer dependent on fossil fuels and where the conservation and restoration of nature is treated as indispensable to our survival. This is not fantasy. This is science.

Science is showing us the way forward, but you do not need to be a scientist to understand that climate change is the defining issue of our time. If our world warms past 1.5 °C, our way of life will profoundly change for the worse. Why not manage the transition in a way that is orderly and equitable? Human beings caused this problem, but with our vast knowledge and ingenuity, we can also fix it.

We are resilient. We can adapt. We can change.

Chairman of the Leonardo DiCaprio Foundation Leonardo DiCaprio

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Executive Summary

Abstract An overview of the motivations behind the writing of this book, the scientific background and context of the research. Brief outline of all methodologies used, followed by assumptions and the storyline of each scenario. Presentation of main results of the renewable energy resources assessment, transport scenario, long-term energy pathway, the power sector analysis, employment analysis and an assessment for required metals for renewable energy and storage technologies. Key results of non-energy greenhouse mitigation scenarios which are developed in support of the energy scenario in order to achieve the 1.5 °C target. Concluding remarks and policy recommendations including graphs and tables.

Introduction The Paris Climate Agreement aims to hold global warming to well below 2 degrees Celsius (°C) and to "pursue efforts" to limit it to 1.5 °C. To accomplish this, countries have submitted *Intended Nationally Determined Contributions* (INDCs) outlining their post-2020 climate actions (Rogelj 2016). This research aimed to develop practical pathways to achieve the Paris climate goals based on a detailed bottom-up examination of the potential of the energy sector, in order to avoid reliance on net negative emissions later on.

The study described in this book focuses on the ways in which humans produce energy, because energy-related carbon dioxide (CO_2) emissions are the main drivers of climate change. The analysis also considers the development pathways for non-energy-related emissions and mitigation measures for them because it is essential to address their contributions if we are to achieve the Paris climate change targets.

State of Research—Climate Beyond reasonable doubt, climate change over the last 250 years has been driven by anthropogenic activities. In fact, the human-induced release of greenhouse gas emissions into the atmosphere warms the planet even more than is currently observed as climate change, but some of that greenhouse-gas-induced warming is masked by the effect of aerosol emissions.

Carbon dioxide emissions are so large that they are the dominant driver of human-induced climate change. A single kilogram of CO_2 emitted will increase the atmospheric CO_2 concentration over hundreds or even thousands of years. Since the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report, the finding that cumulative CO_2 emissions are roughly linearly related to temperature has shaped scientific and political debate. The remaining permissible CO_2 emissions that are consistent with a target temperature increase of 2 °C or 1.5 °C and their comparison with remaining fossil fuel resources are of key interest.

The IPCC Fifth Assessment Report concluded that beyond 2011, cumulative CO_2 emissions of roughly 1000 $GtCO_2$ are permissible for a "likely below 2.0 °C" target change, and approximately 400 $GtCO_2$ are permissible for a 1.5 °C target change. However, the recently published IPCC Special Report on the 1.5 °C target suggests substantially higher carbon emissions of 1600 $GtCO_2$ will achieve a 2.0 °C change and 860 GtCO2 will achieve a 1.5 °C change, which must be reduced by a further 100 $GtCO_2$ to account for additional Earth system feedback over the twenty-first century. One of the key reasons behind this difference is definitional: how far do we consider that we are away from 1.5 °C warming? While that question seems simple, it is surprisingly complex when the observational data on coverage, the internal variability and the pre-industrial to early-industrial temperature differences are considered.

This study does not resolve the differences in opinions about carbon budgets, but it does provide emission pathways that are consistent with the 1.5 °C target increase in the 1.5 °C Scenario, or with the "well below 2.0 °C" target increase in the 2.0 °C Scenario consistent with other scenarios in the literature and classified as such by the IPCC Special Report on 1.5 °C.

Global Trends in the Energy Sector In 2017, the ongoing trends continued: solar photovoltaics (PV) and wind power dominated the global market for new power plants; the price of renewable energy technologies continued to decline; and fossil fuel prices remained low. A new benchmark was reached, in that the new renewable capacity began to compete favourably with existing fossil fuel power plants in some markets. Electrification of the transport and heating sectors is gaining attention, and although the amount of electrification is currently small, the use of renewable technologies is expected to increase significantly.

The growth of solar PV has been remarkable and is nearly double that of the second-ranking wind power. The capacity of new solar PV in 2017 was greater than the combined increases in the coal, gas and nuclear capacities. Renewable energy technologies achieved a global average generation share of 23% in the year 2015, compared with 18% in the year 2005. Storage is increasingly used in combination with variable renewables as battery costs decline, and solar PV plus storage has started to compete with gas peaking plants. However, bioenergy (including traditional biomass) remains the leading renewable energy source in the heating (buildings and industry) and transport sectors.

Since 2013, global energy-related carbon dioxide (CO_2) emissions from fossil fuels have remained relatively flat. Early estimates based on preliminary data suggest that this changed in 2017, with global CO_2 emissions increasing by around 1.4% (REN21-GSR 2018). These increased emissions were primarily attributable to increased coal consumption in China, which grew by 3.7% in 2017 after a 3-year decline. The increased Chinese consumption, as well as a steady growth of around 4% in India, is expected to lead to an upturn in global coal use, reversing the annual global decline from 2013 to 2016.

In 2017, as in previous years, renewables saw the greatest increases in capacity in the power sector, whereas the growth of renewables in the heating, cooling and transport sectors was comparatively slow. Sector coupling—the interconnection of power, heating and transport and particularly the electrification of heating and transport—is gaining increasing attention as a means of increasing the uptake of renewables in the transport and thermal sectors. Sector coupling also allows the integration of large proportions of variable renewable energy, although this is still at an early stage. For example, China is specifically encouraging the electrification of heating, manufacturing and transport in high-renewable areas, including promoting the use of renewable electricity for heating to reduce the curtailment of wind, solar PV and hydropower. Several US states are examining options for electrification, specifically to increase the overall renewable energy share.

Methodology for Developing Emission Pathways The complete decarbonisation of the global energy supply requires entirely new technical, economic and policy frameworks for the electricity, heating and cooling sectors as well as for the transport system. To develop a global plan, the authors combined various established computer models:

- *Generalized Equal Quantile Walk (GQW)*: This statistical method is used to complement the CO_2 pathways with non-CO_2 regional emissions for relevant greenhouse gases (GHGs) and aerosols, based on a statistical analysis of the large number (~700) of multi-gas emission pathways underlying the recent IPCC Fifth Assessment Report and the recently published IPCC Special Report on 1.5 °C. The GQW method calculates the median non-CO_2 gas emission levels every 5 years—conditional on the energy-related CO_2 emission level percentile of the "source" pathway. This method is a further development under this project—building on an earlier Equal Quantile Walk method—and is now better able to capture the emission dynamics of low-mitigation pathways.
- *Land-based sequestration design*: A Monte Carlo analysis across temperate, boreal, subtropical and tropical regions has been performed based on various literature-based estimates of sequestration rates, sequestration periods and areas available for a number of sequestration options. This approach can be seen as a quantified literature-based synthesis of the potential for land-based CO_2 sequestration, which is not reliant on biomass plus sequestration and storage (bioenergy with carbon capture and storage, BECCS).
- *Carbon cycle and climate modelling (Model for the Assessment of Greenhouse Gas-Induced Climate Change, MAGICC)*: This study uses the MAGICC climate model, which also underlies the classification used by both the IPCC Fifth Assessment Report and the IPCC Special Report on 1.5 °C in terms of the abilities of various scenarios to maintain the temperature change below 2 °C or 1.5 °C. MAGICC is constantly evolving, but its core goes back to the 1980s, and

it represents one of the most established reduced-complexity climate models in the international community.

- *Renewable Resource Assessment [R]E-SPACE*: RE-SPACE is based on a Geographic Information Systems (GIS) approach and provides maps of the solar and wind potentials in space-constrained environments. GIS attempts to emulate processes in the real world at a single point in time or over an extended period (Goodchild 2005). The primary purpose of GIS mapping is to ascertain the renewable energy resources (primarily solar and wind) available in each region. It also provides an overview of the existing electricity infrastructures for fossil fuel and renewable sources.
- *Transport model (TRAEM)*: The transport scenario model allows the representation of long-term transport developments in a consistent and transparent way. The model disaggregates transport into a set of different modes and calculates the final energy demand by multiplying each transport mode's specific transport demand with powertrain-specific energy demands, using a passenger km (pkm) and tonne km (tkm) activity-based bottom-up approach.
- *Energy system model (EM)*: The energy system model (a long-term energy scenario model) is used as a mathematical accounting system for the energy sector. It helps to model the development of energy demands and supply according to the development of drivers and energy intensities, energy potentials, future costs, emission targets, specific fuel consumption and the physical flow between processes. The data available significantly influence the model architecture and approach. The energy system model is used in this study to develop long-term scenarios for the energy system across all sectors (power, heat, transport and industry), without applying cost-optimization based on uncertain cost assumptions. However, an ex-post analysis of costs and investments shows the main economic effects of the pathways.
- *Power system models [R]E 24/7*: Power system models simulate electricity systems on an hourly basis with geographic resolution to assess the requirements for infrastructure, such as the grid connections between different regions and electricity storage, depending on the demand profiles and power-generation characteristics (Teske 2015). High-penetration or renewable energy-only scenarios will contain significant proportions of variable solar PV and wind power because they are inexpensive. Therefore, power system models are required to assess the demand and supply patterns, the efficiency of power generation and the resulting infrastructural needs. Meteorological data, typically in 1 h steps, are required for the power-generation model, and historical solar and wind data were used to calculate the possible renewable power generation. In terms of demand, either historical demand curves were used, or if unavailable, demand curves were calculated based on assumptions of consumer behaviour in the use of electrical equipment and common electrical appliances. Figure 1 provides an overview of the interaction between the energy- and GIS-based models. The climate model is not directly linked with it but provided the carbon budgets for the 2.0 °C and the 1.5 °C Scenarios.

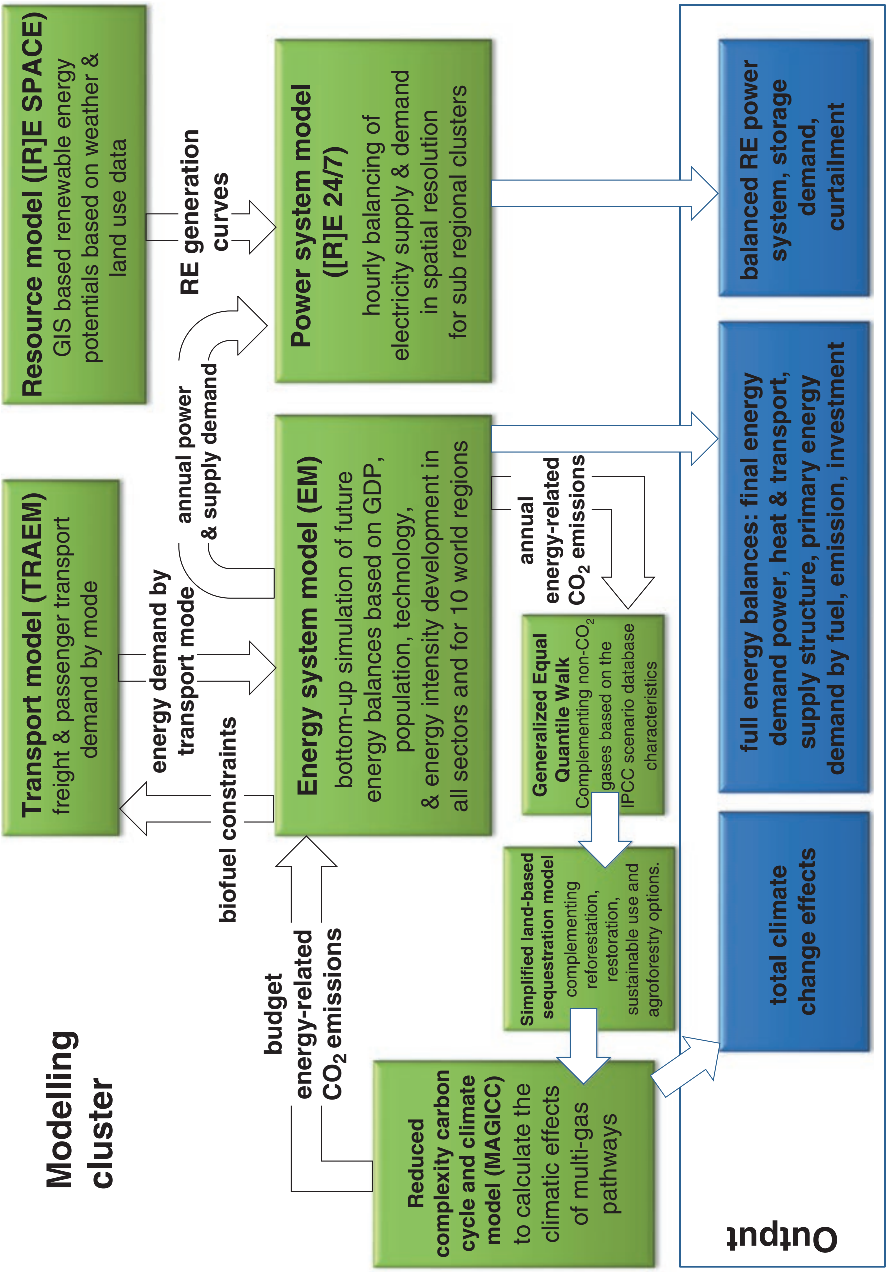

Fig. 1 Interactions between the models used in this study

Besides the climate and energy models, employment effects and the metal resource requirements for selected materials have been calculated. Now that the methodology has been outlined, the next sections present the results and assumptions for the nonenergy GHG mitigation scenarios, followed by the energy sector scenarios

Nonenergy-GHG Mitigation Scenarios The most important sequestration measure could be large-scale reforestation, particularly in the subtropics and tropics (see yellow pathways in Fig. 2). The second most important pathway in terms of the amount of CO_2 sequestered is the sustainable use of existing forests, which basically means reduced logging within those forests. In subtropical, temperate and boreal regions, this could provide substantial additional carbon uptake over time. The time horizon for this sequestration option is assumed to be slightly longer in temperate and boreal regions, consistent with the longer time it takes for these forest ecosystems to reach equilibrium. The "forest ecosystem restoration" pathway is also important, which basically assumes a reduction in logging rates to zero in a fraction of forests.

Overall, the median assumed sequestration pathways, shown in Fig. 2, would result in the sequestration of 151.9 GtC. This is approximately equivalent to all historical land-use-related CO_2 emissions and indicates the substantial challenges that accompany these sequestration pathways.
Given the competing forms of land use throughout the world today, the challenge of reversing overall terrestrial carbon stocks back to pre-industrial levels cannot be underestimated. There would be significant benefits, but also risks, if this

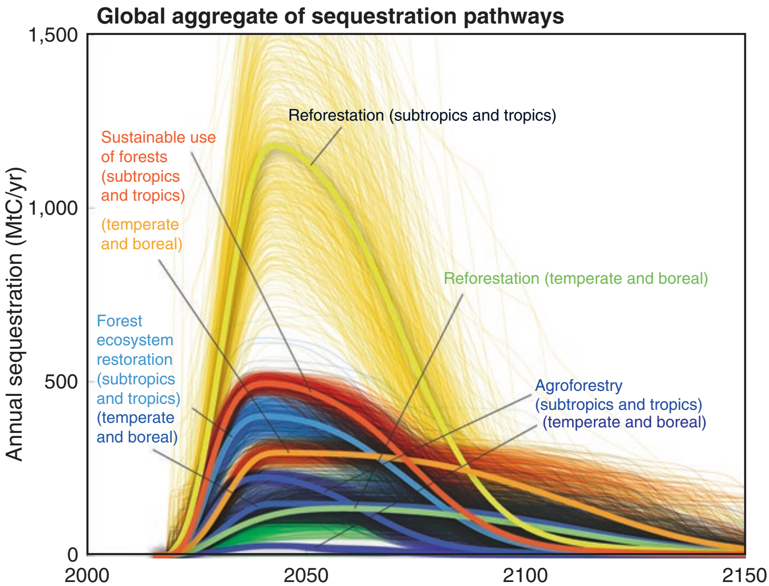

Fig. 2 Sequestration pathways—annual sequestration over time

sequestration option were to be used *instead* of mitigation. However, the benefits are clearly manifold, ranging from biodiversity protection, reduced erosion, improved local climates, protection from wind and potentially reduced air pollution.

Assumptions for Scenarios Scenario studies cannot predict the future. Instead, scenarios describe what is required for a pathway that will limit warming to a certain level and that is feasible in terms of technology implementation and investment. Scenarios also allow us to explore the possible effects of transition processes, such as supply costs and emissions. The energy demand and supply scenarios described in this study have been constructed based on information about current energy structures and today's knowledge of energy resources and the costs involved in deploying them. As far as possible, the study also takes into account potential regional constraints and preferences.

The energy modelling used primarily aims to generate transparent and coherent scenarios, ambitious but still plausible storylines, out of several possible techno-economic pathways. Knowledge integration is the core of this approach because we must consider different technical, economic, environmental and societal factors. Scenario modelling follows a hybrid bottom-up/top-down approach, with no objective cost-optimization functions. The analysis considers key technologies for successful energy transition and focuses on the role and potential utility of efficiency measures and renewable energies. Wind and solar energies have the highest economic potential and dominate the pathways on the supply side. However, the variable renewable power from wind and PV remains limited to a maximum of 65%, because sufficient secured capacity must always be maintained in the electricity system. Therefore, we also consider concentrating solar power (CSP) with high-temperature heat storage as a solar option that promises large-scale dispatchable and secured power generation.

The 5.0 °C Scenario (Reference Scenario): The reference scenario only takes into account existing international energy and environmental policies and is based on the International Energy Agency (IEA) World Energy Outlook (IEA 2017). Its assumptions include, for example, continuing progress in electricity and gas market reforms, the liberalization of cross-border energy trade and recent policies designed to combat environmental pollution. The scenario does not include additional policies to reduce GHG emissions. Because the IEA's projections only extend to 2040, we extrapolate their key macroeconomic and energy indicators forward to 2050. This provides a baseline for comparison with the 2.0 °C and 1.5 °C Scenarios.

The 2.0 °C Scenario: The first alternative scenario aims for an ambitious reduction in GHG emissions to zero by 2050 and a global energy-related CO_2 emission budget of around 590 Gt between 2015 and 2050. This scenario is close to the assumptions and results of the Advanced E[R] scenario published in 2015 by Greenpeace (Teske et al. 2015). However, it includes an updated base year, more coherent regional developments in energy intensity, and reconsidered trajectories and shares of the deployment of renewable energy systems. Compared with the 1.5 °C Scenario, the

2.0 °C Scenario allows for some delays due to political, economic and societal processes and stakeholders.

The 1.5 °C Scenario: The second alternative scenario aims to achieve a global energy-related CO_2 emission budget of around 450 Gt, accumulated between 2015 and 2050. The 1.5 °C Scenario requires immediate action to realize all available options. It is a technical pathway, not a political prognosis. It refers to technically possible measures and options without taking into account societal barriers. Efficiency and renewable potentials need to be deployed even more quickly than in the 2.0 °C Scenario, and avoiding inefficient technologies and behaviours is an essential strategy for developing regions in this scenario.

Global Transport Transport emissions have increased at a rapid rate in recent decades and accounted for 21% of total anthropogenic CO_2 emissions in 2015. The reason for this steady increase in emissions is that passenger and freight transport activities are increasing in all world regions, and there is currently no sign that these increases will slow in the near future. The increasing demand for energy for transport has so far been predominantly met by GHG-emitting fossil fuels. Although (battery) electric mobility has recently surged considerably, it has done so from a very low base, which is why in terms of total numbers, electricity remains an energy carrier with a relatively minor role in the transport sector.

The key results of our transport modelling demonstrate that meeting the 2.0 °C Scenario, and especially the 1.5 °C Scenario, will require profound measures in terms of rapid powertrain electrification and the use of biofuels and synthetically produced fuels to shift transport performance to more efficient modes. This must be accompanied by a general limitation of further pkm and tkm growth in the OECD countries.

The *5.0 °C Scenario* follows the IEA World Energy Outlook (WEO) scenario until 2040, with extrapolation to 2050. Only a minor increase in electrification over all transport modes is assumed, with passenger cars and buses increasing their electric vehicle (EV) shares. For example, this study projects a share of 30% for battery electric vehicles (BEVs) in China by 2050 in response to the foreseeable legislation and technological advancement in that country, whereas for the world car fleet, the share of BEVs is projected to increase to only around 10%. Growth in the shares of electric powertrains and two- and three-wheel vehicles in the commercial road vehicle fleet will be small, as will the rise in further rail electrification. Aviation and navigation (shipping) are assumed to remain fully dependent on conventional kerosene and diesel, respectively.

In the *2.0 °C Scenario* minimal progress in electrification until 2020 will occur, whereas a significant increase in electrification of the transport sector between 2020 and 2030 is projected. This will occur first in OECD regions, followed by emerging economies and finally in developing countries. Battery-driven electric passenger cars are projected to achieve shares of between 21% and 30%, whereas heavy commercial electric vehicles and buses could achieve even higher shares of between 28% and 52% by 2030. This uptake will require a massive build-up of battery

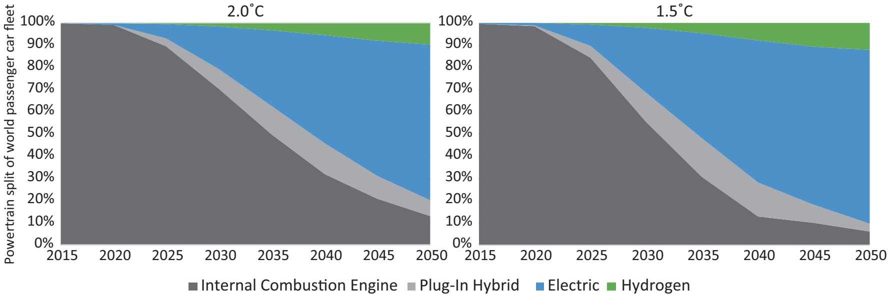

Fig. 3 Powertrain split of the world passenger car fleet in the 2 °C Scenario (left) and 1.5 °C Scenario (right)

production capacity in coming years. Two- and three-wheel vehicles—mainly used in Asia and Africa—will be nearly completely electrified (batteries and fuel cells) by 2030. Looking ahead to 2050, 60–70% of buses and heavy trucks will become (battery-driven) electric, and fuel-cell electric vehicles will increase their market share to around 37%. In the 2.0 °C Scenario, developing countries in Africa and countries in the oil-producing countries of the Middle East will remain predominantly dependent on internal combustion engines, using bio- or synthetic-based fuels.

In the *1.5 °C Scenario*, an earlier and more rapid increase in electric powertrain penetration is required, with the OECD regions at the forefront. The emerging economic regions must also electrify more rapidly than in the 2.0 °C Scenario. On a global level, internal combustion engines will be almost entirely phased out by 2050 in both the 2.0 °C and 1.5 °C Scenarios. In OECD regions, cars with internal combustion engines (using oil-based fuels) will be phased out by 2040, whereas in Latin America or Africa, for example, a small share of internal combustion engine internal combustion engine (ICE)-powered cars, fuelled with biofuels or synthetic fuels, will still be on the road but will be constantly replaced by electric drivetrains (Fig. 3).

Efficiency improvements are modelled across all transport modes until 2050, resulting in improved energy intensity over time. We project an increase in annual efficiency of 0.5–1% in terms of MJ/tonnes km or MJ/passenger km, depending on the transport mode and region. Regardless of the types of powertrains and fuels, increasing the efficiency at the MJ/pkm or MJ/tkm level will result from the following measures:

- Reductions in powertrain losses through more efficient motors, gears, power electronics, etc.
- Reductions in aerodynamic drag
- Reductions in vehicle mass through lightweighting
- The use of smaller vehicles
- Operational improvements (e.g. through automatic train operation, load factor improvements)

Transport performance will increase in all scenarios on a global scale but with different speeds and intensities across modes and world regions. Current trends in transport performance until 2050 are extrapolated for the 5.0 °C Scenario. In relative terms, all transport carriers will increase their performance from the current levels, and in particular, energy-intensive aviation, passenger car transport and commercial road transport are projected to grow strongly. In the 2.0 °C Scenario and 1.5 °C Scenario, we project a strong increase in rail traffic (starting from a relatively low base) and slower growth or even a decline in the use of the other modes in all world regions (Fig. 4).

The modal shifts from domestic aviation to rail and from road to rail are modelled. In the 2.0 °C and 1.5 °C Scenarios, passenger car pkm must decrease in the OECD countries (but increase in the developing world regions) after 2020 in order to maintain the carbon budget. The passenger car pkm decline will be partly compensated by an increase in the performances of other transport modes, specifically public transport rail and bus systems.

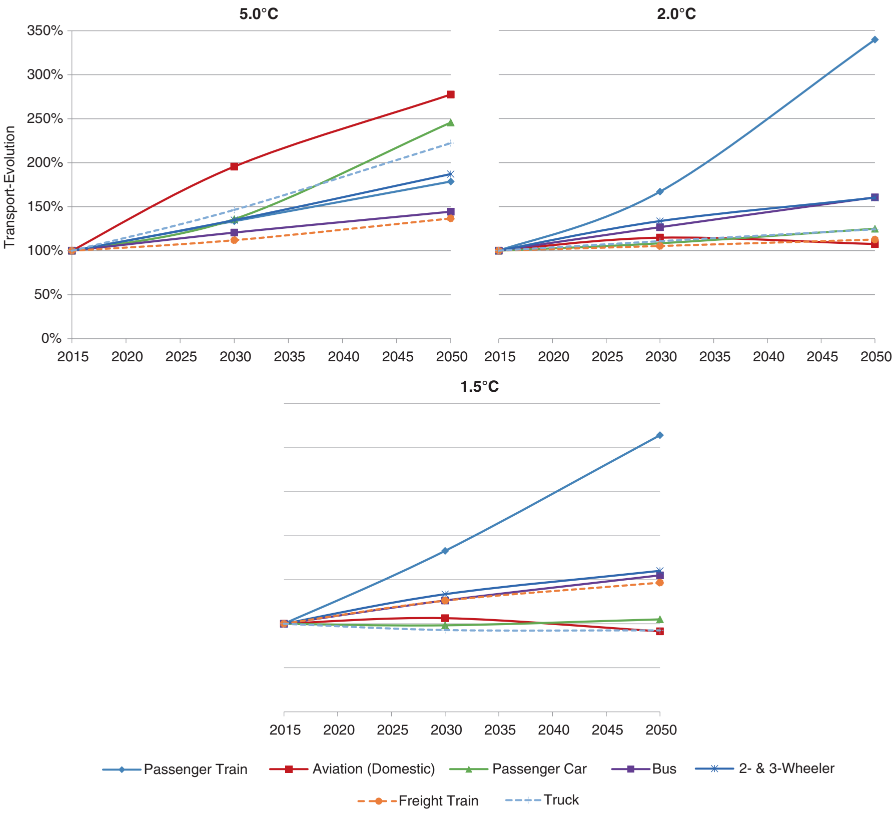

Fig. 4 Relative growth in world transport demand (2015, 100% pkm/tkm) in the 5.0 °C, 2.0 °C and 1.5 °C Scenarios

Global Renewable Energy Potential To develop the 2.0 °C and 1.5 °C Scenarios, the economic renewable energy potential in a space-constrained environment was analysed. Land is a scarce resource. The use of land for nature conservation, agricultural production, residential areas and industry, as well as for infrastructure such as roads and all aspects of human settlement, limits the amount of land available for utility-scale solar and wind projects. Furthermore, solar and wind generation requires favourable climatic conditions, so not all available areas are suitable for renewable power generation. To assess the renewable energy potential based on the area available, all scenario-relevant regions and subregions were analysed with the [R]E-SPACE methodology to quantify the available land area in square kilometres with a defined set of constraints:

- Residential and urban settlements
- Infrastructure for transport (e.g. rail, roads)
- Industrial areas
- Intensive agricultural production land
- Nature conservation areas and national parks
- Wetlands and swamps
- Closed grasslands (as the land-use type)

In addition to this spatial analysis, the remaining available land areas were correlated with the available solar and wind resources. For CSP, a minimum solar radiation of 2000 kilowatt hours per square meter and year (kWh/m^2 year) is assumed to be the minimum deployment criterion, whereas the onshore wind potential under an average annual wind speed of 5 m/s has been omitted.

The 2.0 °C Scenario utilizes only a fraction of the available economic potential of the assumed suitable land for utility-scale solar PV and CSP plants. This estimate does not include solar PV rooftop systems, which have significant additional potential. India has the highest solar utilization rate of 8.5%, followed by Europe and the Middle East, each of which utilizes around 5%. Onshore wind potential has been utilized to a larger extent than solar potential. In the 2.0 °C Scenario, space-constrained India will utilize about half of all the onshore wind energy utilized, followed by Europe, which will utilize one fifth. This wind potential excludes offshore wind, which has significant potential, but mapping the offshore wind potential was beyond the scope of this analysis.

The 1.5 °C Scenario is based on the accelerated deployment of all renewables and the more ambitions implementation of efficiency measures. Thus, the total installed capacity of solar and wind power plants by 2050 is not necessarily larger than it is in the 2.0 °C Scenario, and the utilization rate is in the same order of magnitude. The increased deployment of renewable capacity in the OECD Pacific (Australia), the Middle East and Africa will be due to the production of synthetic bunker fuels based on hydrogen or synthetic fuels (*synfuels*) to supply the global transport energy for international shipping and aviation.

Key results of the global long-term energy scenarios show that the efficiency and uptake of renewable energy are two sides of the same coin. All sectors, including transport, industry and all commercial and residential buildings, must use energy efficiently and from a huge range of renewable energy technologies. Compared with the 5.0 °C Scenario, which was defined using assumptions from the IEA, the alternative scenarios require more stringent efficiency levels. The 1.5 °C Scenario involves the even faster implementation of efficiency measures than in the 2.0 °C Scenario and the decelerated growth of energy services in all regions, in order to avoid a further strong increase in fossil fuel use after 2020.

Global energy intensity will decline from 2.4 MJ/US$GDP in 2015 to 1.25 MJ/US$GDP in 2050 in the 5.0 °C Scenario compared with 0.65 MJ/US$GDP in the 2.0 °C Scenario and 0.59 MJ/US$GDP in the 1.5 °C Scenario. This is a result of the estimated power, heat and fuel demands for all sectors, with more stringent efficiency levels in the alternative scenarios than in the 5.0 °C case. It reflects a further decoupling of the energy demand and gross domestic product (GDP) growth as a prerequisite for the rapid decarbonisation of the global energy system.

Total final energy demand is estimated based on assumptions about the demand drivers, specific energy consumption and the development of energy services in each region. In the 5.0 °C Scenario, the global energy demand will increase by 57% from 342 EJ/year in 2015 to 537 EJ/year in 2050. In the 2.0 °C Scenario, the final energy will be 19% lower than the current consumption and will reach 278 EJ/year by 2050. The final energy demand in the 1.5 °C Scenario will be 253 EJ, 26% below the 2015 demand, and, in 2050, will be 9% lower than in the 2.0 °C Scenario.

Global electricity demand will significantly increase in the alternative scenarios due to the electrification of the transport and heating sectors, which will replace fuels, but will also be due to a moderate increase in the electricity demand of "classical" electrical devices on a global level. In the 2.0 °C Scenario, the electricity demand for heating will be about 12,600 TWh/year from electric heaters and heat pumps, and, in the transport sector, there will be an increase of about 23,400 TWh/year due to electric mobility. The generation of hydrogen (for transport and high-temperature process heat) and the manufacture of synthetic fuels for transport will add an additional power demand of 18,800 TWh/year. The gross power demand will thus rise from 24,300 TWh/year in 2015 to 65,900 TWh/year in 2050 in the 2.0 °C Scenario, 34% higher than in the 5.0 °C Scenario. In the 1.5 °C Scenario, the gross electricity demand will increase to a maximum of 65,300 TWh/year in 2050.

Global electricity generation from renewable energy sources will reach 100% by 2050 in the alternative scenarios. "New" renewables—mainly wind, solar and geothermal energy—will contribute 83% of the total electricity generated. The contribution of renewable electricity to total production will be 62% by 2030 and 88% by 2040. The installed capacity of renewables will reach about 9500 GW by 2030 and 25,600 GW by 2050. The proportion of electricity generated from renewables in 2030 in the 1.5 °C Scenario is assumed to be 73%. The 1.5 °C Scenario will have a generation capacity of renewable energy of about 25,700 GW in 2050.

From 2020 onwards, the continuing growth of wind and PV to 7850 GW and 12,300 GW, respectively, will be complemented by the generation of up to 2060 GW of solar thermal energy as well as limited biomass-derived (770 GW), geothermal

(560 GW) and ocean-derived energy (around 500 GW) in the 2.0 °C Scenario. Both the 2.0 °C and 1.5 °C Scenarios will lead to the generation of high proportions (38% and 46%, respectively) of energy from variable power sources (PV, wind and ocean) by 2030, which will increase to 64% and 65%, respectively, by 2050. This will require a significant change in how the power system is operated. The main findings of the power sector analysis are summarized in the section below.

Calculated average electricity-generation costs in 2015 (referring to full costs) were around 6 ct/kWh. In the 5.0 °C Scenario, these generation costs will increase, assuming rising CO_2 emission costs in the future, until 2050, when they reach 10.6 ct/kWh. The generation costs will increase in the 2.0 °C and 1.5 °C Scenarios until 2030, when they will reach 9 ct/kWh, and then drop to 7 ct/kWh by 2050. In both alternative scenarios, the generation costs will be around 3.5 ct/kWh lower than in the 5.0 °C Scenario by 2050. Note that these estimates of generation costs do not take into account integration costs such as power grid expansion, storage and other load-balancing measures.

Total electricity supply costs in the 5.0 °C Scenario will increase from today's $1560 billion/year to more than $5 500 billion/year in 2050, due to the growth in demand and increasing fossil fuel prices. In both alternative scenarios, the total supply costs will be $5050 billion/year in 2050, about 8% lower than in the 5.0 °C Scenario.

Global investment in power generation between 2015 and 2050 in the 2.0 °C Scenario will be around $49,000 billion, which will include additional power plants to produce hydrogen and synthetic fuels and the plant replacement costs at the end of their economic lifetimes. This value is equivalent to approximately $1360 billion per year on average, which is $28,600 billion more than in the 5.0 °C Scenario ($20,400 billion). An investment of around $51,000 billion for power generation will be required between 2015 and 2050 in the 1.5 °C Scenario ($1420 billion per year on average). In both alternative scenarios, the world will shift almost 95% of its total energy investment to renewables and cogeneration.

Fuel Cost Savings Because renewable energy has no fuel costs other than biomass, the cumulative savings in fuel cost in the 2.0 °C Scenario will reach a total of $26,300 billion in 2050, equivalent to $730 billion per year. Therefore, the total fuel costs in the 2.0 °C Scenario will be equivalent to 90% of the energy investments in the 5.0 °C Scenario. The fuel cost savings in the 1.5 °C Scenario will sum to $28,800 billion or $800 billion per year.

Final energy demand for heating will increase by 59% in the 5.0 °C Scenario from 151 EJ/year in 2015 to around 240 EJ/year in 2050. Energy efficiency measures will help to reduce the energy demand for heating by 36% in 2050 in the 2.0 °C Scenario, relative to that in the 5.0 °C case, and by 40% in the 1.5 °C Scenario.

Global Heat Supply In 2015, renewables supplied around 20% of the final global energy demand for heating, mainly from biomass. Renewable energy will provide 42% of the world's total heat demand in 2030 in the 2.0 °C Scenario and 56% in the 1.5 °C Scenario. In both scenarios, renewables will provide 100% of the total heat demand in 2050. This will include the direct use of electricity for heating, which will increase by a factor of 4.2–4.5 between 2015 and 2050 and will constitute a final share of 26% in 2050 in the 2.0 °C Scenario and 30% in the 1.5 °C Scenario.

Estimated investments in renewable heating technologies to 2050 will amount to more than $13,200 billion in the 2.0 °C Scenario (including investments for plant replacement after their economic lifetimes)—approximately $368 billion per year. The largest share of investment is assumed to be for heat pumps (around $5700 billion), followed by solar collectors and geothermal heat use. The 1.5 °C Scenario assumes an even faster expansion of renewable technologies. However, the lower heat demand (compared with the 2.0 °C Scenario) will result in a lower average annual investment of around $344 billion per year.

Energy demand in the transport sector will increase in the 5.0 °C Scenario from around 97 EJ/year in 2015 by 50% to 146 EJ/year in 2050. In the 2.0 °C Scenario, assumed changes in technical, structural and behavioural factors will reduce this by 66% (96 EJ/year) by 2050 compared with the 5.0 °C Scenario. Additional modal shifts, technological changes and a reduction in the transport demand will lead to even higher energy savings in the 1.5 °C Scenario of 74% (or 108 EJ/year) in 2050 compared with the 5.0 °C case.

Transport Energy Supply By 2030, electricity will provide 12% (2700 TWh/year) of the transport sector's total energy demand in the 2.0 °C Scenario, and, in 2050, this share will be 47% (6500 TWh/year). In 2050, around 8430 PJ/year of hydrogen will be used as a complementary renewable option in the transport sector. In the 1.5 °C Scenario, the annual electricity demand will be about 5200 TWh in 2050. The 1.5 °C Scenario also assumes a hydrogen demand of 6850 PJ/year by 2050. Biofuel use will be limited to a maximum of around 12,000 PJ/year in the 2.0 °C Scenario. Therefore, around 2030, synthetic fuels based on power-to-liquid will be introduced, with a maximum amount of 5820 PJ/year in 2050. Because of the lower overall energy demand in transport, biofuel use will decrease in the 1.5 °C Scenario to a maximum of 10,000 PJ/year. The maximum synthetic fuel demand will amount to 6300 PJ/year.

Global primary energy demand in the 2.0 °C Scenario will decrease by 21% from around 556 EJ/year in 2015 to 439 EJ/year. Compared with the 5.0 °C Scenario, the overall primary energy demand will decrease by 48% by 2050 in the 2.0 °C Scenario (5.0 °C, 837 EJ in 2050). In the 1.5 °C Scenario, the primary energy demand will be even lower (412 EJ) in 2050 because the final energy demand and conversion losses will be lower.

Global Primary Energy Supply Both the 2.0 °C and 1.5 °C Scenarios aim to rapidly phase out coal and oil, after which renewable energy will have a primary energy share of 35% in 2030 and 92% in 2050 in the 2.0 °C Scenario. In the 1.5 °C Scenario, renewables will have a primary share of more than 92% in 2050 (this will include nonenergy consumption, which will still include fossil fuels). Nuclear energy is phased out in both the 2.0 °C and 1.5 °C Scenarios. The cumulative primary energy consumption of natural gas in the 5.0 °C Scenario will sum to 5580 EJ, the cumulative coal consumption will be about 6360 EJ, and the crude oil consumption to 6380 EJ. In the 2.0 °C Scenario, the cumulative gas demand is 3140 EJ, the cumulative coal demand 2340 EJ and the cumulative oil demand 2960 EJ. Even lower fossil fuel use will be achieved under the 1.5 °C Scenario: 2710 EJ for natural gas, 1570 EJ for coal and 2230 EJ for oil. In both alternative scenarios, the primary energy supply in 2050 will be based on 100% renewable energy (Fig. 5).

Bunker Fuels In 2015, the annual bunker fuel consumption was in the order of 16,000 PJ, of which 7400 PJ was for aviation and 8600 PJ for navigation. Annual CO_2 emissions from bunker fuels accounted for 1.3 Gt in 2015, approximately 4% of the global energy-related CO_2 emissions. In the 5.0 °C case, we assume the development of the final energy demand for bunkers according to the IEA World Energy Outlook 2017, Current Policies scenario. This will lead to a further increase in the demand for bunker fuels by 120% until 2050 compared with the base year 2015. Because no substitution with "green" fuels is assumed, CO_2 emissions will rise by the same order of magnitude. Although the use of hydrogen and electricity in aviation is technically feasible (at least for regional transport) and synthetic gas use in navigation is an additional option under discussion, this analysis adopts a conservative approach and assumes that bunker fuels are only replaced by biofuels and synthetic liquid fuels. In the 2.0 °C and 1.5 °C Scenarios, we assume the limited use of sustainable biomass potentials and the complementary central production of power-to-liquid synfuels.

In the 2.0 °C Scenario, this production is assumed to take place in three world regions: Africa, the Middle East and OECD Pacific (especially Australia), where synfuel generation for export is expected to be most economic. The 1.5 °C Scenario requires even faster decarbonisation, so it follows a more ambitious low-energy pathway. The production of synthetic fuels will cause significant additional electricity demand and a corresponding expansion of renewable power-generation capacities. In the case of liquid bunker fuels, these additional renewable

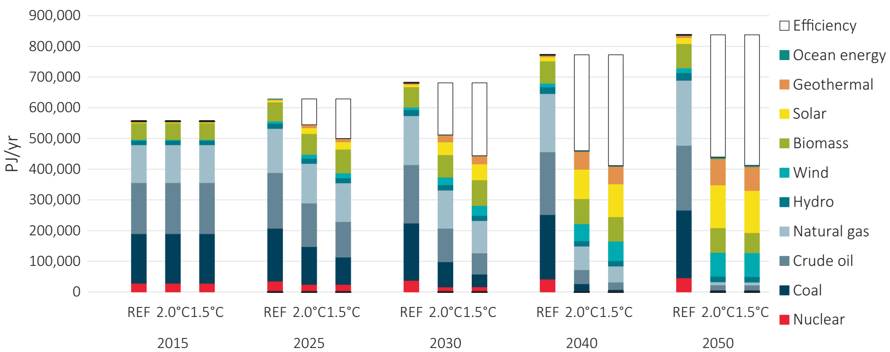

Fig. 5 Global projections of total primary energy demand (PED) by energy carrier in the various scenarios

power-generation capacities could amount to 1100 GW in the 2.0 °C Scenario and more than 1200 GW in the 1.5 °C Scenario if the flexible utilization of 4000 full-load hours per year can be achieved. However, such a scenario requires high electrolyser capacities and high-volume hydrogen storage to ensure not only flexibility in the power system but also high utilization rates by downstream synthesis processes (e.g. via Fischer-Tropsch plants).

Annual global energy-related CO_2 emissions will increase by 40% in the 5.0 °C Scenario, from 31,180 Mt in 2015 to more than 43,500 Mt in 2050. The stringent mitigation measures in both alternative scenarios will cause annual emissions to fall to 7070 Mt in 2040 in the 2.0 °C Scenario and to 2650 Mt in the 1.5 °C Scenario, with further reductions to almost zero by 2050. In the 5.0 °C Scenario, the cumulative CO_2 emissions from 2015 until 2050 will sum to 1388 Gt. In contrast, in the 2.0 °C and 1.5 °C Scenarios, the cumulative emissions for the period from 2015 until 2050 will be 587 Gt and 450 Gt, respectively. Therefore, the cumulative CO_2 emissions will decrease by 58% in the 2.0 °C Scenario and by 68% in the 1.5 °C Scenario compared with the 5.0 °C case. Thus, a rapid reduction in annual emissions will occur in both alternative scenarios.

Global Power Sector Analysis

Global and regional long-term energy results were used to conduct a detailed power sector analysis with the methodology described in Sect. 1.7 of Chap. 3. Both the 2.0 °C and 1.5 °C Scenarios rely on high proportions of variable solar and wind generation. The aim of the power sector analysis was to gain insight into the stability of the power system in each region—subdivided into up to eight subregions—and to gauge the extent to which power grid interconnections, dispatch generation services and storage technologies are required. The results presented in this chapter are projections calculated based on publicly available data. Detailed load curves for some subregions and countries were not available, or, in some cases, the relevant information is classified. Therefore, the outcomes of the [R]E 24/7 model are estimates and require further research with more detailed localized data, especially regarding the available power grid infrastructures. The power sector projections for developing countries, especially in Africa and Asia, assume unilateral access to energy services by the residential sector by 2050 and require transmission and distribution grids in regions where there are none at the time of writing. Further research, in cooperation with local utilities and government representatives, is required to develop a more detailed understanding of the power infrastructure needs.

Development of Global Power Plant Capacities The size of the global market for renewable power plants will increase significantly under the 2.0 °C Scenario. The annual market for solar PV power must increase by a factor of 4.5, from close to 100 GW in 2017 to an average of 454 GW by 2030. The annual onshore wind market must expand to 172 GW by 2025, about three times higher than in 2017. The offshore wind market will continue to increase in importance within the renewable power sector. By 2050, offshore wind installations will increase to 32 GW annually—11 times higher than in 2017. Concentrated solar power (CSP) plants will play an important role in the generation of dispatchable solar electricity to supply bulk power, especially for industry, and to provide secured capacities to power systems. By 2030, the annual CSP market must increase to 78 GW, compared with 3 GW in 2020 and only 0.1 GW in 2017.

In the 1.5 °C Scenario, the phase-out of coal and lignite power plants is accelerated, and a total capacity of 618 GW—equivalent to approximately 515 power stations (1.2 GW on average)—must end operation by 2025. This will mean a phase-out of two coal power plants per week from 2020 onwards, on average. The replacement power will come from a variety of renewable power generators, both variable and dispatchable. The annual market for solar PV energy must be around 30% higher than it was in 2025, as under the 2.0 °C Scenario. The onshore wind market also has an accelerated trajectory under the 1.5 °C Scenario, whereas the offshore wind market is assumed to be almost identical to that in the 2.0 °C Scenario, because of long lead times for these projects. The same is assumed for CSP plants, which are utility-scale projects, and significantly higher deployment seems unlikely in the time remaining until 2025.

Utilization of Power Plant Capacities On a global scale, in the 2.0 °C and 1.5 °C Scenarios, the shares of variable renewable power generation will increase from 4% in 2015 to 38% and 46%, respectively, by 2030, and will increase to 64% and 65%, respectively, by 2050. The reason for the variations in the two cases is the different assumptions made regarding efficiency measures, which may lead to lower overall demand in the 1.5 °C Scenario than in the 2.0 °C Scenario. During the same period, dispatchable renewables—CSP plants, bioenergy generation, geothermal energy and hydropower—will remain around 32% until 2030 on a global average and then decrease slightly to 29% under the 2.0 °C Scenario (and to 27% under the 1.5 °C Scenario) by 2050. The system share of dispatchable conventional generation capacities—mainly coal, oil, gas and nuclear energy—will decrease from a global average of 60% in 2015 to only 14% in 2040. By 2050, the remaining dispatchable conventional gas power plants will be converted to operate on hydrogen as a synthetic fuel, to avoid stranded investments and to achieve higher dispatch power capacities. Increased variable shares—mainly in the USA, the Middle East region and Australia—will produce hydrogen for local and the export markets, as fuel for both renewable power plants and the transport sector.

Development of Maximum and Residual Loads for the Ten World Regions The maximum load will increase in all regions and within similar ranges under both the 2.0 °C and 1.5 °C Scenarios. The load in OECD countries will rise most strongly in response to increased electrification, mainly in the transport sector, whereas the load in developing countries will increase as the overall electricity demand increases in all sectors.

The most significant increase will be in Africa, where the maximum load will surge by 534% over the entire modelling period due to favourable economic development and increased access to energy services by households. In OECD Pacific (South Korea, Japan, Australia and New Zealand), efficiency measures will reduce the maximum load to 87% by 2030 relative to that in the base year, and it will increase to 116% by 2050 with the expansion of electric mobility and the increased electrification of the process heat supply in the industry sector. The 1.5 °C Scenario calculates slightly higher loads in 2030 due to the accelerated electrification of the industry, heating and business sectors, except in three regions (the Middle East, India and Non-OECD Asia Other Asia), where the early application of efficiency measures will lead to an overall lower demand at the end of the modelling period, for the same GDP and population growth rates.

In this analysis, the residual load is the load remaining after the variable renewable power generation. Negative values indicate that the energy generated from solar and wind exceeds the actual load and must be exported to other regions, stored or curtailed. In each region, the average generation should be consistent with the average load. However, maximum loads and maximum generations do not usually occur at the same time, so surplus electricity can be produced and must be exported or stored as far as possible. In rare individual cases, solar- or wind-based generation plants can also temporarily reduce their output to a lower load, or some plants can be shut down. Any reduction in energy generation from solar and wind sources in response to low demands is defined as "curtailment". In this analysis, curtailment rates of up to 5% by 2030 and 10% by 2050 are assumed to have no substantial negative economic impact on the operation of power plants and therefore will not trigger an increase in storage capacities. Figure 6 illustrates the development of maximum loads across all ten world regions under the 2.0 °C and 1.5 °C Scenarios.

Global Storage and Dispatch Capacities The world market for storage and dispatch technologies and services will increase significantly in the 2.0 °C Scenario. The annual market for new hydro-pumped storage plants will grow on average by 6 GW per year to a total capacity of 244 GW in 2030. During the same period, the total installed capacity of batteries will increase to 12 GW, requiring an annual market of 1 GW. Between 2030 and 2050, the energy service sector for storage and storage technologies must accelerate further. The battery market must grow by an annual installation rate of 22 GW and, as a result, will overtake the global cumulative capacity of pumped hydro between 2040 and 2050. The conversion of gas infrastructure from natural gas to hydrogen and synthetic fuels will start slowly between 2020 and 2030, with the conversion of power plants with annual capacities of around 2 GW. However, after 2030, the transformation of the global gas industry to hydrogen will accelerate significantly, with the conversion of a total of 197 GW gas power plants and gas cogeneration facilities each year. In parallel, the average capacity of gas and hydrogen plants will decrease from 29% (2578 h/year) in 2030 to 11% (975 h/year) by 2050, converting the gas sector from a supply-driven to a service-driven industry.

At around 2030, the 1.5 °C Scenario will require more storage throughput than the 2.0 °C Scenario, but the storage demands for the two scenarios will be equal at the end of the modelling period. It is assumed that the higher throughput can be managed with equally higher installed capacities, leading to full-load hours of up to 200 h per year for batteries and hydro-pumped storage.

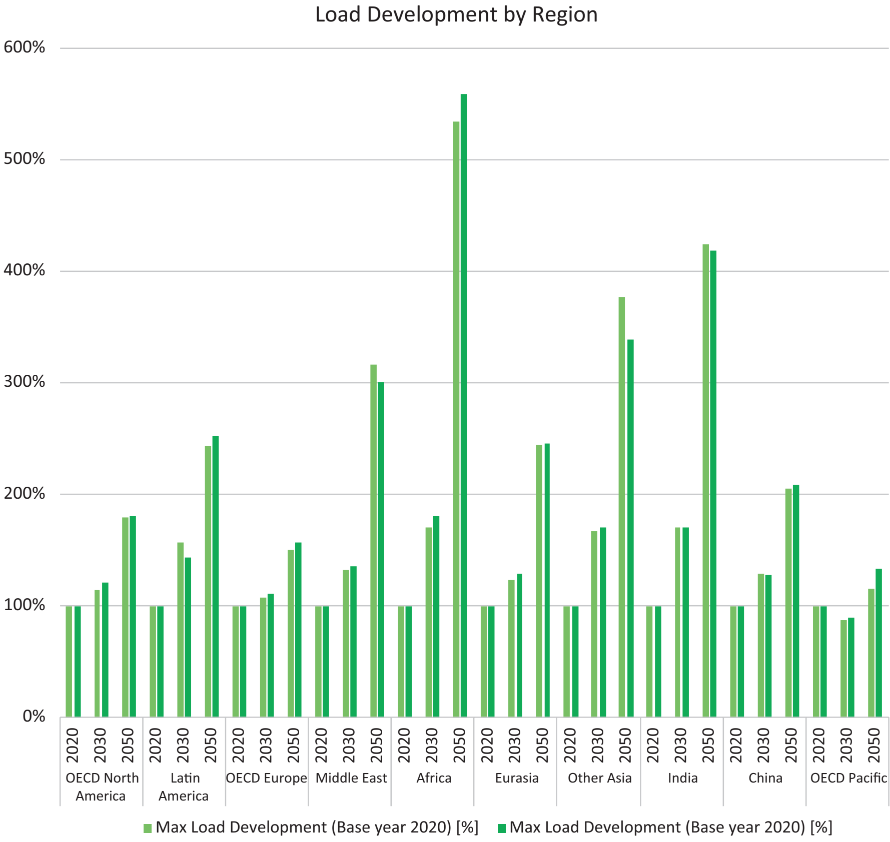

Fig. 6 Development of maximum loads in ten world regions in 2020, 2030 and 2050 under the 2.0 °C and 1.5 °C Scenarios

Trajectories for a Just Transition of the Fossil Fuel Industry The implementation of the 2.0 °C and 1.5 °C Scenarios will have a significant impact on the global fossil fuel industry. While this may appear to be stating the obvious, current climate debates have not yet led to an open debate about the orderly withdrawal from the coal, oil and gas extraction industries. Instead, the political debate about coal, oil and gas is focused on the security of supply and price security. However, mitigating climate change is only possible when fossil fuels are phased out.

Coal: Under the 5.0 °C Scenario, the required production of thermal coal—excluding coal for nonenergy uses, such as steel production—will remain at 2015 levels, with an annual increase of around 1% per year until 2050. Under the 2.0 °C Scenario, coal production will decline sharply between 2020 and 2030 at a rate of around 6% per year. By 2030, global coal production will be equal to China's annual production in 2017, at 3.7 billion tonnes, whereas that volume will be reached in 2025 under the 1.5 °C Scenario.

Oil: Oil production in the 5.0 °C Scenario will grow steadily by 1% annually until the end of the modelling period in 2050. Under the 2.0 °C Scenario, oil production will decline by 3% annually until 2025 and then by 5% per year until 2030. After 2030, oil production will decline by around 7% per year on average, until the oil produced for energy use is phased out entirely by 2050. The oil production capacity of the USA, Saudi Arabia and Russia in 2017 would be sufficient to supply the global demand in 2035 calculated under the 2.0 °C Scenario. The 1.5 °C Scenario reduces the required production volume by half by 2030, reducing it further to the equivalent of the 2017 production volume of just one of the three largest oil producers (USA, Saudi Arabia or Russia) by 2040.

Gas: In the 5.0 °C Scenario, gas production will increase steadily by 2% a year for the next two decades, leading to an overall production increase of about 50% by 2050. Compared with coal and oil, the gas phase-out will be significantly slower in the 2.0 °C and 1.5 °C Scenarios. These scenarios also assume that the gas infrastructure, such as gas pipelines and power plants, will be used afterwards for the hydrogen and/or renewable methane produced with electricity from renewable sources. Under the 2.0 °C Scenario, gas production will only decrease by 0.2% per year until 2025, by 1% until 2030 and, on average, by 4% annually until 2040. This represents a rather slow phase-out and will allow the gas industry to gradually transfer to hydrogen. The phase-out in the 1.5 °C Scenario is equally slow, and a 4%/year reduction will occur after 2025.

The trajectories predicted by the 2.0 °C and 1.5 °C Scenarios for global coal, oil and gas production are consistent with the Paris Agreement targets and can be used to calculate possible employment effects, in terms of job losses in the fossil fuel industry, job gains in the renewable energy industry and options for transitioning the gas industry into an industry based on renewably produced hydrogen.

Employment The transition to a 100% renewable energy system is not just a technical task, it is also a socially and economically challenging process. It is imperative that this transition is managed in a fair and equitable way. One of the key concerns is the employment of workers in the affected industries. However, it should be noted that the "just transition" concept is concerned not only with workers' rights but also with the broader community. This includes considering, for example, community participation in decision-making processes, public dialogue and policy mechanisms that create an enabling environment for new industries to ensure local economic development. Although it is acknowledged that a just transition is important, there are limited data on the effects that this transition will have on employment. There is even less information on the types of occupations that will be affected by the transition, either by project growth or declines in employment. This study provides projections for jobs in construction, manufacturing, operations and maintenance and fuel and heat supply across 12 technologies and 10 world regions, based on the 5.0 °C, 2.0 °C and 1.5 °C Scenarios. Projected employment is calculated regionally, but the results are presented at the global level.

Employment—Quantitative Results The 2.0 °C and 1.5 °C Scenarios will generate more energy-sector jobs in the world as a whole at every stage of the projection. The 1.5 °C Scenario will increase renewable energy capacities faster than the 2.0 °C Scenario, and, therefore, employment will increase faster. By 2050, both scenarios will create around 47 million jobs, so employment will be within similar ranges.

- In 2025, there will be 30.9 million energy-sector jobs under the 5.0 °C Scenario, 45.5 million under the 2.0 °C Scenario and 52.3 million under the 1.5 °C.
- In 2030, there will be 31.7 million energy-sector jobs under the 5.0 °C Scenario, 52.9 million under the 2.0 °C Scenario and 58.5 million under the 1.5 °C Scenario.
- In 2050, there will be 29.9 million energy-sector jobs under the 5.0 °C Scenario, 48.7 million under the 2.0 °C Scenario and 46.3 million under the 1.5 °C Scenario.

Under the 5.0 °C Scenario, job will drop to 4% below the 2015 levels by 2020 and then remain quite stable until 2030. Strong growth in renewable energy will lead to an increase of 44% in total energy-sector jobs by 2025 under the 2.0 °C Scenario and 66% under the 1.5 °C Scenario. In the 2.0 °C (1.5 °C) Scenario, renewable energy jobs will account for 81% (86%) in 2025 and 87% (89%) in 2030, with PV having the greatest share of 24% (26%), followed by biomass, wind and solar heating.

Employment—Occupational Calculations Jobs will increase across all occupations between 2015 and 2025, except in metal trades, which display a minor decline of 2%, as shown in Fig. 7. However, these results are not uniform across regions. For example, China and India will both experience a reduction in the number of jobs for managers and clerical and administrative workers between 2015 and 2025.

Mineral and Metal Requirements Under the 2.0 °C and 1.5 °C Scenarios Within the context of the increasing requirements for metal resources by renewable energy and storage technologies, the rapid increases in demands for both cobalt and lithium are of greatest concern. The demands for both metals will exceed the current production rates by 2023 and 2022, respectively. The demands for these metals will increase more rapidly than will that for silver, partly because solar PV is a more established technology and silver use has become very efficient, whereas the electrification of the transport system and the rapid expansion in lithium battery use have only begun to accelerate in the last few years. The potential to offset primary demand is different depending on the technology. Offsetting demand through secondary sources of cobalt and lithium has the most potential to reduce total primary demand, as these technologies have a shorter lifetime of approximately 10 years. The cumulative demands for both metals will exceed current reserves, but with high recycling rates, they can remain below the resource levels. However, there is a delay in the period during which recycling can offset demand, because there must be sufficient batteries in use and they must exhaust their current purpose before they can be collected and recycled. This delay could be further extended by strategies that reuse vehicular batteries as stationary storage, which might reduce costs in the

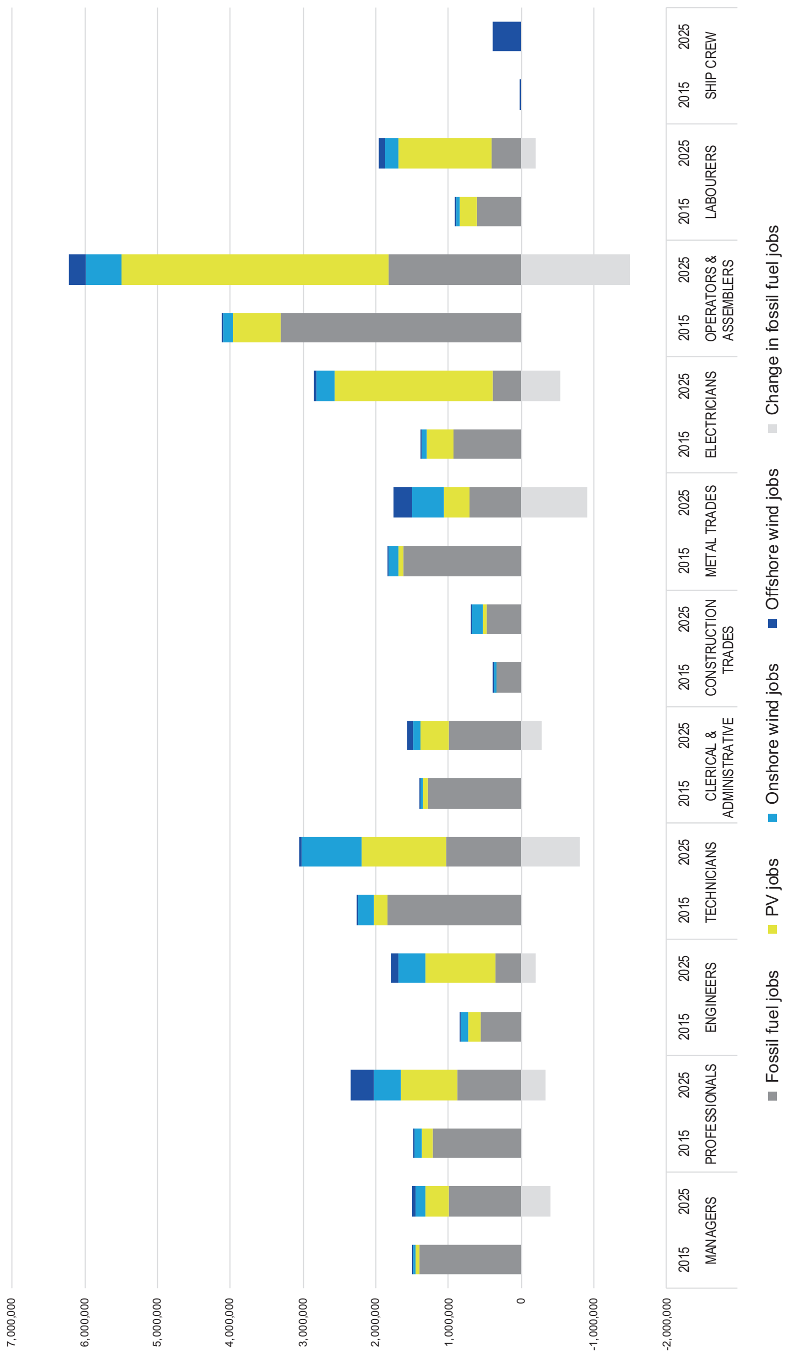

Fig. 7 Division of occupations between fossil fuel and renewable energy industries in 2015 and 2025

short term and increase the uptake of PV. The efficiency of cobalt in batteries also significantly reduces its demand, and this reduction is already happening as manufacturers move towards lower cobalt chemistries.

Increasing the efficiency of the material used is potentially the most successful strategy to offset the demand for PV metals, and recycling will have a smaller impact on demand because the lifespan of solar PV panels is long and their potential for recycling is low. Although the increased demand for silver by 2050 will not be as extreme as that for cobalt or lithium, it will still be considerable. This is important, especially when considering that solar PV currently consumes approximately 9% of end-use silver. It is possible to create silver-less solar panels, but these panels are not expected to be on the market in the near future.

Examination of the Climate Implications of Our Scenarios

One of the Paris Agreement's most outstanding achievements has been the consensus by 195 countries to limit climate change to well below 2 °C and to pursue their best efforts to limit it to 1.5 °C. Together with the goal to reduce emissions to net zero levels, the international agreement clearly sets a framework in which regional and national emission trajectories can be designed and evaluated. The strong focus on a <2.0 °C temperature increase is partly driven by the knowledge that 2 °C warming does not equate to a safe climate: not for small islands that are threatened by rising seas, not for farmers dependent on rainfall in drought-stricken areas and not for communities that are threatened by extreme rainfall events or more intense cyclones.

Here, we use probabilistic methods to examine the scenarios that have been developed to evaluate their implications for long-term temperature and sea-level rises, using models and settings that are also used in the recent IPCC Special Report on 1.5 °C warming. Our lowest scenario has—by design—an approximate 50% or higher chance of a 2100 temperature level that is below 1.5 °C—after a slight overshoot. In contrast to the SSP1_19 scenario, which is the main 1.5 °C-compliant scenario in the next IPCC Assessment Report, our 1.5 °C Scenario does not rely on massive net negative emissions. Even the most stringent mitigation scenarios developed in this study are unable to halt sea-level rise. In fact, a 30 cm rise in sea level by 2100, which will continue thereafter, seems to be the unavoidable legacy of our past use of fossil fuels, unless we remove this CO_2 from the atmosphere in much larger amounts than even the complete reforestation of the planet would permit.

Faced with the grim challenge of ongoing climate risks on the one side and the many positive effects and economic benefits of switching from fossil fuels to renewables on the other, the path is clear. A rapid shift towards a new era of smart, renewable and sector-coupled energy supply, combined with clever demand-side measures and adaptations to the impacts of climate change, will allow us and our children to address the legacy of our past reliance on fossil fuels.

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