# The Long-Term Strategy of the United States

## Pathways to Net-Zero Greenhouse Gas Emissions by 2050

November 2021

The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050. Published by the United States Department of State and the United States Executive Office of the President, Washington DC. November 2021.

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# Preface

In the United States and around the world, we are already feeling the impacts of a changing climate. Here at home, in 2021 alone we have seen historic droughts and wildfires in the West, unprecedented storms and flooding in the Southeast, and record heatwaves across the country. We see the same devastating evidence around the world in places like the fire-ravaged Amazon, the sweltering urban center of Delhi, and the shrinking coastlines of island nations like Tuvalu. The science is clear: we are headed toward climate disaster unless we achieve net-zero global emissions by midcentury. We also know this crisis presents vast opportunities to build a better economy, create millions of good-paying jobs, clean our waters and air, and ensure all Americans can live healthier, safer, stronger lives.

The time is now for decisive action, and the United States is boldly tackling the climate challenge. In 2021, we rejoined the Paris Agreement, set an ambitious Nationally Determined Contribution to reduce net greenhouse gas emissions by 50-52% in 2030, launched the Global Methane Pledge, and have undertaken additional concrete actions to advance climate action domestically and internationally. These investments are critical to immediately accelerate our emissions reductions.

This 2021 Long-Term Strategy represents the next step: it lays out how the United States can reach its ultimate goal of net-zero emissions no later than 2050. Achieving net-zero emissions is how we—and our fellow nations around the globe—will keep a 1.5°C limit on global temperature rise within reach and prevent unacceptable climate change impacts and risks.

The Long-Term Strategy shows that reaching net-zero no later than 2050 will require actions spanning every sector of the economy. There are many potential pathways to get there, and all pathways start with delivering on our 2030 Nationally Determined Contribution. This will put the United States firmly on track to reach net-zero by 2050 and support the overarching vision of building a more sustainable, resilient, and equitable economy.

The benefits of a net-zero future will not only be felt by future generations. Mobilizing to achieve net-zero will also deliver strong net benefits for all Americans starting today. Driving down greenhouse gases will create high-quality jobs, improve public health in every community, and spur investments that modernize the American economy while reducing costs and risks from climate change. Reducing air pollution through clean energy will alone help avoid 300,000 premature deaths in the United States—alleviating these and other severe impacts that also fall disproportionately on communities of color and low-income communities. Investments in emerging clean industries will enhance our competitiveness and propel sustained economic growth.

Modernizing the American economy to achieve net-zero can fundamentally improve the way we live, creating more connected, more accessible, and healthier communities. That does not mean it will happen quickly or without hard work. There will be many challenges on our path to net-zero that will require us to marshal all our ingenuity and dedication. But it can, and must, be done. And even as we invest at home, the new technologies and investments outlined in this strategy will also help scale up low-cost, carbon-free solutions for the world.

We can create a healthy, vibrant, and abundant world for our children. This plan is our promise to them—and it is one we must keep.

**Signed**,

John F. Kerry

**John Kerry**
Special Presidential Envoy for Climate

**Gina McCarthy**
National Climate Advisor

# Executive Summary

Addressing the climate crisis requires immediate and sustained investment to eliminate net global greenhouse gas emissions by mid-century—and this presents a transformational opportunity for the United States and the world. Investing in the clean technologies, infrastructure, workforce, and systems of the future creates an unprecedented opportunity to improve quality of life and create vibrant, sustainable, resilient, and equitable economies.

As we undertake this global transformation, the United States and other major economies must act quickly to keep a safer climate within reach. Across the United States and around the world, climate change is already harming communities—particularly the most vulnerable that are least equipped to cope, rebuild, and adapt. Wildfires, storms, floods, extreme heat, and other climate-fueled impacts are causing deaths, injuries, degraded health, economic hardship, and damage to the earth's ecosystems—all from warming of only roughly 1.0°C. Failure to immediately curtail emissions will condemn the world to nearly triple that level of warming, unleashing far more frequent and severe climate impacts and far more extreme downside risks.

The most recent report from the Intergovernmental Panel on Climate Change (IPCC) vividly illustrates, with robust scientific confidence, the need to limit warming to 1.5°C, or as close as possible to that crucial benchmark, to avoid these severe climate impacts. Achieving this target will require cutting global greenhouse gas (GHG) emissions by at least 40% below 1990 levels by 2030, reaching global net-zero GHG emissions by 2050 or soon after, and moving to net negative emissions thereafter [1]. To meet these global milestones, we must retool the global energy economy, transform agricultural systems, halt and reverse deforestation, and decisively address non-carbon dioxide emissions—focusing particular attention on methane ($CH_4$), which accounts roughly 0.5°C of the current observed net warming of 1.0°C.[1] We must also pursue negative emissions through robust and verifiable nature-based and technological carbon dioxide removal.

In light of this urgency, the United States has set a goal of net-zero greenhouse gas emissions by no later than 2050.

**This U.S. net-zero 2050 goal is ambitious.** It puts the United States ahead of the trajectory required to keep 1.5°C within reach through three decades of investment in clean power, electrification of transportation and buildings, industrial transformation, reductions in methane and

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[1] Greenhouse gas emissions in total have contributed 150% of the observed warming of 1.0°C, but emissions of cooling aerosols have counteracted some of that warming.

other potent non-carbon dioxide climate pollutants, and bolstering of our natural and working lands.

**Delivering on our 2030 Nationally Determined Contribution (NDC) will put the United States firmly on track to net-zero.** The United States has committed to an ambitious and achievable goal to reduce net GHG emissions 50-52% below 2005 levels in 2030.[2] This is the decisive decade to deliver on a set of new policies [2] to accelerate existing emissions reduction trends—for example, expanding rapidly the deployment of new technologies like electric vehicles and heat pumps, and building the infrastructure for key systems like our national power grid. These types of near-term actions will put us on firm footing to meet our 2050 goal (as illustrated by Figure ES-1 below).

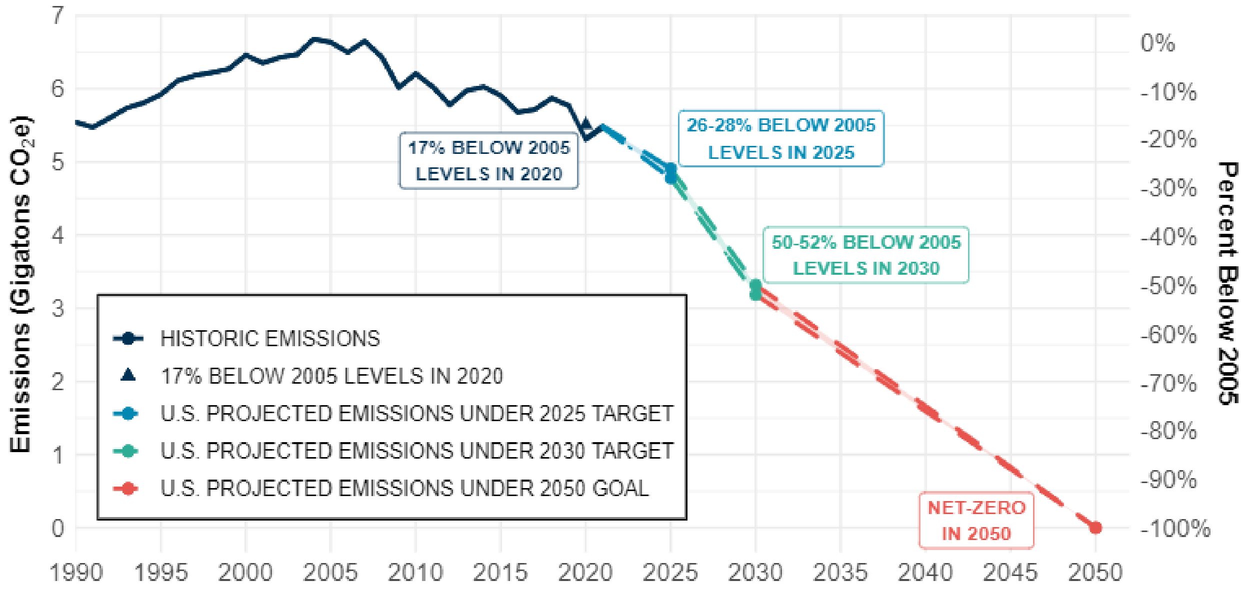

**Figure ES-1: United States historic emissions and projected emissions under the 2050 goal for net-zero.** This figure shows the historical trajectory of U.S. net GHG emissions from 1990 to 2019, the projected pathway to the 2030 NDC of 50-52% below 2005 levels, and the 2050 net-zero goal. The United States has also set a goal for 100% clean electricity in 2035; that goal is not an economy-wide emissions goal so does not appear in this figure, but it will be critical to support decarbonization in the electricity sector, which will in turn help the U.S. reach its 2030 and 2050 goals in combination with broad electrification of end uses. For the period 1900-2020, real US emissions increased through 2007, then declined through 2020, reaching 17% below 2005 levels in 2020 (approx. 5.5 gigatons CO2e). For the period 2020-2025, projected US emissions fall to 26-28% below 2005 levels in 2025 (approx. 5 gigatons CO2e). For the period 2025-2030,

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[2] The United States formally communicated this 2030 target in its Nationally Determined Contribution on April 21, 2021.

projected US emissions fall more sharply, reaching 50-52% below 2005 levels in 2030 (approx. 3 gigatons CO2e). For the period 2030-2050, projected US emissions fall slightly less sharply, reaching -100% from 2005 levels in 2050 (0 gigatons CO2e).

**This report presents the 2021 Long-Term Strategy (LTS) of the United States.** It illustrates multiple pathways to a net-zero economy no later than 2050 [3] [4] [5]. It confirms how actions taken now and through this decade are critical to make these net-zero pathways possible. The report draws from a diverse analytical toolkit,[3] including a global integrated assessment model covering all GHGs and economic sectors, a national carbon dioxide ($CO_2$) model with high energy sector resolution, models of the U.S. land sector, and a rich set of non-governmental literature. Pursuant to Article 4.19 of the Paris Agreement, this report also serves to communicate our Long-Term Strategy to the international community.

**Mobilizing to achieve net-zero will deliver strong net benefits for all Americans.** Driving down GHGs will spur investments that modernize the American economy, address the distributional inequities of environmental pollution and climate vulnerability, improve public health in every community, and reduce the severe costs and risks from climate change. Benefits include:

- *Public health*. Reducing air pollution through clean energy will avoid 85,000–300,000 premature deaths, and health and climate damages of $150–$250 billion through 2030. It will avoid $1–3 trillion in damages through 2050 in the United States alone. These measures will also help alleviate the pollution burdens disproportionately borne by communities of color, low-income communities, and indigenous communities.
- *Economic growth*. Investments in nascent clean industries will enhance competitiveness and propel sustained growth. The United States can lead in crucial clean technologies like batteries, electric vehicles, and heat pumps, without sacrificing critical worker protections.
- *Reduced conflict.* Drought, floods, and other disasters fueled by climate change have caused large-scale displacements and conflict. The U.S. Department of Defense recognizes climate change as a vital, globally destabilizing national security threat [6]. Early action by the United States will encourage faster climate action globally, including by driving down the costs of carbon-free technologies. These actions will ultimately support security and stability worldwide.
- *Quality of life.* Modernizing the American economy to achieve net-zero can fundamentally improve the way we live. Measures like high-speed rail and transit-oriented

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[3] The core analyses presented in this report are shared with the U.S. National Climate Strategy and the U.S. National Communication and Biennial Report to the UN Framework Convention on Climate Change (UNFCCC).

development not only reduce emissions but also create more connected, accessible, and healthier communities.

**The 2050 net-zero emissions goal is achievable.** The United States can deliver net-zero emissions across all sectors and GHGs through multiple pathways, but all viable routes to net-zero involve five key transformations:

1. *Decarbonize electricity.* Electricity delivers diverse services to all sectors of the American economy. The transition to a clean electricity system has been accelerating in recent years—driven by plummeting costs for solar and wind technologies, federal and subnational policies, and consumer demand. Building on this success, the United States has set a goal of 100% clean electricity by 2035, a crucial foundation for net-zero emissions no later than 2050.
2. *Electrify end uses and switch to other clean fuels.* We can affordably and efficiently electrify most of the economy, from cars to buildings and industrial processes. In areas where electrification presents technology challenges—for instance aviation, shipping, and some industrial processes—we can prioritize clean fuels like carbon-free hydrogen and sustainable biofuels.
3. *Cut energy waste.* Moving to cleaner sources of energy is made faster, cheaper, and easier when existing and new technologies use less energy to provide the same or better service. This can be achieved through diverse, proven approaches, ranging from more efficient appliances and the integration of efficiency into new and existing buildings, to sustainable manufacturing processes.
4. *Reduce methane and other non-$CO_2$ emissions.* Non-$CO_2$ gases such as methane, hydrofluorocarbons (HFCs), nitrous oxide ($N_2O$), and others, contribute significantly to warming—with methane alone contributing fully half of current net global warming of 1.0°C. There are many profitable or low-cost options to reduce non-$CO_2$ sources, such as implementing methane leak detection and repair for oil and gas systems and shifting from HFCs to climate-friendly working fluids in cooling equipment. The U.S. is committed to taking comprehensive and immediate actions to reduce methane domestically. And through the Global Methane Pledge, the U.S. and partners seek to reduce global methane emissions by at least 30% by 2030, which would eliminate over 0.2°C of warming by 2050. The U.S. will also prioritize research and development to unlock the innovation needed for deep emissions reductions beyond currently available technologies.
5. *Scale up $CO_2$ removal.* In the three decades to 2050, our emissions from energy production can be brought close to zero, but certain emissions such as non-$CO_2$ from agriculture will be difficult to decarbonize completely by mid-century. Reaching net-zero emissions will therefore require removing carbon dioxide from the atmosphere, using

processes and technologies that are rigorously evaluated and validated. This requires scaling up land carbon sinks as well as engineered strategies.

Figure ES-2 illustrates how the five key transformations can combine in different pathways to achieve net-zero emissions by 2050. The exact pathway will depend on how quickly change occurs across different sectors. Nevertheless, some broad patterns are clear. For example, energy system transformations contribute roughly 4.5 gigatons of $CO_2$ equivalent per year (Gt $CO_2$e/yr.) of overall emissions reductions, or about 70% of overall reductions. These energy emissions reductions are delivered by cutting energy waste, decarbonizing electricity, and transitioning energy sources including through fuel switching and electrification. Addressing non-$CO_2$ gases, including methane, nitrous oxide, and fluorinated gases, reduces another 1 Gt of annual emissions. Enhancing land sinks and scaling up $CO_2$ removal technologies also deliver about 1 Gt of negative emissions. While these figures are a helpful rough guide, the exact contribution from each area varies between pathways (as shown in Figure ES-2). The eventual U.S. pathway to net-zero emissions will depend on the evolution of technologies, the specifics of policy and regulatory packages, and factors such as economic growth, sociodemographic shifts, and market prices for commodities and fuels across the next three decades.

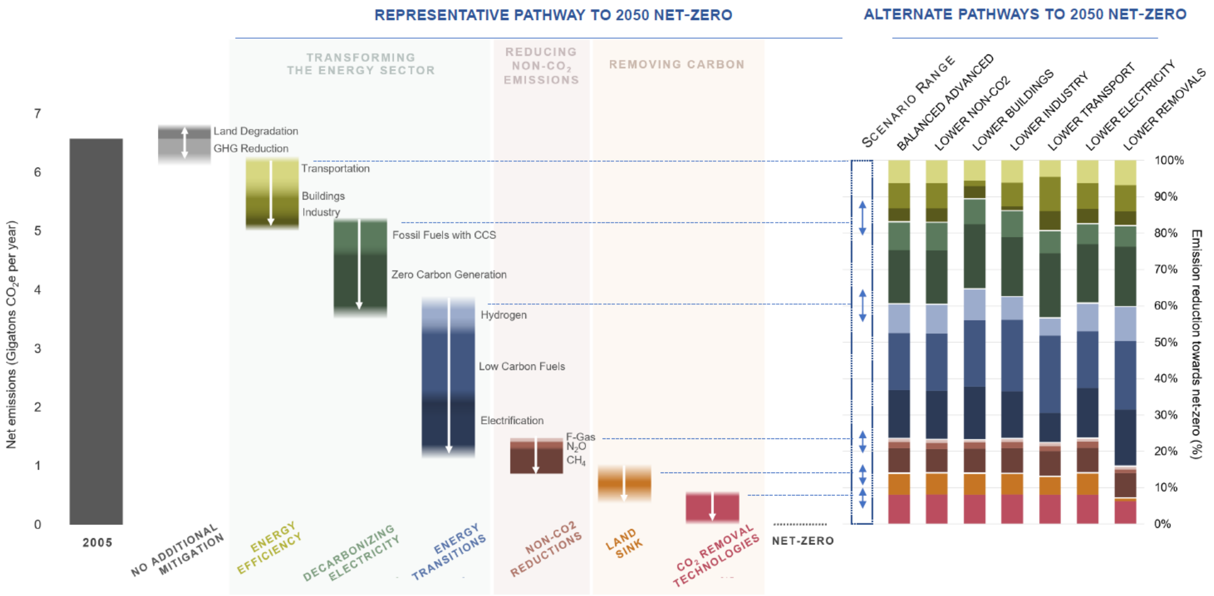

**Figure ES-2: Emissions Reductions Pathways to Achieve 2050 Net-Zero Emissions in the United States.** Achieving net-zero across the entire U.S. economy requires contributions from all sectors, including: efficiency, clean power, and electrification; reducing methane and other non-$CO_2$ gases; and enhancing natural and technological $CO_2$ removal. The left side of the figure shows a representative pathway with high levels of action across all sectors to achieve net-zero by 2050. The right side shows a set of alternative pathways depending on variations in uncertain factors such as trends in relative technology costs and the strength of the land sector carbon sink.  Across all scenarios, contributions from energy efficiency range from 10-19% (transportation contributions range from 5-7%, buildings from 2-9%, and industry from 1-5%). Contributions from decarbonizing electricity range from 22-25% (renewables contributions range from 15-18%, and fossil fuel with CCS from 6-8%). Contributions from energy transitions range from 34-44% (hydrogen contributions range from 5-10%, low-carbon fuels from 16-21%, and electrification from 8-15%). Contributions from non-CO2 reductions range from 9-10% (contributions from methane range from 6-7%, N2O from 1-2%, and F-gas reduction at 1%). Contributions from land sink enhancement range from 1-6%. Contributions from CO2 removal range from 6-8%.

Achieving net-zero by no later than 2050 requires sustained, coordinated action spanning four strategic pillars:

1. *Federal leadership.* Federal leadership is critical to reduce emissions 50-52% below 2005 levels in 2030 and set up the economy to achieve net-zero emissions by 2050. This could include investments and incentives that support the deployment of clean technologies in all sectors, policies to enhance and support our natural and working lands, partnerships to catalyze market transformation, improved integration of climate into financial markets including enhanced climate risk disclosure, and the promulgation and enforcement of new and existing regulations rooted in law.
2. *Innovation.* In driving the deployment of currently competitive technologies as rapidly as possible, federal policies will serve to further reduce costs through economies of scale and learning-by-doing. In addition, new technologies will be necessary to drive deeper reductions in the late 2020's through 2050. Federally-supported research, development, demonstration, and deployment can be the prime mover—along with federal, subnational, and private sector procurement—to carry new carbon-free technologies and processes from the lab to U.S. factories to the market. Research and development today will lay the technology foundation necessary to maximize economic benefits from the post-2030 transformation to net-zero.
3. *Non-federal leadership.* The U.S. federal system is based on the national government sharing power with elected governments at subnational levels. In our system, policy authorities related to economic activity, energy, transportation, land use, and more are shared with Tribal governments, states, cities, counties, and others. U.S. climate action therefore necessarily spans all levels of government. Recent trends demonstrate the significant impacts that these subnational policies can have on the overall U.S. emissions

trajectory, in ways that complement national policies and can provide a broader base for learning and for accelerating action.

4. *All-of-society action.* The long-term transformations to get to 2050 net-zero emissions will require the United States to bring all its greatest strengths to bear, including innovation, creativity, and diversity. Already, many non-governmental organizations are acting ambitiously to address climate change within their own operations or support the overall transition of the U.S. economy. Even more broad-based engagement on research, education, and implementation through our universities, cultural institutions, investors, businesses, and other non-governmental organizations will be required to reach our 2050 goal.

**Implementation is underway.** These four principles form the core of our strategy to achieve our 2030 NDC and 100% clean electricity by 2035. We are moving rapidly, rooted in actions from across the federal government and other governmental and non-governmental actors. These actions and policies are part of our Long-Term Strategy and are described in a forthcoming companion report to this document, *The U.S. National Climate Strategy* (NCS) [2]. The NCS describes an overarching approach that covers all aspects of federal action, which will also support broader non-federal and all-of-society efforts. Both the NCS and this Long-Term Strategy have been informed by a robust stakeholder engagement process. These actions provide the near-term implementation momentum to achieve the 2030 NDC, 2035 100% clean electricity goal, and the 2050 net-zero goal.

**If other major economies adopt similar ambition, we can keep 1.5°C within reach.** The U.S. currently emits 11% of annual global GHGs (second to China, which emits 27% of the global total). Cutting our emissions at least in half by 2030 and eliminating our emissions by 2050 will therefore make an important direct contribution to keeping a safer 1.5°C future within reach. These efforts will also spur cost reductions for clean technologies through scale and learning-by-doing. More importantly, U.S. climate leadership has already helped propel other major economies to adopt 2030 NDCs that are aligned with the imperative to cut global emissions at least 40% by 2030 to improve our chances of limiting global warming to less than 1.5°C. At the Leaders' Summit on Climate in April of 2021, President Biden announced our ambitious NDC, joined by Canadian and Japanese leaders who also set strong new 2030 targets. The European Union (EU) and United Kingdom (UK) had already set strong targets and, since the Summit, others, including the Republic of Korea and South Africa, have come forward with NDCs that achieve the pace of reductions that would be needed globally to keep 1.5°C within reach. These countries represent well over half of the global economy, but further action by other major economies will be necessary to ensure the 1.5$^{o}$C target is met.

Globally, this is the moment for all the world's major economies to act to rapidly reduce emissions to meet ambitious 2030 NDC targets and to develop and communicate strategies to achieve ambitious 2050 net-zero goals.

## *Box 1: Four Components of U.S. Reporting on Climate Actions and Strategy*

Communicating actions and progress toward climate goals is a critical component of transparency to support global ambition under the Paris Agreement. The United States is committed to these principles and, accordingly, is issuing four reports detailing complementary aspects of our current climate activities and planned strategy. The same key assumptions and methodologies are shared in the analytics that inform all four reports. Each report serves a different role in communicating the overall situation and strategy of the United States, and there are details in each that are not reproduced across all reports. Together they present a vision for our climate strategy and emissions pathways.

1. **The U.S. National Climate Strategy** details how we will deliver our U.S. NDC for 2030 [2]. It focuses on the immediate policies and actions that will put America on track to reduce emissions by 50-52% below 2005 levels in 2030 and put in place the technology and infrastructure necessary to achieve net-zero emissions no later than 2050.
2. **The Long-Term Strategy of the United States to Reach Net-Zero Emissions by 2050** (this report), pursuant to Article 4.19 of the Paris Agreement, shows how these current and near-term policies and other actions across the country, as described in the NCS, deliver a pathway through the 2030s and 2040s to reach our 2050 net-zero goal. As a contribution under the Paris Agreement, it is part of a process that serves to support enhanced global action and ambition.
3. **The U.S. National Communication and Biennial Report** provides detailed information on existing policies and measures across all areas of U.S. climate action as of December 2020 [7]. It fulfills our obligations for reporting and transparency under the UN Framework Convention on Climate Change (UNFCCC) and fits into a broader international reporting framework in which other countries also participate.
4. **The U.S. Adaptation Communication** provides forward-looking priorities for accelerating adaptation and building resilience domestically and abroad [8]. It outlines domestic climate impacts and vulnerabilities, progress on adaptation, lessons learned, and immediate policies and other approaches that will increase adaptive capacity, enhance resilience, and reduce vulnerability to climate change. It complements and builds upon resilience and adaptation actions laid out in the National Climate Strategy and U.S. National Communication and Biennial Report.

# Chapter 1: An Integrated U.S. Climate Strategy to Reach Net-Zero Emissions by 2050

Climate change already inflicts serious damage on the United States and the world, particularly the most vulnerable that are least equipped to adapt—and the science is clear that, without faster global action, these impacts will become much more frequent and severe. Two recent reports from the Intergovernmental Panel on Climate Change [1] [9] affirm with robust scientific confidence the need to keep warming under 1.5°C to reduce the greatest global risks and avoid significant, wide-ranging, and severe impacts. To keep 1.5°C within reach, the United States has a goal of achieving net-zero emissions economy-wide by no later than 2050 [3] [4] [5].

The Paris Agreement establishes a framework to rapidly increase global ambition to hold warming well below 2°C while pursuing efforts to limit warming to 1.5°C. This framework includes nationally determined contributions (NDCs)—commitments that target near-term emissions reductions, review progress, and seek to extend and strengthen their NDCs in regular 5-year cycles. The Paris Agreement also specifically calls on all countries to "formulate and communicate their long-term, low GHG emission development strategies." Such Long-Term Strategies support global ambition by encouraging countries to understand their options and set their own longer-term emissions reduction goals [10]. In developing and communicating these strategies [11], countries can foresee and address challenges such as slow infrastructure turnover or the need for just transitions from fossil fuels and other high-emission technologies. Developing and sharing publicly these near- and long-term strategies helps elucidate and manage path dependencies and better connect short-term and long-term objectives. Accordingly, this process can both guide national action and encourage greater global ambition over time.

The United States is simultaneously pursuing multiple climate mitigation goals (Figure 1). Each goal serves as an important milestone toward rapidly reducing our GHG emissions to net-zero. While this report emphasizes the longer period of 2021-2050, the overall U.S. strategy integrates actions for both near-term and 2050 goals:

- The 2030 NDC of 50-52% reductions below 2005 levels, covering all sectors and all gases
- The goal for 100% carbon pollution-free electricity by 2035
- The goal for net-zero emissions no later than 2050.

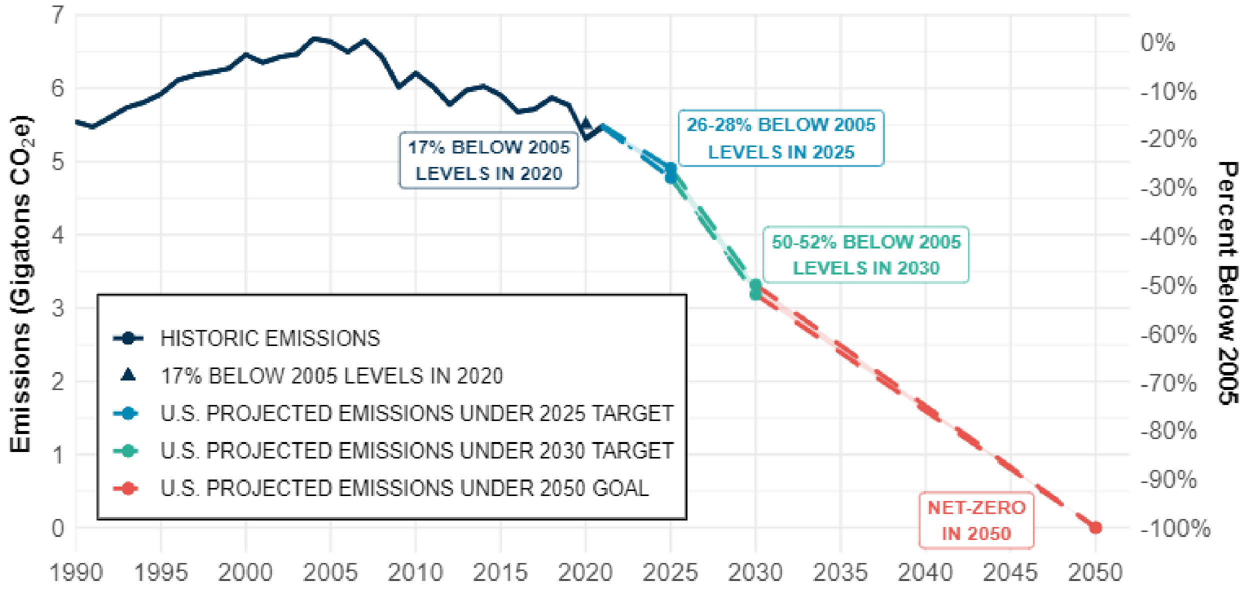

**Figure 1: United States historic emissions and projected emissions under the 2050 goal for net-zero.** This figure shows historical U.S. GHG emissions from 1990 to 2019, the projected pathway to the 2030 NDC of 50-52% below 2005 levels, and the 2050 net-zero goal. The United States has also set a goal for 100% clean electricity in 2035. That goal is not an economy-wide emissions goal so does not appear in this figure, but it will be critical to support decarbonization in the electricity sector, which will in turn help the U.S. reach its 2030 and 2050 goals. For the period 1900-2020, real US emissions increased through 2007, then declined through 2020, reaching 17% below 2005 levels in 2020 (approx. 5.5 gigatons CO2e). For the period 2020-2025, projected US emissions fall to 26-28% below 2005 levels in 2025 (approx. 5 gigatons CO2e). For the period 2025-2030, projected US emissions fall more sharply, reaching 50-52% below 2005 levels in 2030 (approx. 3 gigatons CO2e). For the period 2030-2050, projected US emissions fall slightly less sharply, reaching -100% from 2005 levels in 2050 (0 gigatons CO2e).

These near-term actions are being implemented rapidly, rooted in policies from across the federal government and other governmental and non-governmental actors in the United States. These actions and policies are described in detail in a companion to this document, *The U.S. National Climate Strategy* (NCS) [2]. The NCS lays out an overarching policy approach being undertaken today that covers all aspects of federal action, in support of all-of-society efforts. These actions provide the near-term implementing momentum to achieve the 2030 NDC, meet the 2035 100% clean electricity goal, and put the U.S. in a strong position to take the additional actions necessary to achieve net-zero by 2050. The information on near-term implementation in the NCS should therefore be viewed as integral to the U.S. Long-Term Strategy. Accordingly, although this report focuses on the period from 2021 to 2050, it refers to the NCS for further descriptions of near-term implementation of long-term goals.

The Biden Administration consulted diverse stakeholders to inform the overall U.S. climate strategy that is reflected in the U.S. Long-Term Strategy (LTS) report. This consultation covered a wide range of stakeholders, from major unions that work on behalf of millions of American workers, to groups representing tens of millions of advocates, fence line communities, and young Americans. Engagement to develop our strategy also included groups representing scientists; hundreds of governmental leaders like governors, mayors, and Native American leaders; hundreds of businesses; hundreds of schools and institutions of higher education; as well as with many specialized researchers focused on questions of pollution reduction. The NCS report referenced above has similarly been developed through extensive consultations of diverse stakeholders, whose perspectives and input have informed the overall climate strategy that is reflected in this LTS report.

The United States presented its first Long-Term Strategy report in 2016 [12], focused on reducing net GHGs 80-90% below 2005 levels by 2050. In 2021, the United States put forward a new, ambitious goal of net-zero emissions no later than 2050. This report presents an updated 2021 Long-Term Strategy of the United States that defines multiple pathways for the American economy to achieve net-zero emissions by 2050. It includes analysis of what transformational pathways to net-zero could look like over time for emissions in different sectors and for different GHGs. The report draws from a diverse analytical toolkit,[4] integrating insights from a global integrated assessment model covering all greenhouses and economic sectors, a national $CO_2$ model with high resolution on the electricity sector, models of U.S. land sector, and more. The analysis presented here was based on an interagency effort and is grounded in a broader body of existing scholarship and literature for how to understand both near- and long-term high-ambition emissions pathways in the national and global context. While the analyses presented here provide new and original insights, they also draw from and reference this broader body of work.

This report is organized as follows. Chapter 2 focuses on the decisive decade from now to 2030 and highlights the U.S. priorities which will both dramatically reduce GHG emissions and lay the foundation for achieving net-zero emissions no later than 2050. Chapter 3 gives an overview of the economy-wide emissions pathways to 2050. Chapter 4 describes pathways for energy-related $CO_2$ emissions reduction across electricity, transportation, buildings, and industry. Chapter 5 presents the key opportunities for methane and other non-$CO_2$ emissions reductions,

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[4] These core analyses in this report are shared with two companion volumes, the U.S. National Climate Strategy and the U.S. National Communication and Biennial Report to the UNFCCC.

including in the energy, waste, agriculture, and industrial sectors. Chapter 6 focuses on $CO_2$ removals through lands and technologies for carbon dioxide removal. Chapter 7 presents a vision of the many benefits that will be created on the path to a net-zero emissions economy, including transformative improvements in public health, avoided climate damages, enhanced climate security, and job growth. Finally, Chapter 8 concludes with a vision of the U.S. accelerating global climate progress with ambitious domestic climate action.

### *Box 2: The U.S. 2050 Net-Zero Goal*

The United States has set a goal of net-zero emissions by no later than 2050. The goal includes all major GHGs ($CO_2$, $CH_4$, $N_2O$, HFCs, PFCs, $SF_6$, $NF_3$) and is economy-wide. The goal is on a net basis, including both sources of emissions and removals. It does not include emissions from international aviation or international shipping. At this time, the United States does not expect to use international market mechanisms toward achievement of this net-zero goal. Progress toward the goal will be assessed and the U.S. LTS may be updated, as appropriate.

## Chapter 2: The Decisive Decade to 2030

Putting the United States on a path to net-zero emissions economy-wide no later than 2050 requires taking transformative actions this decade and achieving near-term milestones in line with this goal. This is why the United States set an economy-wide target of reducing its net GHG emissions by 50-52% below 2005 levels in 2030 (Figure 2). The United States will also soon release a complementary report, *The U.S. National Climate Strategy* (NCS) [2], following this 2021 Long-Term Strategy, to provide additional detail on the steps the United States is taking to achieve our 2030 target—and in doing so, to put the United States on a track to achieve its 2050 net-zero goal. This 2030 commitment anchors the U.S. approach during this decade to build a sustainable, resilient, and equitable economy by rapidly deploying widely available low-carbon technologies and investing in the infrastructure, innovation, and workforce that is the foundation of this economic transformation.

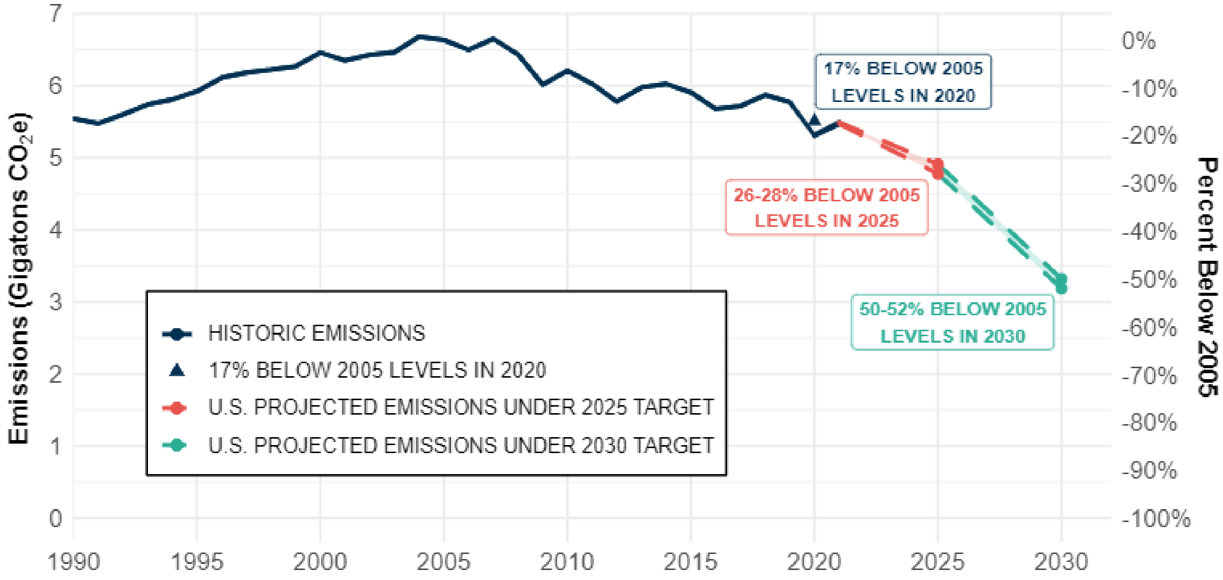


**Figure 2: United States historic emissions and projected emissions under the 2030 NDC target.** This figure shows the historical trajectory of U.S. GHG emissions and the pathway to the 2030 GHG reduction targets. The 2030 NDC target is ambitious, and policies and measures have put the American economy on a declining emissions trend consistent with these goals. The 2030 targets put the United States on a faster track than a straight-line path to net-zero in 2050 would require. For the period 1900-2020, real US emissions increased through 2007, then declined through 2020, reaching 17% below 2005 levels in 2020 (approx. 5.5 gigatons CO2e). For the period 2020-2025, projected US emissions fall to 26-28% below 2005 levels in 2025 (approx. 5 gigatons CO2e). For the period 2025-2030, projected US emissions fall more sharply, reaching 50-52% below 2005 levels in 2030 (approx. 3 gigatons CO2e).

This decade will be decisive—and the benefits of achieving our 2030 goal will be significant. Transitioning to a clean energy economy will create between 500,000 and one million net new jobs across the country this decade [13] [14]. Moreover, reducing air pollution through these efforts will avoid 85,000–300,000 premature deaths [14] [15]. This transition will require a multi-pronged approach involving the private sector, sub-national governments, and federal government to generate new regulations, direct investment, and programs at all levels of government.

Near-term actions to accelerate this transition are being implemented rapidly, rooted in actions from across the federal government and other governmental and non-governmental actors in the United States. These actions and policies are described in detail in the NCS report, which lays out an overarching policy approach being undertaken today–informed by ongoing engagement of diverse stakeholders–that covers all aspects of federal action, in support of all-of-society efforts. These actions provide the near-term implementing momentum to achieve the 2030 NDC, 2035 100% clean electricity goal, and the 2050 net-zero goal.  A summary of these elements is provided below.

## 2.1 Electricity

Fast and cost-effective emission-reducing investments are available in the electric power sector, which is currently the second-largest producer of emissions in the United States. That is why the United States set a goal to reach a 100% carbon pollution-free electricity system by 2035, which can be achieved through multiple cost-effective technology and investment pathways. In fact, this transition has already been accelerating in recent years—driven by plummeting costs of key technologies like solar, onshore wind, offshore wind, and batteries, as well as enhanced policies and increased consumer demand for clean, reliable, and affordable power. Further acceleration of clean energy deployment can be catalyzed through providing incentives and standards to reduce pollution from power plants; investing in technologies to increase the flexibility of the electricity system, such as transmission, energy efficiency, energy storage, smart and connected buildings, and non-emitting fuels; and leveraging carbon capture and storage (CCS) and nuclear. Significant deployment of energy efficiency reduces overall demand and can lower peak load, reducing grid capital costs and making investments in carbon-free power generation go further. Research, development, demonstration, and deployment of new software and hardware solutions will further support the transformation to a carbon pollution-free, resilient, reliable, and affordable electricity system.

## 2.2 Transportation

Vehicles have become the largest emissions source in the United States—driven by fossil fuel use in light-duty cars, trucks, and SUVs, followed by medium- and heavy-duty trucks, buses, air, off-road vehicles, rail, and shipping. There are many opportunities to reduce GHG emissions from transportation while also saving money for households and businesses, improving environmental quality and health in communities, and providing more choices for moving people and goods. At its core, this requires electrifying most vehicles to run on ever-cleaner electricity and shifting to low-carbon or carbon-free biofuels and hydrogen in applications like long-distance shipping and aviation.

To support this outcome, the United States set a goal for half of all new light-duty cars sold in 2030 to be zero-emission vehicles, to produce 3 billion gallons of sustainable aviation fuel by 2030, and to accelerate deployment and reduce costs in every mode of transportation. This will occur through lower vehicle costs; fuel economy and emissions standards in light-, medium- and heavy-duty vehicles; incentives for zero-emission vehicles and clean fuels; investment in a new charging infrastructure to support multi-unit dwellings, public charging, and long-distance travel; scaling up biorefineries; comprehensive innovation investments to reduce hydrogen costs; and investment in infrastructure that supports all modes of clean transportation—such as transit, rail, biking, micro mobility, and pedestrian options.

Making progress this decade requires investing in domestic manufacturing and reliable supply chains for clean fuels, batteries, and vehicles. In addition, research, development, demonstration, and deployment of electrification and zero- or low-carbon fuels for aviation and shipping will ensure we have the technology to continue reducing emissions across the entire transportation sector in the years leading to 2050.

## 2.3 Buildings

Buildings and their energy-consuming systems—electricity used and fossil fuels burned on site for heating air, heating water, and cooking—have long lifetimes. Therefore, the priority in this decade is to rapidly improve energy efficiency and increase the sales share of clean and efficient electric appliances—including heat pumps for space conditioning, heat pump water heaters, electric and induction stoves, and electric clothes dryers—while also improving the affordability of energy and the equitable access to efficient appliances, efficiency retrofits, and clean distributed energy resources in buildings. This includes investment in public buildings such as public housing, government facilities, schools, and universities. Research and demonstration investments now will also advance new solutions for efficient, grid-interactive, and electrified buildings.

Achieving 100% clean power generation by 2035 will also eliminate upstream emissions from electricity and facilitate carbon-free and efficient electrification of appliances and equipment in buildings. Moreover, partnerships like the Environmental Protection Agency (EPA) ENERGY STAR and the advancement of building energy codes and appliance standards will ensure that building envelopes, electric appliances, and other equipment become increasingly efficient over time. Efficient electric space heating and cooling and water heating offer important opportunities to employ grid-interactive demand to lower energy bills for households and businesses while more cost-effectively utilizing carbon-free electricity.

## 2.4 Industry

The industrial sector emits GHGs through multiple complex pathways. This includes $CO_2$ emitted indirectly through electricity and directly through on-site fossil fuel combustion and power generation, as well as emissions of $CO_2$ and non-$CO_2$ GHGs leaked from on-site use or emitted through industrial processes (such as cement production). Industrial decarbonization can be delivered through energy efficiency; industrial electrification; low-carbon fuels, feedstock, and energy sources; and industrial CCS. Achieving clean power by 2035 will eliminate the emissions from grid power consumed by industry and make possible the carbon-free electrification of certain industrial processes that are currently dominated by fossil fuel use. Low- and medium-temperature process heat are candidates for industrial electrification in the near term through increased use of industrial heat pumps, electric boilers, or electromagnetic heating processes.

Additional technologies and process innovations are also needed to address other industrial emissions, including high-temperature heat and process emissions from steel, petrochemical, and cement production. Fundamentally new processes will be needed to address the chemical process emissions associated with the production of these commodity materials that have large GHG emissions footprints. Energy efficiency measures make carbon-free electricity and other low-carbon industrial fuels stretch as far as possible and as early as possible.

The United States will also scale support for related research, development, demonstration, commercialization, and deployment of zero-carbon industrial innovations. This includes incentives for carbon capture and new sources of clean hydrogen—produced from renewable energy, nuclear energy, or waste—to power industrial facilities. To drive the market for these solutions, the United States government will also use its procurement power to support early markets for these very low- and zero-carbon industrial goods.

Additionally, monitoring and control technologies are needed to prevent the release to the atmosphere of non-$CO_2$ GHGs from industrial operations, including methane, fluorinated gases, black carbon, and other potent short-lived climate pollutants. The United States has finalized regulations to phase down the use of fluorinated gases consistent with our obligations under the Kigali Amendment to the Montreal Protocol. Addressing methane emissions will also require setting stringent standards for oil and gas production and investing in plugging leaks from coal, oil, and gas mines and wells.

## 2.5 Agriculture, Forestry, and Land Use

America's vast lands provide opportunities to both reduce emissions and sequester carbon. Capitalizing on these opportunities includes: continuing to expand forest area, extending rotation lengths, protecting forest area, integrating trees into urban areas and agriculture, scaling up climate-smart agricultural practices such as cover crops, and employing rotational grazing on our agricultural lands. Even more leverage can be derived through programs and incentives to improve agricultural productivity; such practices and technologies can free up land for other uses, as well as reduce agricultural methane and $N_2O$ emissions through, for example, improved manure management and improved cropland nutrient management. Enhanced investment in forest protection and forest management, along with science-based and sustainable efforts to reduce the scope and intensity of catastrophic wildfires and to restore fire-damaged forest land, are vital to protecting and growing the largest land sink. Alongside these efforts, the United States will support nature-based coastal resilience projects including pre-disaster planning, as well as efforts to increase carbon sequestration in waterways and oceans by pursuing "blue carbon." Finally, climate-smart practices can also lower the emissions intensity of biofuels needed for decarbonizing transportation. Actions taken now and through this decade will ensure we maximize the potential of our lands and waters to sequester carbon to the greatest extent possible by 2050.

Across these sectors, the U.S. federal government is working with Tribal governments, states, and localities to support rapid deployment of new carbon-pollution-free technologies and facilities while ensuring they meet robust and rigorous standards for workers, public and environmental safety, and environmental justice. Accomplishing the goals this decade and setting up the economy for further reductions after 2030 also requires investment in innovation and U.S. manufacturing to lower the cost of new technologies needed in the future, grow the domestic manufacturing base and supply chains for those technologies, and train the workforce needed.

# Chapter 3: Pathways to 2050 Net-Zero Emissions in the United States

The decisive decade through 2030 is central to setting the United States—and the world—on a pathway that keeps warming of 1.5°C within reach.  For all countries, 2030 is an essential waypoint that is part of a longer path to reach global net-zero emissions by mid-century. The ambitious policies and goals described in Chapter 2 will set the United States on a pathway to achieve our 2030 target. At the same time, these actions will also catalyze the longer-term changes in the American energy, industrial, and land systems required to achieve net-zero by 2050.

This chapter presents the results of a comprehensive analysis undertaken to assess potential pathways to net-zero emissions in the United States by no later than 2050. These pathways are all grounded in our strategy to achieve our 2030 NDC and our goal of 100% carbon pollution-free electricity by 2035. These transition pathways are not only affordable, but, because of the benefits from reduced climate change and improved public health, they will also create wide-ranging benefits (see Chapter 7). It will require ambitious action and investment grounded in intensive engagement with communities, workers, and businesses to ensure that the benefits of the transition are equitably distributed—with a focus on those communities that remain overburdened and underserved.

## 3.1 Assessing Mitigation Opportunities to Achieve Net-Zero Emissions

Achieving rapid emissions reductions requires integrating near-term policy drivers with a strategy to assess and manage longer-term factors like capital stock turnover and technological innovation. To this end, this LTS employs diverse analytical approaches to project the impact of alternate assumptions about policies, technologies, and other drivers. These afford a broad understanding for what long-term net-zero technology transformations would look like globally [16] as well as providing roadmaps for how to affect those transitions rapidly [17].

In light of the Paris goals to develop and communicate national emissions reductions pathways, such analytical approaches have also been applied to understanding specific national circumstances and opportunities, including those within the United States. Some of these U.S.-specific studies focus on policy frameworks to drive near-term action that would set the U.S. on a pathway to longer-term net-zero or 1.5°C-compatible emissions [18] [19] [20]. In parallel, others look at the potential for integrating all-of-society strategies that include diverse levels of government and other actors [21]. Others have focused on overall long-term technological transformations and associated emission reduction strategies that would be necessary for reduction to net-zero in the U.S. by 2050. Many of these 2050 studies address emissions reduction across the entire economy and for all gases [14] [22] [23]; others focus on specific areas or sectors such as energy, electricity [13] [24], transportation [25], or manufacturing [26]. This research has advanced thinking about what is possible within the United States and what robust strategies to reach 2050 net-zero could look like. The assessment and analytical approaches presented here are original to this report but also recognize the many insights offered in this wider literature, including but not limited to studies specifically on 2050 net-zero pathways. Insights from this literature are consistent in what they tell us about the critical elements supporting the long-term emissions reduction trajectory for the United States.

This trajectory rests on the integration of five complementary technological transformations:

1. *Decarbonize electricity.* Electricity delivers diverse services to all sectors of the American economy. The transition to a clean electricity system has been accelerating in recent years—driven by plummeting costs for solar and wind technologies, federal and subnational policies, and consumer demand. Building on this success, the United States has set a goal of 100% clean electricity by 2035, a crucial foundation for net-zero by 2050.
2. *Electrify end uses and switch to other clean fuels.* We can affordably and efficiently electrify most of the economy—from cars to buildings and industrial processes. In areas where electrification presents technology challenges—for instance aviation, shipping, and some industrial processes—we can prioritize clean fuels like carbon-free hydrogen and sustainable biofuels.
3. *Cut energy waste.* Moving to cleaner sources of energy is made faster, cheaper, and easier when existing and new technologies use less energy to provide the same or better service. This can be achieved through diverse, proven approaches, ranging from new and more efficient appliances and the integration of efficiency into new and existing buildings, to sustainable alternate manufacturing processes and the integration of efficiency into new and existing buildings.
4. *Reduce methane and other non-$CO_2$ emissions.* Non-$CO_2$ gases such as methane, HFCs, nitrous oxide, and others contribute significantly to warming, with methane alone contributing fully half of current net global warming of 1.0°C. There are many profitable or low-cost options to reduce non-$CO_2$ sources, such as implementing methane leak detection and repair for oil and gas systems and shifting from HFCs to climate-friendly working fluids in cooling equipment. The U.S. is committed to taking comprehensive and immediate actions to reduce methane domestically. And through the Global Methane Pledge, the U.S. and partners seek to reduce global methane emissions by at least 30% by 2030, which would eliminate over 0.2°C of warming by 2050. The U.S. will also prioritize research and development to unlock the innovation needed for deep emissions reductions beyond currently available technologies.

6. *Scale up* $CO_2$ *removal*. In the three decades to 2050, our emissions from energy production can be brought close to zero but certain emissions such as non-$CO_2$ from agriculture will be difficult to decarbonize completely by mid-century. Reaching net-zero emissions will therefore require removing carbon dioxide from the atmosphere, using processes and technologies that are rigorously evaluated and validated. This requires scaling up land carbon sinks as well as engineered strategies.

There are many plausible pathways through 2050 to achieving a net-zero emissions economy. However, developments in these sectors over time are interdependent. For example, widespread adoption in leading energy efficiency practices in buildings could significantly impact overall electricity demand, reducing the amount of new clean energy installations required. The insight that sectors are interdependent demonstrates the importance of policy and incentives to realize the benefits of decarbonization across the economy. Recent developments in energy, manufacturing, and information technology have made swift and substantial reductions possible. Well-designed policies can help to ensure rapid and affordable economy-wide decarbonization. For example, accelerated shifting to carbon-free power makes end-use electrification an even more effective strategy to drive down emissions. In addition, policies can maximize the benefits of decarbonization and ensure that underserved communities benefit equitably from the transition to a clean energy system. For example, inclusive investment programs to scale up financing for efficient electric home upgrades can help level the playing field for underserved households and ensure effective consumer protections.

## 3.2 Current U.S. GHG Emissions Trends in 2021

Net U.S. GHG emissions peaked in 2007 [27] after growing through much of the previous century, driven mainly by combustion of fossil fuels to meet growing demand for energy services. Since their peak, net U.S. GHG emissions have declined, driven by a combination of forces. Federal policy has played a crucial role, including through sustained research and development investments which propelled an initial shift from coal to gas power and the simultaneous and now dominant growth of renewables; incentives for renewables and zero-emission vehicles; and sector-specific regulations such as emissions standards for power plants, fuel economy standards, and appliance efficiency standards. Tribal governments, U.S. states, cities, counties, and other non-federal actors have played a similarly crucial role across all sectors of the economy. Moreover, this federal and subnational investment and policy has propelled a virtuous cycle of technology cost reductions inducing even larger markets for key carbon-free technologies which, in turn, drives further cost reductions through scale and learning.

## 3.3. Analysis of Potential U.S. Trajectories to Net-Zero Emissions by 2050

The new analysis presented here offers insights into what the overall emissions profile for the United States could look like between now and 2050 under a set of alternate assumptions about the evolution of technological costs, economic growth, and other drivers to 2050. We use two economy-wide models (GCAM and OP-NEMS), a range of sensitivity scenarios, supplemental models for key sectors, and comparisons to the growing literature on pathways to net-zero emissions. This provides transparency on what the possible pathways to 2050 net-zero might look like, and how those different pathways would affect the evolution of specific sectors and rates of deployment for specific technologies.

The assessment presented in this chapter reflects model outputs that are subject to several types of uncertainty. The goal of showing these outputs is to illustrate the evolution of the U.S. economy and resulting emissions over time.  While the technology assumptions and policy goals for the decade to 2030 are largely understood, there is increasing uncertainty after 2030 on how any individual technology or sector will evolve. We show several different pathways based on alternate assumptions. These sensitivities illustrate a range of credible and plausible pathways to net-zero by 2050.

### *3.3.1 Descriptions of the Models*

#### Global Change Assessment Model (GCAM)

The LTS scenarios were produced in the Global Change Analysis Model (GCAM) by the Pacific Northwest National Laboratory. The Global Change Analysis Model (GCAM) is an integrated assessment model covering all major GHGs and all sectors of the economy, linking the world's energy, agriculture, and land use systems with a climate model. It is used to explore the interactions of emissions-reducing investments and activities across the U.S. and global economy. The model is designed to assess climate change policies and technology strategies for the globe over long time scales. GCAM runs in 5-year time steps from 2005 to 2100 and includes 32 geopolitical regions in the energy and economy module and 384 land regions in the agriculture and land use module. The model tracks emissions and atmospheric concentrations of GHGs ($CO_2$ and non-$CO_2$), carbonaceous aerosols, sulfur dioxide, and reactive gases and provides estimates of the associated climate impacts, such as global mean temperature rise and sea level rise. GCAM can incorporate emissions pricing and emission constraints in conjunction with the numerous technology options including solar, wind, nuclear, and carbon capture and sequestration. The model has been exercised extensively to explore the effect of technology and policy on climate change and the cost of mitigating climate change. GCAM is a community model primarily developed and maintained at the Joint Global Change Research Institute, a partnership between Pacific Northwest National Laboratory (PNNL) and the University of Maryland [28]

## Office of Policy – National Energy Modeling System (OP-NEMS)

The LTS scenarios were constructed using a version of the National Energy Modeling System (NEMS) developed by the U.S. Department of Energy (DOE) Office of Policy (OP-NEMS). NEMS is an integrated energy-economy modeling system for the United States that projects the produc-tion, imports, conversion, and consumption of energy, subject to assumptions on macroeco-nomic and financial factors, world energy markets, resource availability and costs, cost and performance characteristics of energy technologies, and demographics. The version of NEMS used in this report has been run by OnLocation, Inc., with modeling approach determined with input from the DOE Office of Policy and other DOE technology offices. Because OP-NEMS pro-jects only $CO_2$ emissions related to the energy sector, external assumptions were provided re-garding non-$CO_2$ GHGs and land use, land-use change, and forestry. OP-NEMS includes enhancements for clean hydrogen, sustainable biofuels, and industrial carbon capture, transport, and storage [29].

## Global Timber Model (GTM)

The Global Timber Model (GTM) is a dynamic intertemporal optimization economic model that determines timber harvests, timber investments, and land use optimally over time under assumed future market, policy, and environmental conditions. This model's approach provides a simulation of harvesting, planting, and management intensity decisions that landowners might undertake in response to timber and carbon market demands, including future price expectations. These activities include afforestation and land use change, forest management, and forest products activity in response to policies and markets. The model generates projections using detailed biophysical and economic forestry data for different countries or regions globally, including the U.S., China, Canada, Russia, and Japan. It used macroeconomic data from Annual Energy Outlook 2021 for the U.S. and global parameters from Shared Socioeconomic Pathway 2 (SSP2) [30]. The model has been widely used to assess forest dynamics and carbon outcomes under various demand and land carbon sink scenarios, climate impacts, and other applications [31] [32].

Forestry and Agriculture Sector Optimization Model with Greenhouse Gases (FASOM-GHG) The Forestry and Agriculture Sector Optimization Model with Greenhouse Gases (FASOM-GHG) model is a partial-equilibrium dynamic intertemporal, price-endogenous, mathematical programming model depicting land transfers and other resource allocations between and within the agricultural and forest sectors in the United States. FASOM-GHG includes detailed representations of agricultural and forest product markets, contemporary forest inventories, inter-sectoral resource competition and land change costs, and costs of mitigation strategies. The results from FASOM-GHG yield a dynamic simulation of prices, production, management, consumption, GHG effects, and other environmental and economic indicators within these two sectors, under the chosen policy scenario. The result provides insight into cross-sectoral inter- and intra-regional responses to policy stimuli reflecting the spatial heterogeneity in production of agriculture and forestry products across the U.S. To date, FASOM-GHG and its predecessor models have been used to examine the effects of GHG mitigation policy, climate change impacts, public timber harvest policy, federal farm program policy, bioenergy prospects, and pulpwood production by agriculture, among other policies and environmental changes [33].

### U.S. Department of Agriculture Forest Service Resources Planning Act (RPA) modeling system

The LTS scenarios reflect results from the U.S. Department of Agriculture (USDA) Forest Service Resources Planning Act (RPA) modeling system which comprises the Forest Dynamics model, integrated and harmonized with the USDA Forest Service RPA Land Use Change Model and the Forest Resource Outlook Model (FOROM) Global Trade Model [34]. This modeling system supports the projections of renewable resources across the U.S. in the USDA 2020 Resources Planning Act Assessment. Projections were developed under current climate conditions without $CO_2$ fertilization and values are added to USDA agriculture soils projections. The storage and flux of carbon in harvested wood products and solid waste disposal sites was projected using FOROM.

### U.S. EPA Non-CO2 Marginal Abatement Cost (MAC) Model and Report

The U.S. EPA Non-$CO_2$ Marginal Abatement Cost (MAC) Model is a bottom-up engineering cost model that evaluates the cost and abatement potential of non-$CO_2$ mitigation technologies [35]. The associated non-$CO_2$ mitigation report [36] provides a comprehensive economic analysis on the costs of technologies to reduce non-$CO_2$ gases and the potential to reduce them by sector.

## *3.3.2 Scenario Descriptions & Key Assumptions*

The LTS analysis includes multiple scenarios highlighting different pathways for achieving net-zero GHG emissions by 2050. The figures in this chapter present results for a range of assumptions, including the land sink, technologies (i.e., carbon dioxide removal, sector-specific technologies, and non-$CO_2$ mitigation technologies), energy prices, population, and economic growth. The advanced LTS scenario assumptions account for currently available opportunities as we build back from the pandemic by using advanced assumptions for electricity, transportation, industry, and buildings as modeled in GCAM and OP-NEMS.

| **Scenario Name** | **Scenario Technology Assumptions** | **Scenario Modelling Software** |
|---|---|---|
| Balanced Advanced | Medium carbon removal; advanced electricity, transportation, industry, buildings, and non-CO2 technology. | GCAM only |
| Lower Non-CO2 | Medium carbon removal; advanced electricity, transportation, industry, and buildings technology; lower non-CO2 technology. | GCAM only |
| Lower Industry | Medium carbon removal; advanced electricity, transportation, industry, and non-CO2 technology; lower industry technology. | GCAM only |
| Lower Transportation | Medium carbon removal; advanced electricity, industry, buildings, and non-$CO_2$ technology; lower transportation technology. | GCAM only |
| Lower Electricity | Medium carbon removal; advanced transportation, industry, and buildings technology; lower electricity technology | GCAM only |
| Lower Removals | Lower carbon removal; advanced electricity, transportation, industry, buildings, and non-$CO_2$ technology. | GCAM and OP-NEMS |
| Higher Removals / Lower Technology | High carbon removal; advanced electricity technology; lower transportation, industry, buildings, and non-$CO_2$ technology. | GCAM and OP-NEMS |
| High Oil and Gas Price | Medium carbon removal; advanced electricity, transportation, industry, buildings, and non-$CO_2$ technology; high oil price. | GCAM only |
| Low Oil and Gas Price | Medium carbon removal; advanced electricity, transportation, industry, buildings, and non-$CO_2$ technology; low oil price. | GCAM only |
| High Population and GDP | Medium carbon removal; advanced electricity, transportation, industry, buildings, and non-$CO_2$ technology; high population and GDP. | GCAM only |
| Low Population and GDP | Medium carbon removal; advanced electricity, transportation, industry, buildings, and non-$CO_2$ technology; low population and GDP. | GCAM only |

**Table 1: Long-Term Strategy Scenarios.** To explore multiple ways to reach our net-zero emissions goal in 2050, this analysis includes twelve scenarios (shown in the left most column of the table). The ‘Balanced Advanced’ scenario includes medium levels of

carbon removals from the atmosphere through our land use, land use change, and forestry (LULUCF) sink and carbon dioxide removal (CDR) technologies, and advanced technology assumptions allowing for a balanced approach across sectors. The next six scenarios explore lower technology assumptions for electricity, transportation, industry, buildings, non-$CO_2$, and carbon removals, respectively. Next is a scenario that includes higher levels of carbon removals combined with lower technology assumptions for multiple sectors. The last four scenarios explore high and low oil and gas price sensitivities, and high and low population and GDP growth projections.

The underlying assumptions in the scenario sets are as follows. Carbon removal levels represent the sum of the net land sink, derived from modeled projections of land use, land use change, and forestry (LULUCF), and plausible levels of carbon dioxide removal technology adoption such as biomass energy with CCS and direct air capture from the literature [37] [38]. The combined carbon removals from these sources are roughly 1,000, 1,400, and 1,800 $MtCO_2$ per year in 2050 over the low, medium, and advanced cases, respectively. The advanced and lower technology assumptions for the electricity and transportation sectors rely largely upon the National Renewable Energy Laboratory's Annual Technology Baseline. The advanced assumptions for the buildings and industrial sectors draw on the existing literature and programmatic goals for the advanced cases and slower improvements in the lower cases, which are more aligned with standard model parameters. For non-$CO_2$ reductions, the advanced technology assumptions accelerate the availability of low-cost technologies but do not alter long-term costs. Oil and natural gas prices are calibrated to the 2021 EIA Annual Energy Outlook's oil and gas supply cases in the reference scenario, i.e., without a net-zero 2050 target. Population and GDP, the final set of assumptions, span compound annual growth rates from 2020 to 2050 of 0.5% to 0.7% for population and 1.1% to 1.8% for GDP. Also, the LULUCF modeling effort included the use of 5 different models to generate business as usual and potential mitigation outcomes from different land-based activities, including afforestation, improved forest management, harvested wood products storage, and fire reduction techniques. This exercise included alignment of several key inputs and parameters, including use of input data from the Forest Inventory and Analysis database and, in some cases, application of Shared Socioeconomic Pathway (SSP) 2 information for macroeconomic drivers. The land use models applied in this analysis did not incorporate assumptions of demand of CCS or bioenergy as mitigation options, as these modeling aspects were accommodated in GCAM and OP-NEMS.

## 3.4 Economy-Wide Pathways to 2050 Net-Zero Emissions

Achieving the 2050 net-zero goal will require reducing net U.S. emissions from roughly 6.6 Gt $CO_2e$ in 2005 (and 5.7 Gt $CO_2e$ in 2020), to zero by no later than 2050. As described above, this reduction can result from combinations of five major categories of action: energy efficiency;

decarbonizing electricity; fuel switching and energy transitions; sequestering carbon through forests, soils, and $CO_2$ removal technologies; and reducing non-$CO_2$ emissions. Figure 3 presents a vision for how such categories of action can combine to reach net-zero. This figure shows a representative pathway from 2005 net emissions levels through 2050 in the form of a waterfall chart (the left-hand side of the figure). This representative pathway provides a rough approximation for reaching net-zero emissions using contributions from all sectors.

The right-hand side of the figure shows seven additional scenarios from our analysis that are based on different assumptions about how technologies and policies will evolve over time. This includes a "balanced advanced" scenario with high levels of action across all sectors, as well as scenarios where one of the sectors (buildings, industry, transportation, electricity, non-$CO_2$, land sink) contributes a lower level of reductions. These alternate scenarios serve to illustrate how the balance across technologies and policy strategies could vary while still reaching the net-zero 2050 goal.

Several broad lessons from this figure are clear. First, in the absence of additional policies, emissions would remain largely flat moving forward. Results in the figure show reductions from a baseline scenario to 2050—that means that only reductions beyond the baseline scenario are reflected in the colored bars. Achieving net-zero emissions will require actions that go far beyond business as usual.

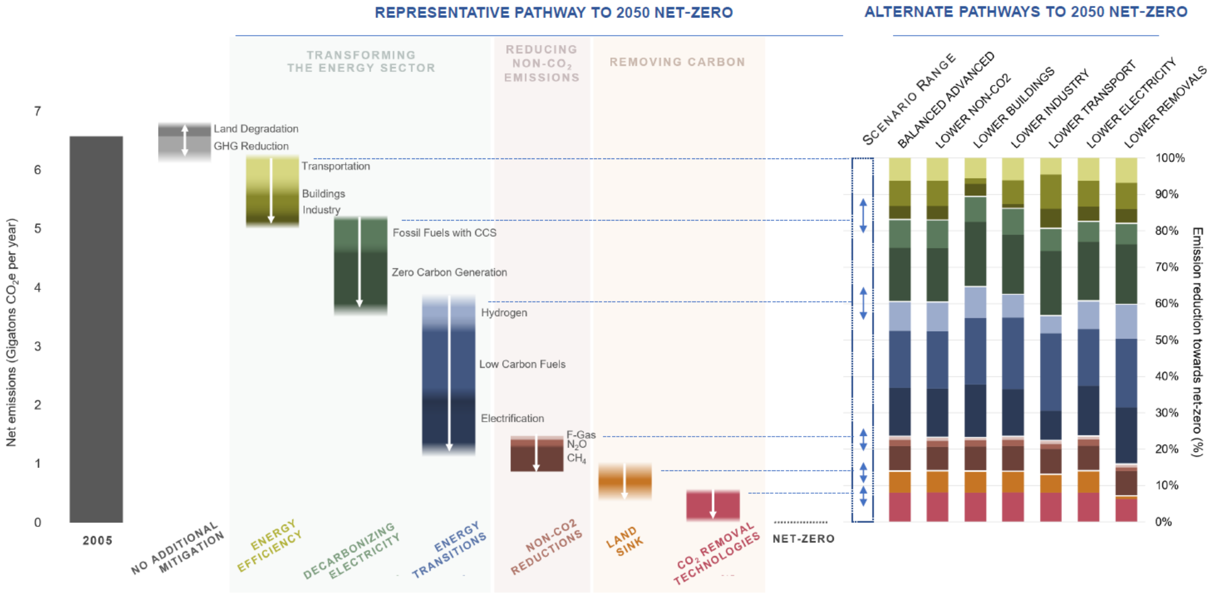


**Figure 3: Emissions Reductions Pathways to Achieve 2050 Net-Zero in the United States.** Achieving net-zero across the entire U.S. economy requires contributions from all sectors, including: efficiency, clean power, and electrification; reducing methane and

other non-$CO_2$ gases; and enhancing natural and technological $CO_2$ removal. The left side of the figure shows a representative pathway with high levels of action across all sectors to achieve net-zero by 2050. The right side shows a set of alternative pathways depending on variations in uncertain factors such as trends in relative technology costs and the strength of the land sector carbon sink. Across all scenarios, contributions from energy efficiency range from 10-19% (transportation contributions range from 5-7%, buildings from 2-9%, and industry from 1-5%). Contributions from decarbonizing electricity range from 22-25% (renewables contributions range from 15-18%, and fossil fuel with CCS from 6-8%). Contributions from energy transitions range from 34-44% (hydrogen contributions range from 5-10%, low-carbon fuels from 16-21%, and electrification from 8-15%). Contributions from non-CO2 reductions range from 9-10% (contributions from methane range from 6-7%, N2O from 1-2%, and F-gas reduction at 1%). Contributions from land sink enhancement range from 1-6%. Contributions from CO2 removal range from 6-8%.

Second, roughly 4.5 Gt of the 6.5 Gt annual reduction from 2005 levels will likely come from transforming the energy system. This starts with decarbonizing electricity by shifting to renewables and other emissions-free power. This shift could lead to over 1 Gt of annual reduction by 2050. A second pillar of energy transformation is simply to use energy more efficiently to provide the same services. Solutions like better insulation, advanced heat pumps for space and water heating, and efficient computers and electronics can save consumers billions on their annual energy bills. Cutting energy waste also reduces the rate of investment needed for new clean energy generation as demand grows. This pillar alone could contribute roughly 1 Gt of annual reductions by 2050. A third pillar of energy transformation is to switch as many uses as possible to clean energy–including clean electricity, but also including low-carbon fuels and clean hydrogen. Efficient electrification of transportation, buildings, and other end uses can also transform the energy sector by reducing overall energy demand. Electric motors in vehicles, for example, are approximately three times more efficient than internal combustion engines, and electric heat pumps are up to three times more efficient than heating with natural gas or electric resistance. These activities would lead to nearly 2 Gt of annual reductions by 2050.

Third, other non-$CO_2$ GHG emissions represent a critical component of the overall reduction strategy, collectively representing roughly 0.5 Gt of reductions by 2050. These gases have sources across many sectors and include methane emissions from agriculture, waste management, and fossil fuel use, HFCs used in refrigeration, and $N_2O$ from agriculture and industry. Such gases often offer low-cost and high-impact reductions. For example, globally, methane accounts for half of the net 1.0°C of warming already occurring. Because of its relatively short lifetime in the atmosphere, compared to CO2, rapidly reducing methane emissions is the single most effective strategy to reduce warming over the next 30 years and is crucial in keeping to the 1.5°C limit. The United States co-leads with the EU the Global Methane Pledge that aims to eliminate over 0.2°C of potential warming by 2050 by cutting global methane pollution at least 30% by 2030 relative to 2020 levels. As of October 2021, over 30 countries representing about 30% of global emissions and 60% of the global economy had joined the Pledge (See Box in Chapter 5). As detailed in the NCS, the United States is implementing comprehensive actions to drive down methane in this decade, including new standards for landfills and oil and gas operations as well as major investments to remediate abandoned coal, oil, and gas mines and wells. The United States is also committed to incentives and innovations to reduce agricultural methane and agricultural $N_2O$ emissions. Finally, a global HFC phasedown is expected to avoid up to 0.5°C of global warming by 2100.

Fourth, removing $CO_2$ from the atmosphere is a necessary component for reaching net-zero. Although most emissions across the economy can be eliminated through the above strategies, a few processes or activities that lead to emissions are currently difficult or costly to eliminate or have no viable existing substitutes, and despite many available cost-effective mitigation opportunities, non-$CO_2$ GHG emissions cannot be fully reduced to zero. This means that reaching net-zero will require additional contributions from removals until viable zero-emission solutions are developed and deployed. Overall, these removals would come from two broad categories of activities. One is through nature-based approaches that rely on natural carbon sinks–land and ocean–by expanding or enhancing conservation, restoration, sustainable management, and other activities that would enhance natural removal of carbon as well as protect our vital natural ecosystems and related services and biodiversity. A second set of approaches is through various technologies and processes that directly capture $CO_2$ from the atmosphere and store it (such as direct air or ocean capture, bioenergy with CCS, or enhanced mineralization). Technologies capable of carbon dioxide removal are available today, but at nascent stages and therefore will require additional research, development, and deployment now through 2050 (more discussion of CDR technologies can be found in section 6.4).

# Chapter 4: Transforming the Energy System Through 2050

The energy sector is pivotal for achieving net-zero emissions by 2050. Achieving net-zero is possible through a range of pathways, which depend on how technologies and policies evolve over the three-decade period. Nevertheless, by modelling a range of pathways with plausible assumptions for this evolution (see Figure 4), we can distinguish broad trends and important drivers of the energy sector transformation.

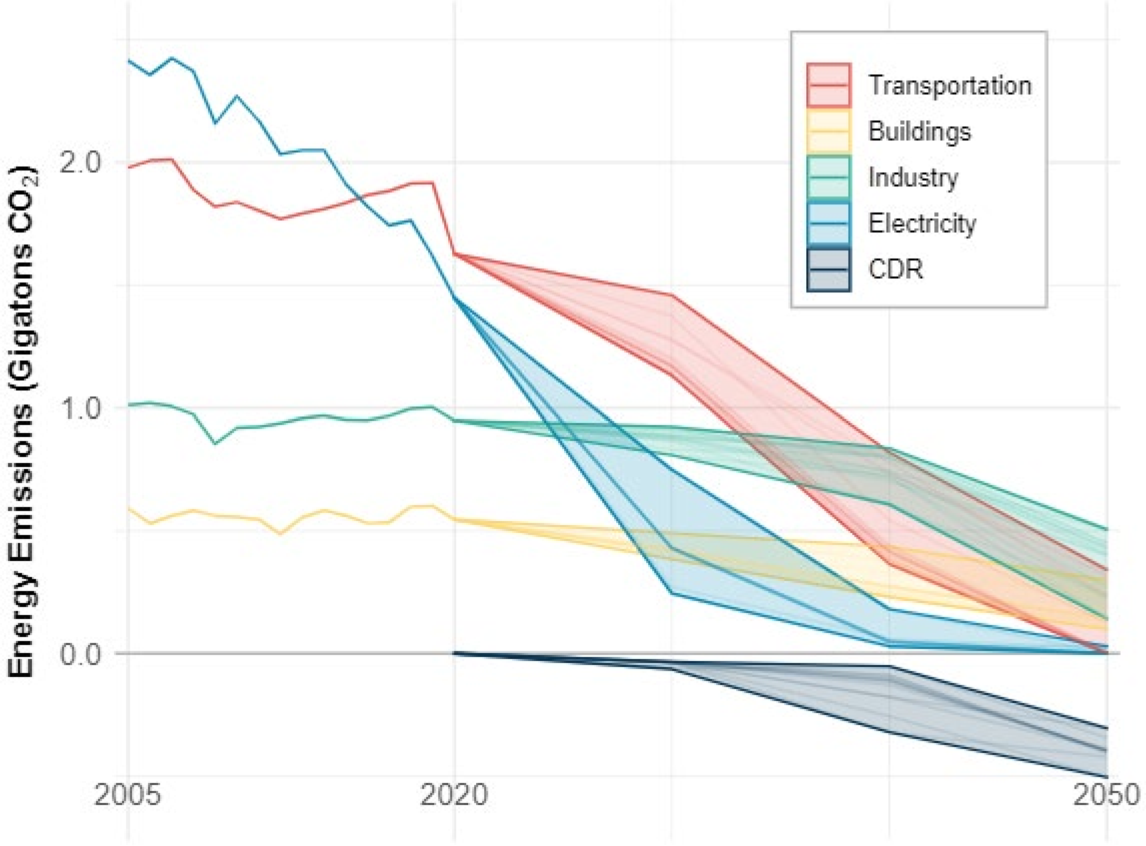


**Figure 4: U.S. Energy $CO_2$ Emissions to 2050 by Economic Sector.** Electricity $CO_2$ emissions and direct $CO_2$ emissions from the transportation, buildings, and industry fall dramatically in all scenarios, with the greatest reductions coming from electricity, followed by transportation, and non-land sink carbon dioxide removals (CDR) increase. Notes: Historical data are from EIA Monthly Energy Reviews, projections include data from all LTS scenarios using both GCAM and OP-NEMS, projections are shown in ten-year time steps. Transportation: Historical transportation emissions slightly decrease from 2005 to 2020 from approximately 2 GtCO2e in 2005 to just below 2 GtCO2e before 2020 and to approximately 1.6 GtCO2e in 2020. Projected transportation emissions decrease to approximately 1.3 GtCO2e by 2030, approximately 0.7 GtCO2e by 2040, and to approximately 0.3 GtCO2e by 2050. The range of projected transportation emissions is roughly

0.5 GtCO2e from 2020 through 2050. Buildings: Historical buildings emissions remain generally steady from 2005 to 2020 at approximately 0.5 GtCO2e. Projected buildings emissions decline steadily, reaching approximately 0.2 GtCO2e by 2050. The range of projected buildings emissions increases steadily from 2020, reaching roughly 0.3 GtCO2e by 2050. Industry: Historical industry emissions remain generally steady from 2005 to 2020 at approximately 1 GtCO2e. Projected industry emissions decline slightly to reach approximately 0.8 GtCO2e through 2040, then decline more sharply to reach approximately 0.3 GtCO2e by 2050. The range of projected transportation emissions is roughly 0.5 GtCO2e from 2020 through 2050. Electricity: Historical electricity emissions decrease sharply from 2005 to 2020 from approximately 2.4 GtCO2e to approximately 1.4 GtCO2e. Projected electricity emissions decrease sharply through 2030 to reach approximately 0.5 GtCO2e, more gradually through 2040 to reach close to 0 GtCO2e, then decrease through 2050 to reach 0 GtCO2e. The range of projected electricity emissions increases from 2020 to 2030, then decreases through 2050. CDR: Projected CDR removals increase from 0 GtCO2e in 2020 to approximately -0.05 GtCo2e in 2030, approximately -0.2 GtCO2e in 2040, and approximately -0.4 GtCO2e in 2050. The range of projected CDR removals is very small through 2030 and increases to approximately -0.2 GtCO2e between 2040 and 2050.

## 4.1 Electricity

The United States has set a goal for 100% carbon pollution-free electricity by 2035, and this goal will provide an important foundation for the Long-Term Strategy of the United States. Electricity is used in every economic sector, and all 2050 net-zero pathways depend on rapidly decarbonizing electricity and expanding the use of this decarbonized electricity into as many uses as possible to displace polluting fuels. The electricity sector, which contributes about a quarter of all U.S. GHG emissions, has been reducing $CO_2$ emissions for years, with major shifts caused in part by increases in renewables and decreases in coal-fired generation (see Figure 5). Continued cost reductions in generation and storage are expected to enable even more rapid reductions of emissions from this sector. New policies, incentives, market reforms, and other actions will be needed to ensure that electricity sector emissions continue to decrease as total electricity demand increases.

The electricity sector will continue to evolve rapidly as it decarbonizes. Expected continued cost reductions in renewable generation as well as battery and other storage technologies could see emissions decreases of roughly 70-90% by 2030 on a path toward the 2035 100% clean electricity goal. As shown in Figure 5, solar and wind generation continues to increase substantially through 2050, while existing nuclear generation remains in operation and could see growth in the 2030s and 2040s. Unabated fossil generation (coal or gas generation without CCS technology) declines, and existing fossil fueled plants start to be fitted with carbon capture. By 2050, clean generation provides zero-emission electricity to the rest of the economy, with all electricity providing 15%-42% of primary energy.

Recent analyses suggest that wholesale electricity prices, on average, are unlikely to change significantly as we shift to a cleaner grid by 2030, with price impact estimates ranging from a 4% *decrease* to a 3% increase [39]. Additionally, the transition to clean electricity is expected to reduce exposure of U.S. consumers to fuel supply shocks [40].

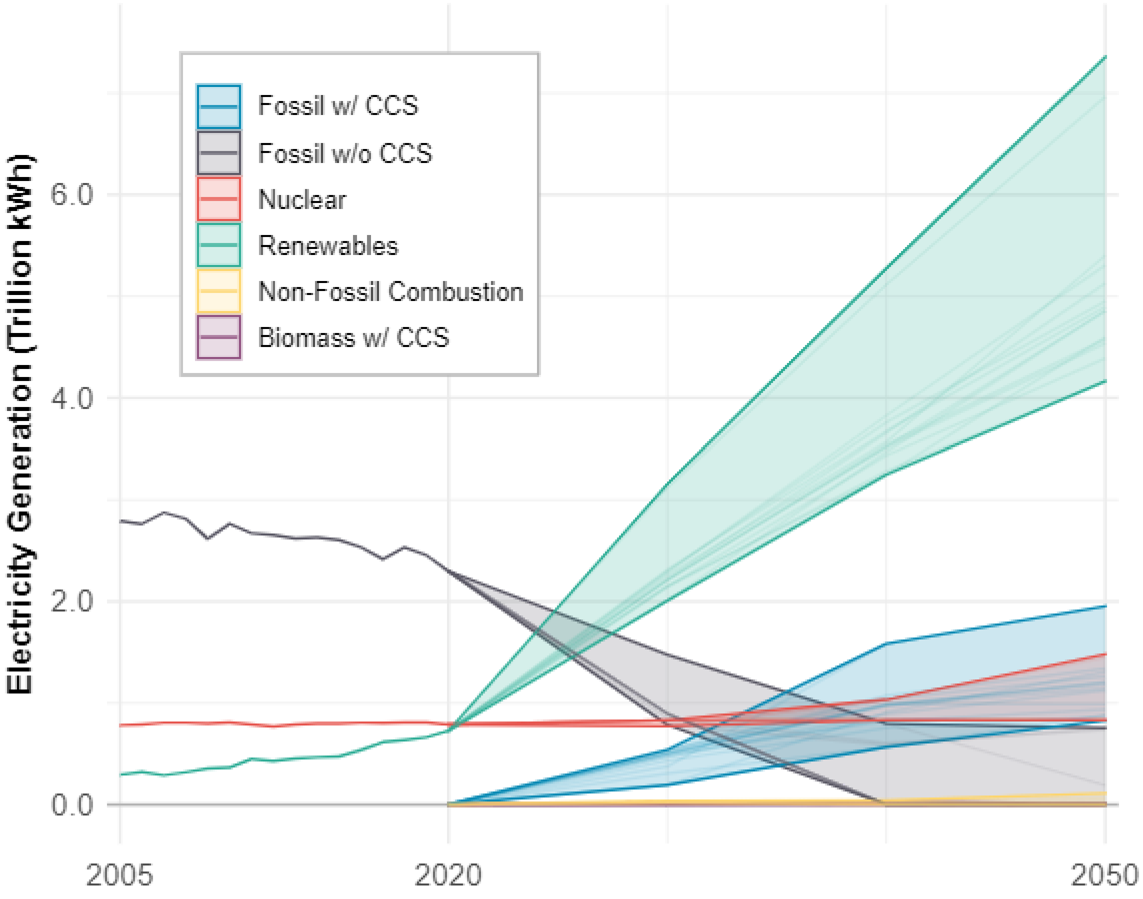


**Figure 5: U.S. Electricity Generation 2005-2050.** Generation by source in trillion kilowatt-hours. Total generation expands to 2050 due to increased use of clean electricity in new applications in transportation, industry, and buildings. Renewable generation increases rapidly to keep pace with growing electricity demand and ensure that the share of renewables continues to expand to 2050. Note: Historical data are from EIA Monthly Energy Reviews, projections include data from all LTS scenarios using both GCAM and OP-NEMS, projections are shown in ten-year time steps. Projected fossil with CCS generation increases from 0 in 2020 to approximately 1-2 trillion kWh by 2050. Historical

> fossil without CCS generation decreased from approximately 2.8 trillion kWh in 2005 to approximately 2.3 trillion kWh in 2020. Projected fossil without CCS generation decreases to 0 between 2040 and 2050. Historical nuclear generation remained roughly steady from 2005 to 2020 at approximately 0.8 trillion kWh. Projected nuclear generation will remain constant or increase up to approximately 1.5 trillion kWh by 2050. Historical renewables generation increased from approximately 0.3 trillion kWh in 2005 to approximately 0.8 trillion kWh in 2020. Projected renewables generation increases to between approximately 4.1 and 7.3 trillion kWh in 2050. Projected non-fossil combustion increases from 0 in 2020 to approximately 0.1 trillion kWh in 2050. Historical biomass with CCS and non-fossil combustion were zero in 2005-2020. Projected biomass with CCS and non-fossil combustion generation remains close to 0 in 2050.

Investment in clean energy generation must continue through mid-century as overall electricity generation increases to meet demand growth from other sectors. Average annual total capacity additions without storage from 2021 to 2030 range from 58 gigawatts per year (GW/yr.) to 115 GW/yr.; in 2031 to 2040 they range from 54 GW/yr. to 167 GW/yr.; and in 2041 to 2050 they range from 67 GW/yr. to 123 GW/yr. Storage capacity additions from 2021 to 2030 average 0.4 GW/yr. to 2.7 GW/yr.; in 2031 to 2040, they range from 3 GW/yr. to 40 GW/yr.; and in 2041 to 2050 they range from 11 GW/yr. to 64 GW/yr.

This rapid evolution and scale of change in the electricity sector is ambitious, with high and sustained deployment of new technologies through mid-century. Many significant challenges and barriers exist [14] [22]. The electricity transition will require adding significant amounts of new zero-carbon electricity capacity at a sufficient pace to replace uncontrolled fossil fuel-fired generation while also providing ample clean supply for a growing economy with increased electrification. New transmission, distribution, and storage infrastructure will be needed to maintain and improve grid reliability, including adapting the electric grid to be flexible to changing supply and demand over all increments of time. In particular, longer-duration storage solutions and appropriate incentive mechanisms will be critical. Absent new action, supply chains may become stressed by limited availability of raw materials (such as rare earth elements), manufacturing capacity, and skilled workforce. Some pathways may also require significant expansion of carbon capture and storage technologies during the overall transition, which bring specific challenges around technology development and siting.

These challenges are substantial but can be addressed through an integrated strategy of investment, innovation, and new technology deployment. Large-scale deployment of renewables can be accelerated by investments in grid infrastructure and advanced technologies. Grid infrastructure investments, including the buildout of new long-distance, high-voltage transmission projects, can enhance resilience, improve reliability, better integrate variable generation resources, lower electricity costs, and unlock the best clean energy resources by connecting them to demand centers. Significant deployment of energy efficiency can also help reduce the scale of investment required by lowering the total energy demand that must be met. Analyses show that as the sector becomes increasingly decarbonized, advanced technologies will be brought online to meet peak load and adjust to seasonal changes in demand. Advanced technologies—which could include clean hydrogen combustion or fuel cells, enhanced geothermal systems, long-duration energy storage, advanced nuclear, and fossil generation with CCS—can provide clean firm resources that can balance increased variable generation. However, these technologies require a rapid, sustained acceleration in research, development, and deployment. The significant investments in generation and transmission will underpin job growth across the nation, creating opportunities in cities and rural areas alike, particularly when paired with workforce training. Expansion of the transmission system, stronger interregional coordination, and distributed generation also provide resilience to natural disasters, saving lives and protecting businesses.

### *Box 3: Rapid Decarbonization in the U.S. Electricity Sector is Underway*

The electricity sector in the United States has been decarbonizing rapidly, with significant increases in renewable deployment in recent years. The shift to lower-emissions sources has been under way for decades, with early contributions from nuclear and then fossil gas. More recently, since around 2010, federal investment policies, tax credits, and regulatory actions, as well as state policies, research and development, and market trends, drove significant renewable deployment. At the same time, between 2010 and 2019, more than 546 coal-fired power units retired, totaling 102 GW of capacity, with another 17 GW of capacity planned for retirement by 2025 [41]. This has led to a dramatic shift in the sources of U.S. electricity, with renewables now accounting for more generation than coal (Figure 6). In addition, the sum of coal and natural gas generation has also declined in the last decade, pointing to the important role of renewable energy.

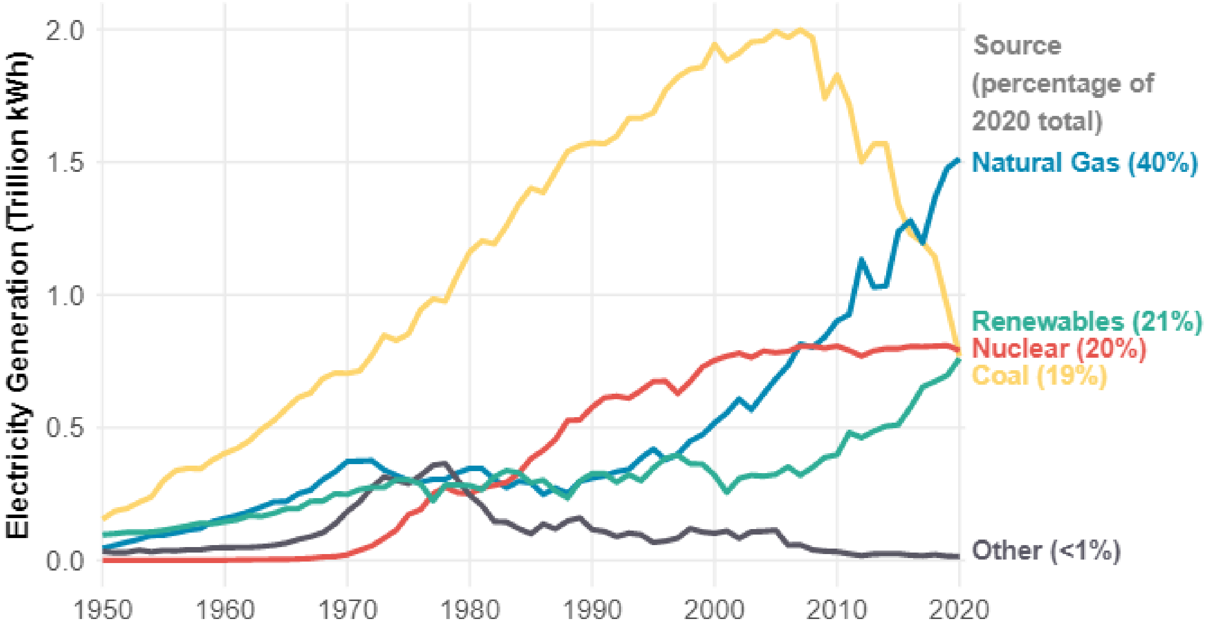


**Figure 6: Annual U.S. Electricity Generation from All Sectors 1950-2020 (trillion kilowatt-hours).** The electricity sector has been rapidly decarbonizing since 2008. This figure shows electricity net generation in all sectors (electric power, industrial, commercial, and residential) and includes both utility-scale and small-scale solar. Rapid increases in solar, wind, and other renewable generation means that in 2020, for the first time, renewable generation surpassed coal generation. Coal generation has declined rapidly, replaced by natural gas and renewables. Source: EIA [42]. Natural gas generation increased from 1950 to 2020, reaching 40% of generation in 2020 (approx. 1.5 trillion kWh). Renewables generation also increased at a slower rate than gas, reaching 21% of generation in 2020 (approx. 0.75 trillion kWh). Nuclear generation increased rapidly through 2000 and remained steady through 2020, reaching 20% of generation in 2020 (approx. 0.75 trillion kWh). Coal generation grew steadily through 2000, making up the majority of electricity generation at its peak around 2008, then decreased rapidly through 2020, reaching 19% of generation in 2020 (approx. 0.75 trillion kWh). Other generation sources increased slightly through 1980, then declined, reaching <1% of generation in 2020 (approx. 0.05 trillion kWh).

One of the challenges to reach the 2050 net-zero goal (as well as the 2035 100% clean electricity goal) is the large amount of new zero-emission capacity (primarily renewables) that will need to be deployed annually to enable an increasingly large share of clean electricity generation. Figure 7 shows some indicative estimates of the magnitude of the annual capacity additions needed to remain on pace toward our goals, in comparison to recent historical levels of capacity additions. Recent trends in renewable deployment are encouraging. Solar and wind capacity additions were about 32 GW in 2020, the highest on record, and are expected to be about 28 GW in 2021. Acceleration will be needed but the deployment rate has been growing quickly.

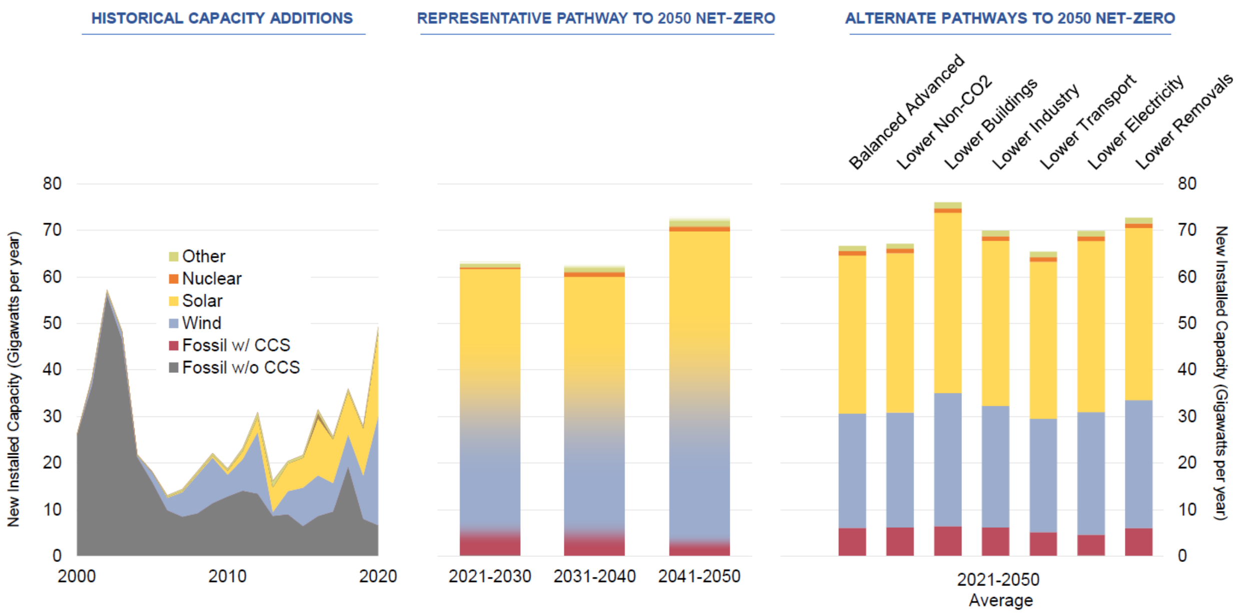


**Figure 7: Electric Generation Capacity Additions 2000-2050.** Renewable capacity additions have been growing rapidly in the past decade (left) and are more closely approaching levels that will be needed to sustain the overall decarbonization trend in electricity needed to reach the 2050 goal. A representative pathway (center) shows deployment of total zero-carbon technologies roughly on the order of 60–70 GW per year. Diverse scenarios in this analysis show a range of potential pathways to achieve net zero (right). Note: Historical data are from EIA Monthly Energy Reviews, projections include data from all LTS scenarios using GCAM. Other scenarios not shown in the figure have cumulative nuclear capacity additions ranging up to 90–100 GW through 2050. Chart one: Electricity capacity additions between 2000 and 2020 primarily consist of fossil without CCS, wind, and solar generation. Fossil with CCS, nuclear, and other capacity additions were marginal. Wind capacity additions begin increasing starting around 2003; solar capacity additions began increasing starting around 2013. By 2020, solar contributed approximately two-fifths of new capacity, wind contributed approximately two-fifths, and fossil without CCS contributed approximately one-fifth. Chart two: A representative pathway to achieve net-zero by 2050 sees approximately 60 GW/yr. of annual new installed capacity from 2021 to 2040, which grows to approximately 70 GW/yr. of annual new installed capacity from 2041 to 2050. In the representative pathway, fossil with CCS contributes approximately 5 GW/yr. of annual new installed capacity, wind contributes

between approximately 30 GW/yr. of annual new installed capacity, with solar contributing the majority of the remaining capacity. Nuclear and other sources provide less than 5 GW/yr. of annual new installed capacity. Chart three: A range of pathways can be taken to achieve net-zero by 2050. Across these scenarios, the average annual new installed capacity between 2021 and 2050 varies from approximately 65 GW/yr. to approximately 75 GW/yr. Nuclear contributes approximately 5GW/yr. across scenarios. Wind additions range from approximately 25-30 GW/yr. Solar additions range from approximately 30-35 GW/yr. Nuclear and other sources provide less than 5 GW/yr. across scenarios.

## 4.2 Transportation

The transportation sector provides vital mobility services for people and goods with on-road vehicles, planes, trains, ships, public transportation, and a wide variety of other modes. It is currently the highest emitting sector, representing 29% of all U.S. emissions [27]. To reduce emissions to net-zero by 2050 we will need to ensure that zero-emission vehicles dominate new sales for most types of vehicles by the early 2030s, as well as infrastructure to support alternate modes of transportation, such as trains, bikes, and public transit.

The United States will continue to increase the use of electricity and sustainably produced low-carbon fuels in the transportation sector while shifting away from fossil sources (Figure 8). Over time, electricity, carbon beneficial biofuels, and hydrogen will become increasingly clean. The availability and adoption of these low-carbon fuels in the coming decades will largely depend on the economics of production and/or procurement, the competitiveness of bioenergy and hydrogen compared to alternative low-carbon technologies across sectors, policy support, private investment and, in the case of bio-based energy, the ability to minimize potential negative land carbon outcomes and other environmental impacts of biomass production. Although demand for transportation services increases through mid-century, the total energy consumed in this sector declines due to a combination of regulations and technological advances which drive efficiency improvements and deliver societal and consumer benefits.

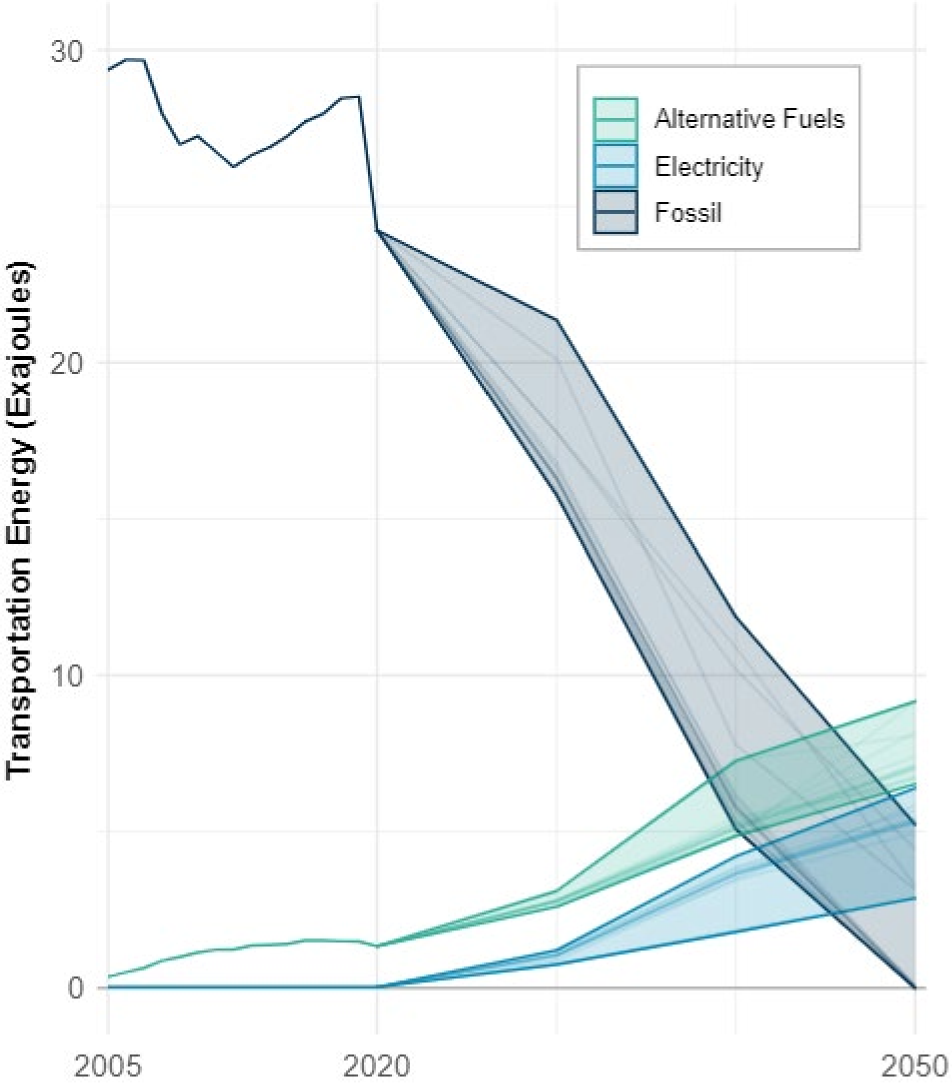


**Figure 8: U.S. Transportation Final Energy Use 2005-2050.** Overall transportation energy in exajoules (EJ) decreases while the use of electricity and alternative fuels, including biomass-derived fuels and hydrogen, increases to power nearly the full U.S. transport system by 2050. While light-duty vehicles are almost all electric by 2050 in most scenarios, there is uncertainty in other transportation sectors. Uncertainties in the future share of low-carbon bioenergy vs. hydrogen makes can affect the potential for electrification in the sector. These results show end use consumption instead of service demand (e.g., per mile travelled), so electricity demand appears smaller than alternative fuels demand due to the major inherent efficiency advantages of electric vehicles. Note: Historical data are from EIA Monthly Energy Reviews, projections include data from all LTS scenarios using both GCAM and OP-NEMS, projections are shown in ten-year time steps. Historical transportation energy use from fossil fuels decreased from approximately 30 exajoules in 2005 to approximately 24 exajoules in 2020. Projected

> transportation energy use from fossil fuels decreases to approximately between 5 and 0 exajoules in 2050. Historical transportation energy use from alternative fuels grew from near zero to approximately 2 exajoules in 2020. Projected transportation energy use from alternative fuels grows to approximately between 6 and 9 exajoules by 2050. Historical transportation energy use from electricity was near zero between 2005 and 2020. Projected transportation energy use from electricity increases to approximately between 3 and 6 exajoules by 2050.

A central component of the U.S. Long-Term Strategy in transportation is the expanded use of new transportation technologies—including a rapid expansion of zero-emission vehicles—in as many applications as possible across light-, medium-, and heavy-duty applications. Already, the growing popularity of electric vehicles (EVs), supported by incentives and continued advances in battery technology, is spurring greater EV adoption and industry goals for even higher EV sales. Other technologies can serve as important complements to EVs. The President's goal and associated policies to ensure half of all new vehicles sold in 2030 zero-emissions vehicles (including battery electric, plug-in hybrid electric, or fuel cell electric vehicles) will continue to spur growth across all zero-emission vehicle types.

This rapid deployment of zero-emissions vehicles is ambitious and will need to occur at a large scale across all vehicle types. Many challenges and barriers exist [14] [22] [25]. For example, costs for electric technologies, fueling, and charging infrastructure remain high in some applications. Some transportation segments, such as aviation, will likely remain difficult to electrify and some legacy vehicles will continue to be necessary in the near term, both of which would require alternate sources of low-carbon fuels that have yet to be deployed at the necessary scale. The existing built environment creates also high dependency on owner-occupied vehicles and presents numerous obstacles to alternate mobility options and shifting between modes such as transit, biking, or walking.

An integrated strategy to address these substantial challenges can help accelerate the development and rapid expansion of new transportation technologies. An expanded network of public transit options and infrastructure will increase urban mobility, helping to reduce emissions and increase equity in mobility. Electrifying segments of the rail system will decarbonize the existing rail system with the added benefit of enabling a more robust electric grid along railroad "right of way." Additionally, "vehicle to grid" innovations may provide support for grid services. Accelerated research, development, demonstration, and deployment of lower-carbon fuels, such as clean hydrogen and sustainable biofuels, will contribute to the decarbonization of applications that may be more difficult to electrify including aviation and marine transportation and some medium- and heavy-duty trucking segments.

## 4.3 Buildings

Buildings house our population and provide a working environment for commercial sectors including offices, colleges and K-12 schools, restaurants, grocery stores, and retail shops. Homes and commercial buildings are responsible for over one-third of $CO_2$ emissions from the U.S. energy system. Of this, roughly two-thirds of buildings sector emissions currently come from electricity, with the remainder coming from direct combustion of gas, oil, and other fuels for space heating, water heating, cooking, and other services, and buildings currently account for about three quarters of U.S. electricity sales [43]. Electricity is used in buildings for lighting, space heating and cooling, water heating, electronics and appliances, and other services. $CO_2$ emissions from buildings have been falling since 2005, due to increases in energy efficiency, the decarbonization of the electricity sector, and a modest trend towards the electrification of end uses. These emissions reductions have been achieved even as commercial building square footage has increased by more than 25% and the population has grown by more than 10% since 2005. All buildings need to be decarbonized with an emphasis on strategies that deliver for overburdened and underserved communities. For example, in the residential sector, households with an annual income below $60,000 account for nearly 50% of all household energy consumption, making it essential that efforts to decarbonize buildings are accessible to all households [44].

The key driver of reducing building emissions is efficient use of electricity for end uses (such as heating, hot water, cooking, and others). Alongside the decarbonization of electricity, these changes can bring building sector emissions to near-zero by 2050. Across multiple possible pathways, building efficiency improvements also reduce the overall demand for energy by the sector, despite the substantial growth in the number of buildings, floorspace, and population expected through 2050 (Figure 9). Within this overall decrease in energy demand, the share of electricity in final energy demand grows as end uses are electrified, from about 50% in 2020 to 90% or more by 2050 because the on-site combustion of gas, oil, and other fuels decreases substantially; however, the growth is also limited through energy efficiency and efficient electrification. Heat pumps and other electric heaters and electric cooking account for more than 60% of sales by 2030 and nearly 100% of sales by 2050. Energy demand in buildings is reduced by 9% in 2030 and 30% in 2050.

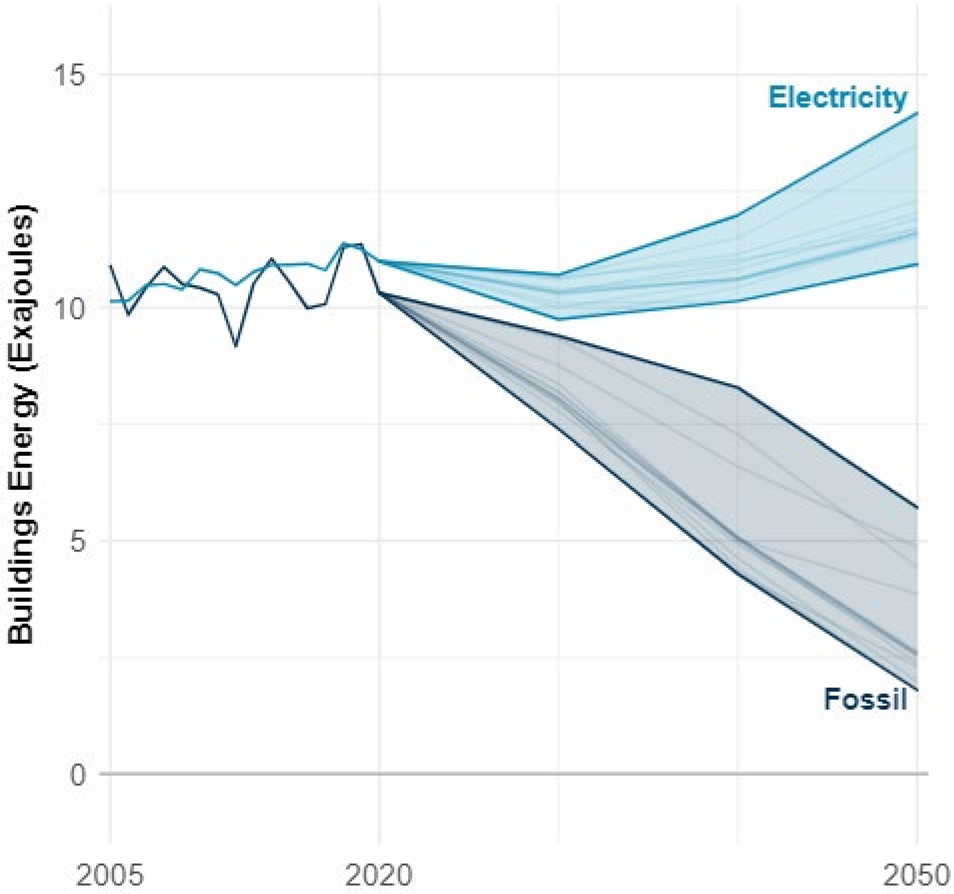


**Figure 9: U.S. Buildings Site Energy 2005-2050.** Overall building site energy use in exajoules (EJ) decreases at the same time as certain applications (e.g., heating) switch from fossil fuels (and some biomass) to clean electricity. Note: Historical data are from EIA Monthly Energy Reviews, projections include data from all LTS scenarios using both GCAM and OP-NEMS. Historical building energy use from electricity increased from approximately 10 exajoules in 2005 to approximately 11 exajoules in 2020. Projected building energy use from electricity increases to between 11 and 14 exajoules in 2050. Historical building energy use from fossil fuels varied widely between 2005 and 2020, beginning at approximately 11 exajoules in 2005 and ending at approximately 10 exajoules in 2020, reaching a peak of approximately 11.5 exajoules around 2019. Projected building energy use from fossil fuels decreases to between 6 and 2 exajoules in 2050.

While recent trends are encouraging, the building sector presents some unique challenges to rapid decarbonization. Foremost is the often-long lifetime of buildings. Many buildings built today will still be in active use by 2050, which means that even immediate actions to improve new buildings take years before making a significant impact in the overall building stock. These factors affect all aspects of buildings including the outer shell; heating, ventilation, and air conditioning systems; and appliances and lighting—although some of these are more amenable to retrofitting than others. In addition, energy efficiency and efficient electrification have barriers relating to their upfront cost structure, financing, competing landlord and tenant incentives. These issues can be particularly difficult in underserved communities, which will also need widespread access to retrofits and new building technologies, though innovative financing tools such as inclusive investment programs can deliver substantial benefits to these communities while reducing or eliminating financing barriers and ensuring consumer protections.

To address these challenges, pursuing multiple options effectively help achieve the necessary rapid emissions reductions in buildings while also reducing the energy cost burden for families and businesses and improving the health and resilience of communities. There are three important sources of emissions reductions: technological advances including from envelope improvements (e.g., attic and wall insulation, sealing leaks, and efficient windows), improved efficiency of electric end uses (e.g., lighting, refrigeration, appliances, and electronics), and the efficient electrification of space and water heating, cooking, and clothes drying in both existing and new buildings. The rapid deployment of heat pumps for space heating and cooling and water heating is the central strategy for the efficient, flexible electrification of buildings. By increasing the amount of demand-responsive heating, cooling, and water heating on the grid, these technologies can respond to shifts in renewable generation levels on short notice and reduce the overall cost of a low- or zero-carbon generation mix.

Efficient and electrified buildings provide substantial consumer benefits. The most important benefit is reduced utility bills for households and businesses which are both direct (through lower energy usage) and indirect (through lower energy prices). More efficient buildings significantly reduces electricity demand and lessen winter peaking loads as the sector electrifies, reducing the cost of new generation, transmission, and distribution, which in turn reduces energy prices for American families and businesses. These bill savings would be most beneficial to low-income households, which typically face the greatest energy burden. Buildings can also support electric vehicle charging infrastructure and rooftop solar installations, key elements of the broader energy transition. More efficient buildings also retain indoor temperature for longer during power outages under extreme weather conditions, improving health and safety. The role of state utility regulators will be especially important, as approval of new rate structures and consumer incentive programs will be vital in realizing the full potential of consumer benefits. Finally, building improvements will come from manufacturing, construction, and installation performed by skilled, well-paid American workers in communities across the country.

## 4.4. Industry

The U.S. industrial sector currently produces roughly 23% of U.S. GHG emissions and 30% of emissions from the energy system [45]. It is heterogeneous, producing a wide range of products with diverse and sometimes specialized processes. The energy-intensive and emissions-intensive industries include mining, steel manufacturing, cement production, and chemical production, and collectively produce nearly half of overall industrial emissions. In addition to the $CO_2$ emissions resulting from industrial demand for electricity, the industrial sector emits GHGs directly from many operations and processes including the use of fossil fuels for on-site energy use and as feedstocks, direct process emissions of $CO_2$ from cement production and other industries, and emission of non-$CO_2$ GHGs such as $N_2O$ from nitric and adipic acid production.

Although there are many hard-to-decarbonize elements of industrial activities, investments in technologies for advanced non-carbon fuels, energy efficiency, and electrification can reduce overall industrial sector $CO_2$ emissions by 69-95% by 2050. A large range of potential pathways for the industrial sector are shown in Figure 10. Overall energy use drops in most scenarios through energy efficiency and materials efficiency investments. In these scenarios, overall electricity use in the sector grows only slightly due to electrification. However, in scenarios that rely on a large quantity of hydrogen, electricity use increases dramatically to produce the hydrogen through electrolysis. In all scenarios, low-carbon fuels (including electricity) grow as a percentage of total energy use.

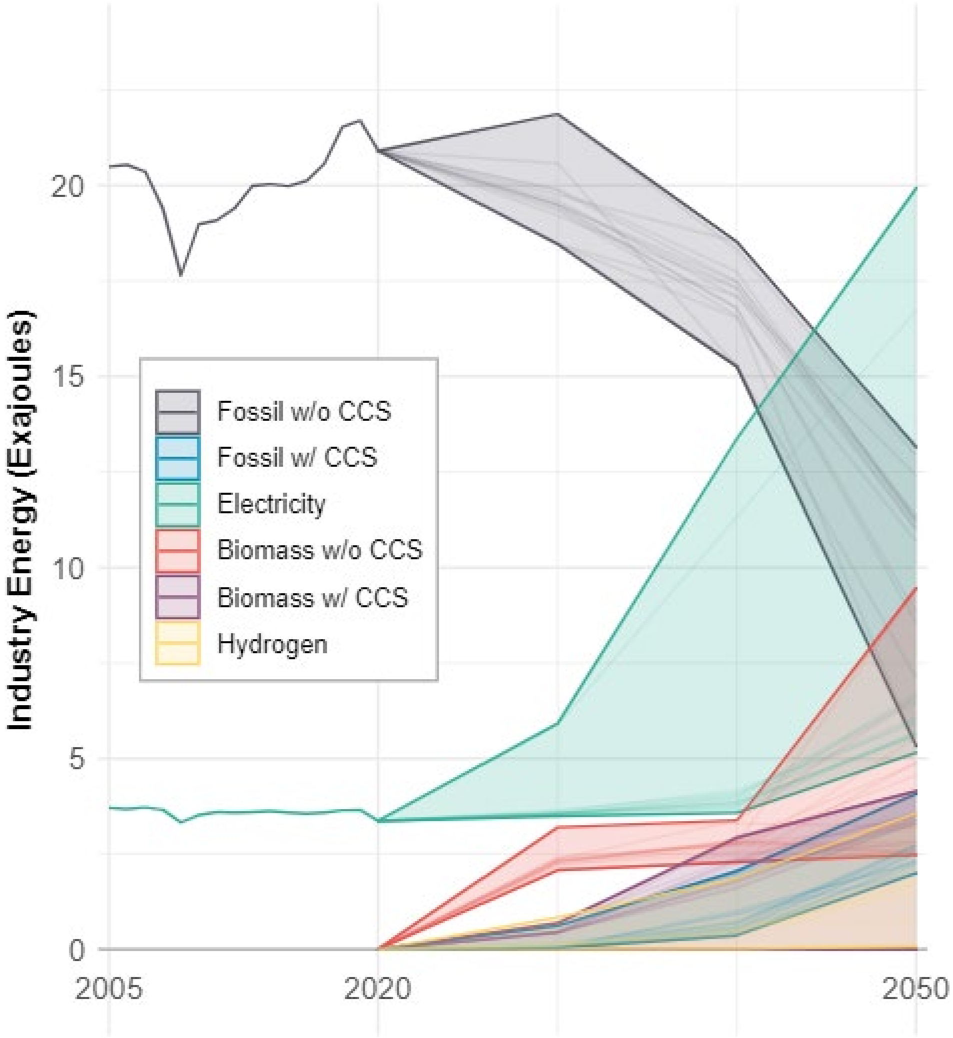


**Figure 10: Industry Final Energy Use 2005-2050.** Overall industrial energy use in exajoules (EJ) decreases to 2050 while certain applications switch from fossil fuels to clean electricity, hydrogen, or biofuels. Electricity use increases further in scenarios with larger hydrogen production due to the high electricity demand for that process. In this analysis, CCS in deployed in industry for process emissions, but there is limited representation of CCS on industrial energy in the models we use. Accordingly, it is likely that a greater share of industrial fossil energy emissions could be captured by 2050 than is shown here. Note: Historical data are from EIA Monthly Energy Reviews, projections include data from all LTS scenarios using both GCAM and OP-NEMS, projections are shown in ten-year time steps. Historical industry energy use from fossil without CCS increased from approximately 20 exajoules in 2005 to approximately 21 exajoules in 2020. Projected industry energy use from fossil without CCS ranges from approximately 18 to 22 exajoules in 2030, before declining steadily to reach between approximately 13 and 5 exajoules in 2050. Historical industry energy use from electricity remained generally

steady from 2005 to 2020 at approximately 4 exajoules. Projected industry energy use from electricity grows to between approximately 5 and 20 exajoules in 2050. Historical industry energy use from fossil with CCS, biomass without CCS, biomass with CCS, and hydrogen were zero from 2005 to 2020. Projected industry energy use from fossil with CCS reaches approximately 2 to 4 exajoules by 2050. Projected industry energy use from biomass without CCS increases to approximately 2 to 10 exajoules by 2050. Projected industry energy use from biomass with CCS increases to approximately 4 exajoules by 2050. Projected industry energy use from hydrogen increases to approximately 3 exajoules by 2050.

Reducing energy-related GHG emissions from industry presents a set of unique challenges [14] [22] [26]. A primary feature of this sector is that it is diverse: unlike electricity or buildings, for example, whose emissions come from a relatively small set of activities, industrial activities and infrastructure are designed around a large set of processes. Some of these processes might have relatively straightforward substitutes, but in other cases either those substitutes may not exist yet or might be higher cost. In some cases, alternate sources of process heating may need to be identified. In other cases, CCS applications may be needed, but these may be expensive or infeasible at existing production facilities. At the same time, scaling up of material efficiency could be challenging because of product design limitations or consumer demand. Many of these challenges also affect the non-$CO_2$ emissions from industry, which are discussed further Chapter 5.

In response to these challenges, the industrial energy transition can be enabled to decarbonize at a sufficiently rapid pace through a diverse set of approaches tailored to the specific needs of each subsector. Key strategies include energy efficiency, material efficiency, electrification, adoption of low-carbon fuels and feedstocks, and CCS. Energy efficiency, waste heat recovery, and accelerated adoption of advanced technologies such as additive manufacturing, can significantly reduce energy demand and lower costs to businesses. Material efficiency incorporates structural changes in manufacturing that include product recycling and reuse, material substitution, and demand reduction. Electrification of heated, fuel-consuming industrial processes and equipment is a viable pathway for some subsectors, such as light industry. Low-carbon fuels and feedstocks, including clean hydrogen and low-carbon biofuels, can reduce emissions from processes that are difficult to electrify. Finally, CCS can be used for emissions that are hard to abate through other means, particularly in the cement, chemicals, and iron and steel industries. Increased investments in research, development, demonstration, and deployment will advance technologies in production of iron and steel, cement, chemicals, and other industries, enabling these sectors to adopt low-carbon production.

# Chapter 5: Reducing Non-$CO_2$ Emissions Through 2050

## 5.1 Introduction

Non-$CO_2$ GHGs make up 20% of the U.S. contributions to global warming [27]. Non-$CO_2$ GHGs are highly potent heat trapping gases, many of which have greater near-term climate impacts than $CO_2$ [36]. As shown in Figure 11, three gases make up the majority of non-$CO_2$ GHG emissions in the United States: methane ($CH_4$), nitrous oxides ($N_2O$), and fluorinated gases (including HFCs) [27]. The three sources that produce the largest proportion of emissions are soil management (i.e. agriculture and land use), livestock, and energy. While mitigation opportunities exist for many sources of non-$CO_2$ GHG emissions, costs and applicability vary. Because it is challenging to eliminate all of these sources, some remaining non-$CO_2$ emissions will need to be offset in 2050 by net-negative $CO_2$ emissions.

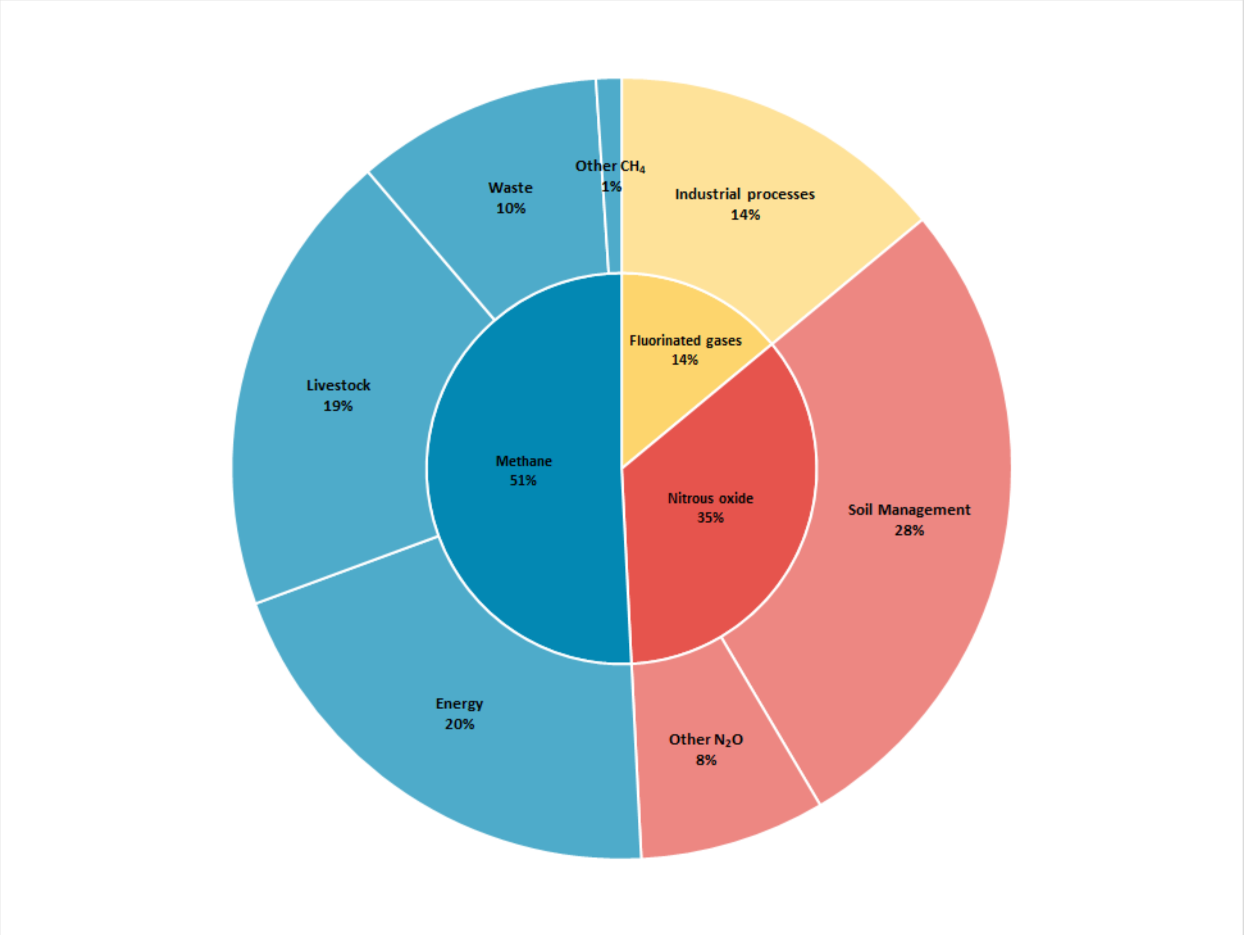


**Figure 11: Sources of U.S. Non-$CO_2$ GHG Emissions, 2019.** Contribution to 2019 U.S. GHG emissions from non-$CO_2$ sources partitioned by type and sector. The contributions are shown in $CO_2$ equivalent, meaning that they are represented in proportion to their global warming contribution 100 years after emission. Approximately half of the global

> warming contribution of non-$CO_2$ gases in 2019 came from methane, with nitrous oxide contributing the second most, followed by fluorinated gases. Methane contributed 51% of US non-CO2 GHG emissions in 2019. The sectors that contributed to methane emissions are: energy (20% of US non-CO2 GHG emissions), livestock (19%), waste (10%), and other (1%). Fluorinated gases contributed 14% of US non-CO2 GHG emissions in 2019. All of these fluorinated gas emissions came from industrial processes (14% of US non-CO2 GHG emissions). Nitrous oxide contributed 35% of US non-CO2 GHG emissions in 2019. The sectors that contributed to nitrous oxide emissions are: soil management (28% of US non-CO2 GHG emissions) and other (8%).

This analysis estimates that the total technical potential for non-$CO_2$ GHG mitigation across all sectors is approximately 35% – without reducing the underlying activities [36]. Reducing the use of fossil fuels through efficiency and fuel switching also has the potential to further drive down non-$CO_2$ GHG emissions by 19%, given the relationship between fugitive methane emissions from the extraction, processing, and end-use of fossil fuels. These reflect multiple technological options that United States can use to achieve the necessary reductions in non-$CO_2$ GHG emissions to reach net-zero total emissions by 2050 (Figure 12). Under these scenario assumptions, there remain non-$CO_2$ GHG emissions in the 2030 and 2050 timeframes, which must be offset by carbon dioxide removal.

Reductions in non-$CO_2$ emissions face several challenges. First is an underdeveloped set of mitigation strategies in certain subsectors. In part because of a lack of historical focus on non-$CO_2$ reductions, the set of available mitigation approaches for these gases is still relatively small and, in many cases, in earlier stages of technological development. This means that through 2050, overall non-$CO_2$ emissions can be held roughly constant by deploying currently available mitigation technologies. Achieving long-term reductions of non-$CO_2$ emissions below current levels requires development of new or more-effective mitigation technologies and approaches. In addition, in a way that is similar to the industrial energy emissions described in Chapter 4, the sources of non-$CO_2$ emissions are diverse. This means that individual strategies must be developed for each sub-sector and gas.

In light of these challenges, this LTS analysis of non-$CO_2$ GHG mitigation potential assumes only modest technological and cost improvements over time. Because these assumptions may be conservative, additional, lower-cost, and more rapid reductions could be realized, and this will remain an area of active inquiry. Achieving more significant long-term reductions of non-$CO_2$ GHG emissions will require major technological advances and new, or more effective, backstop mitigation options. In sectors with less developed current approaches, this could include new research and development into identifying and commercializing new technologies to reduce non-$CO_2$ emissions. In other sectors, new mitigation options are under development and nearing commercialization that could result in large volumes of non-$CO_2$ mitigation and further reduce non-$CO_2$ emissions (see Box 4).

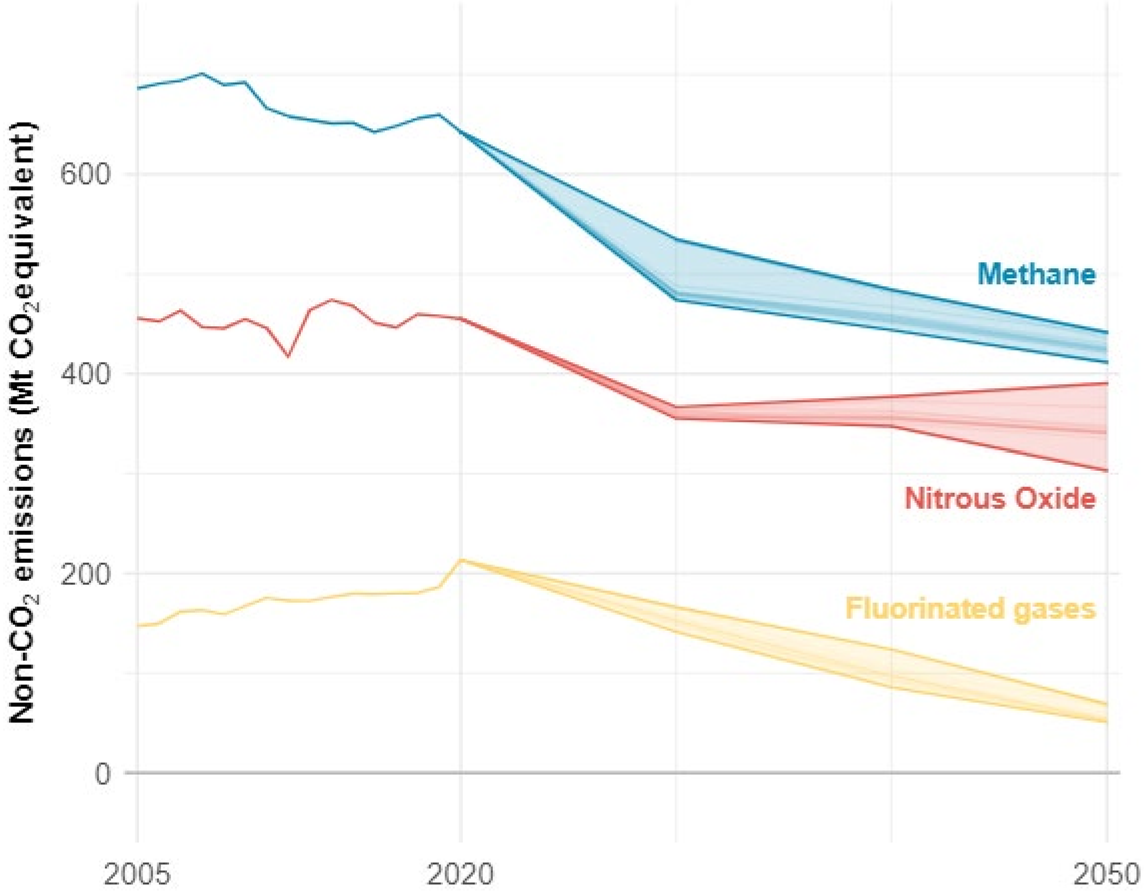


**Figure 12: Pathways for Non-$CO_2$ Reductions from 2020 to 2050**. This figure shows the range of pathways available for non-$CO_2$ mitigation from today to 2050 across all modeled scenarios. In all scenarios there is significant reduction from the 2020 reference, highlighting the importance of non-$CO_2$ abatement. Historical methane emissions decreased from approximately 700 MtCO2e in 2005 to approximately 640 MtCO2e in 2020. Projected methane emissions decrease to approximately 430 MtCO2e in 2050. Historical nitrous oxide emissions remained roughly steady from 2005 to 2020 at approximately 450 MtCO2e. Projected nitrous oxide emissions range from approximately 300 to 400 MtCO2e in 2050. Historical fluorinated gas emissions increased from approximately 150 MtCO2e in 2005 to approximately 200 MtCO2e in 2020. Projected fluorinated gas emissions decrease to approximately 75 MtCO2e in 2050.

## 5.2 Key Abatement Opportunities

Potential reductions in non-$CO_2$ gases can come from a diverse set of actions, and these actions together aggregate to significant levels (Figure 13). Technical potential includes technologies like anaerobic digestion of manure in the agricultural sector and leakage detection and mitigation in the oil and gas sector. As discussed above, some portion of each non-$CO_2$ gas, such as some of the methane and $N_2O$ from the agriculture sector, cannot be abated in the 2050 timeframe, even after applying all available mitigation technologies, and will have to be offset by negative $CO_2$ emissions.

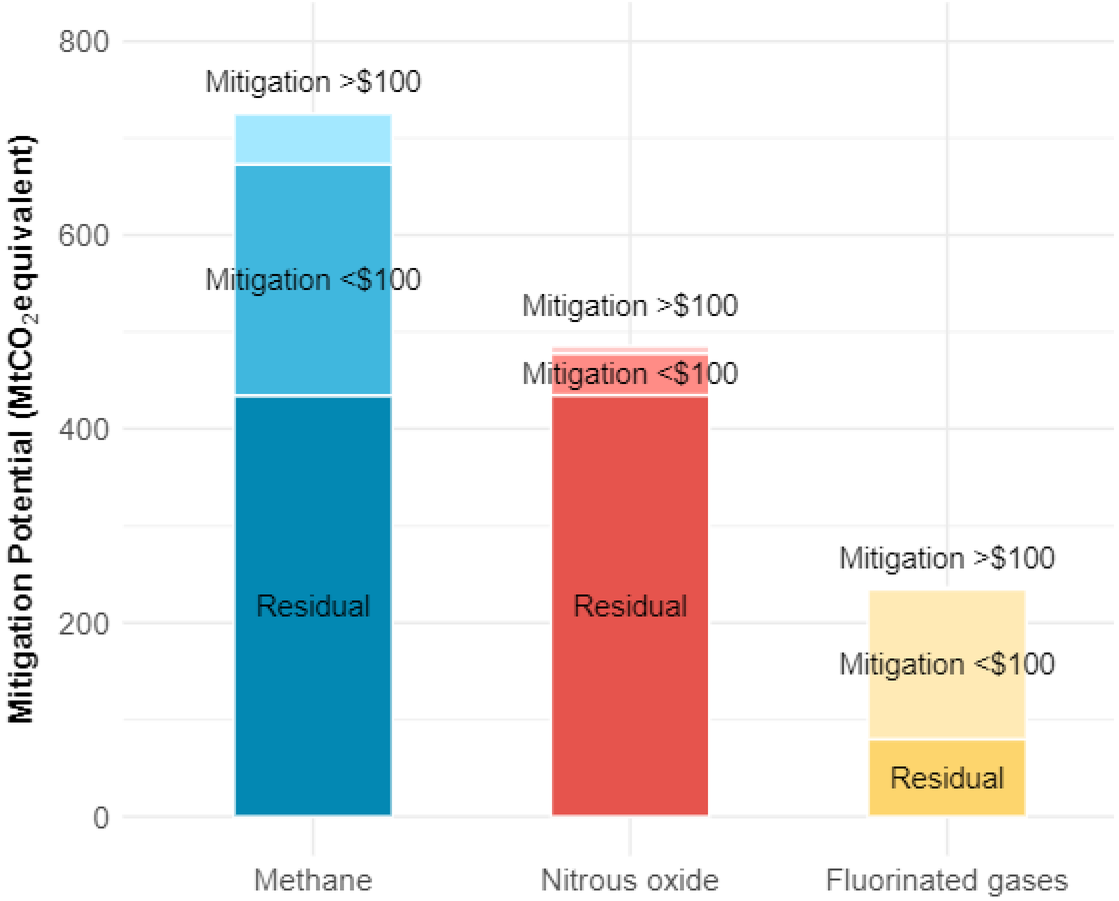
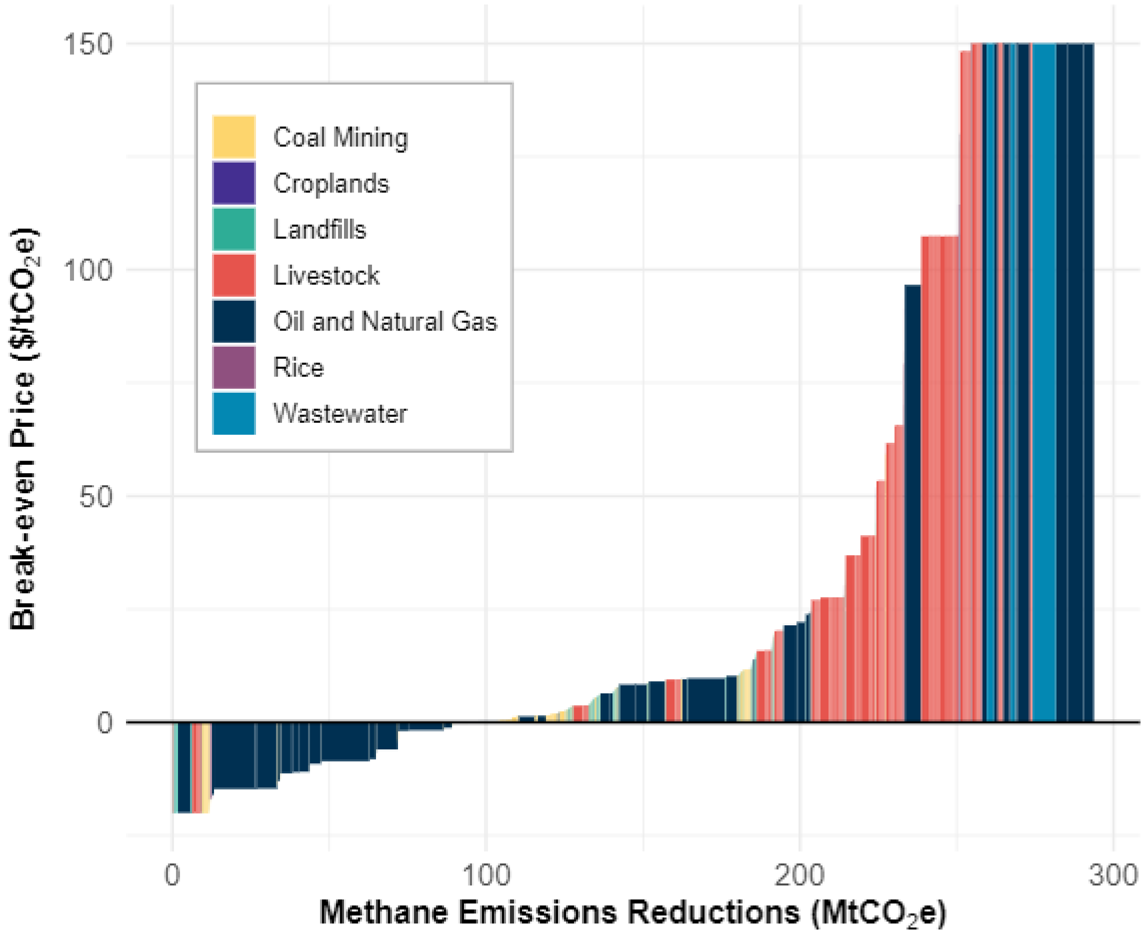


**Figure 13: Non-$CO_2$ Mitigation Technical Potential by Gas ($MtCO_2e$) in 2050.** This figure shows potential reductions in 2050 from non-$CO_2$ emissions in methane, nitrous oxide, and fluorinated GHGs. It is constructed from abatement cost curves using technologies like anaerobic digestion of manure in the agricultural sector and leakage detection and mitigation in the oil and gas sector. Some abatement technologies are negative cost and many cost less than $100 per metric ton of $CO_2e$. Technical abatement potential is most significant for methane and fluorinated gases. For methane emissions in 2050, approximately 250 MtCO2e can be abated at <$100/tCO2e, approximately 50 MtCO2e can be

abated at >$100/tCO2e, leaving approximately 420 MtCO2e in remaining emissions. For nitrous oxide emissions in 2050, approximately 50 MtCO2e can be abated at <$100/tCO2e, with a marginal amount abated at >$100/tCO2e, leaving approximately 420 MtCO2e in remaining emissions. For fluorinated gases in 2050, approximately 150 MtCO2e can be abated at <$100/tCO2e, with a marginal amount abated at >$100/tCO2e, leaving approximately 75 MtCO2e in remaining emissions.

### 5.2.1 Methane

Methane is a potent GHG and accounts for about half of the current observed warming[5] of 1.0°C, according to the latest report of the Intergovernmental Panel on Climate Change [1]. Methane is primarily generated by fossil fuel energy operations (oil, gas, and coal), waste operations, and livestock and agricultural operations. There are cost-effective methane abatement options across all these sectors [36]. Figure 14 shows 2050 methane abatement potential by source.



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[5] Greenhouse gas emissions in total have contributed 150% of the observed warming of 1.0°C, but emissions of cooling aerosols have counteracted some of that warming.

**Figure 14: 2050 Methane Abatement Potential in the United States.** This figure shows sources of methane abatement potential in 2030 in the United States [36]. This marginal abatement cost curve indicates the price at which methane mitigation from various sources of methane are cost-effective. This figure does not include additional abatement that can be achieved by reducing the underlying activities that drive emissions. These additional reductions from activity driver changes are included in the GCAM modeling and reflected in Figure 12. Approximately 100 MtCO2e in methane emissions can be abated at negative cost, primarily from oil and natural gas sources, but also with some contributions from coal mining, landfills, and livestock. Approximately an additional 125 MtCO2e can be abated at ~$50/tCO2e or less, primarily from oil and natural gas and livestock sources. Approximately an additional 50 MtCO2e can be abated at ~$100/tCO2e or less, from livestock and oil and natural gas sources. A remaining approximately 50 MtCO2e can only be abated at prices ~$150/tCO2e or higher.

Methane mitigation opportunities by sector include:

- **Energy Sector Methane.** Energy sector fugitive methane emissions result from operations in the oil and natural gas sector and the coal mining sector. In some cases, a large proportion of oil and gas methane emissions come from a small number of sources. Methane mitigation measures in oil and natural gas typically fall into three categories: equipment modifications or upgrades; changes in operational practices, including directed inspection, repair and maintenance (DI&M); and installation of new equipment [35]. Abatement measures are available to mitigate emissions associated with a variety of system components, including compressors, engines, dehydrators, pneumatic controls, pipelines, storage tanks, wells, and others. Commercially-available mitigation technologies can also recover and reduce $CH_4$ emissions from coal mining operations. These reduction technologies consist of one or more of the following primary components: a drainage and recovery system to remove $CH_4$ from the underground coal seam, an end use application for the gas recovered from the drainage system, and/or a ventilation air methane (VAM) recovery or mitigation system [35]. The $CH_4$ mitigation potential from the energy sector at $100/tCO_2e$ is 144 million metric tons of carbon dioxide equivalent ($MtCO_2e$), or approximately 43% of 2030 energy sector non-$CO_2$ GHG emissions, and remains an important source of potential mitigation through 2050.
- **Waste Methane.** Landfills produce $CH_4$ and other landfill gases through the natural process of bacterial decomposition of organic waste under anaerobic conditions. Landfill gases are generated over a period of several decades, with flows usually beginning within 2 years of disposal. Abatement options to control landfill emissions are grouped into three categories: (1) collection and flaring, (2) landfill gas (LFG) utilization systems,

and (3) enhanced waste diversion practices (e.g., recycling and reuse programs) [35]. Within the waste category, wastewater treatment is the second most important source of non-$CO_2$ GHGs. Methane emissions in wastewater treatment could be significantly reduced by 2050 through currently available mitigation options, such as anaerobic biomass digesters and centralized wastewater treatment facilities. Improved operational practices, such as controlling dissolved oxygen levels during treatment or limiting operating system upsets, can also help reduce $N_2O$ emissions from wastewater treatment [35]. The $CH_4$ mitigation potential from the waste sector non-$CO_2$ GHG at $100/t is 8 $MtCO_2e$, or 6% of total 2030 waste sector emissions, and remains an important source of potential mitigation through 2050.

- **Livestock Methane.** Emissions from livestock include enteric fermentation and manure management. Enteric fermentation is a normal mammalian digestive process, where gut microbes produce $CH_4$. Livestock manure management produces $CH_4$ emissions during the anaerobic decomposition of manure and $N_2O$ emissions during the nitrification and denitrification of the organic nitrogen content in livestock manure and urine [35]. Without altering underlying demand, the mitigation potential of livestock methane at $100/t is 70 $MtCO_2e$, or 27% of 2030 livestock non-$CO_2$ GHG emissions, and remains an important source of potential mitigation through 2050.
- **Cropland and Rice Production Methane.** The anaerobic decomposition of organic matter (i.e., decomposition in the absence of free oxygen) in flooded rice fields produces $CH_4$. GHG mitigation scenarios include several factors that influence the amount of $CH_4$ produced and carbon sequestration in soils, including water management practices and the quantity of organic material available to decompose [35]. The mitigation potential from the agriculture sector at $100/t is 1.7 $MtCO_2e$, or 1% of 2030 agricultural $CH_4$ emissions [36].

### *Box 4: Global Methane Pledge*

In September 2021 at the Major Economies Forum, the United States and European Union jointly announced the Global Methane Pledge. As of October 2021, over 30 supportive countries, representing well over 30% of global methane emissions and 60% of global GDP, had already joined—with many more expected. Countries joining the Global Methane Pledge commit to a collective goal of reducing global methane emissions by at least 30% from 2020 levels by 2030. They also commit to moving towards using highest-tier inventory methodologies to quantify methane emissions, with a particular focus on high emission sources.

Delivering on the Pledge would reduce warming by at least 0.2°C by 2050. In addition, it would prevent over 200,000 premature deaths, hundreds of thousands of asthma-related emergency room visits, and over 20 million tons of crop losses a year by 2030 by reducing ground-level ozone pollution caused in part by methane.

The United States is pursuing significant methane reductions on multiple fronts. The Long-Term Strategy analysis shows that the United States can do its part to meet the global goal of the Global Methane Pledge by reducing domestic methane emissions by over 30% below 2020 by 2030. This level of reduction would avoid 11,000 premature deaths, 1,600 asthma-related emergency room visits, and 4.1 million tons of agricultural losses per year in the United States.

### *5.2.2 Nitrous Oxide*

Nitrous oxide ($N_2O$) is a potent GHG with 298 times more warming potential than carbon dioxide and a long atmospheric lifetime (approximately 114 years). $N_2O$ comes from natural and anthropogenic sources and is removed from the atmosphere mainly by photolysis (i.e., breakdown by sunlight) in the stratosphere. In the United States, the main anthropogenic sources of $N_2O$ are agricultural soil management, livestock waste management, mobile and stationary fossil fuel combustion, adipic acid production, and nitric acid production. $N_2O$ is also produced naturally from a variety of biological sources in soil and water, although this report only covers man-made sources. Figure 15 shows 2050 nitrous oxide abatement potential by source.

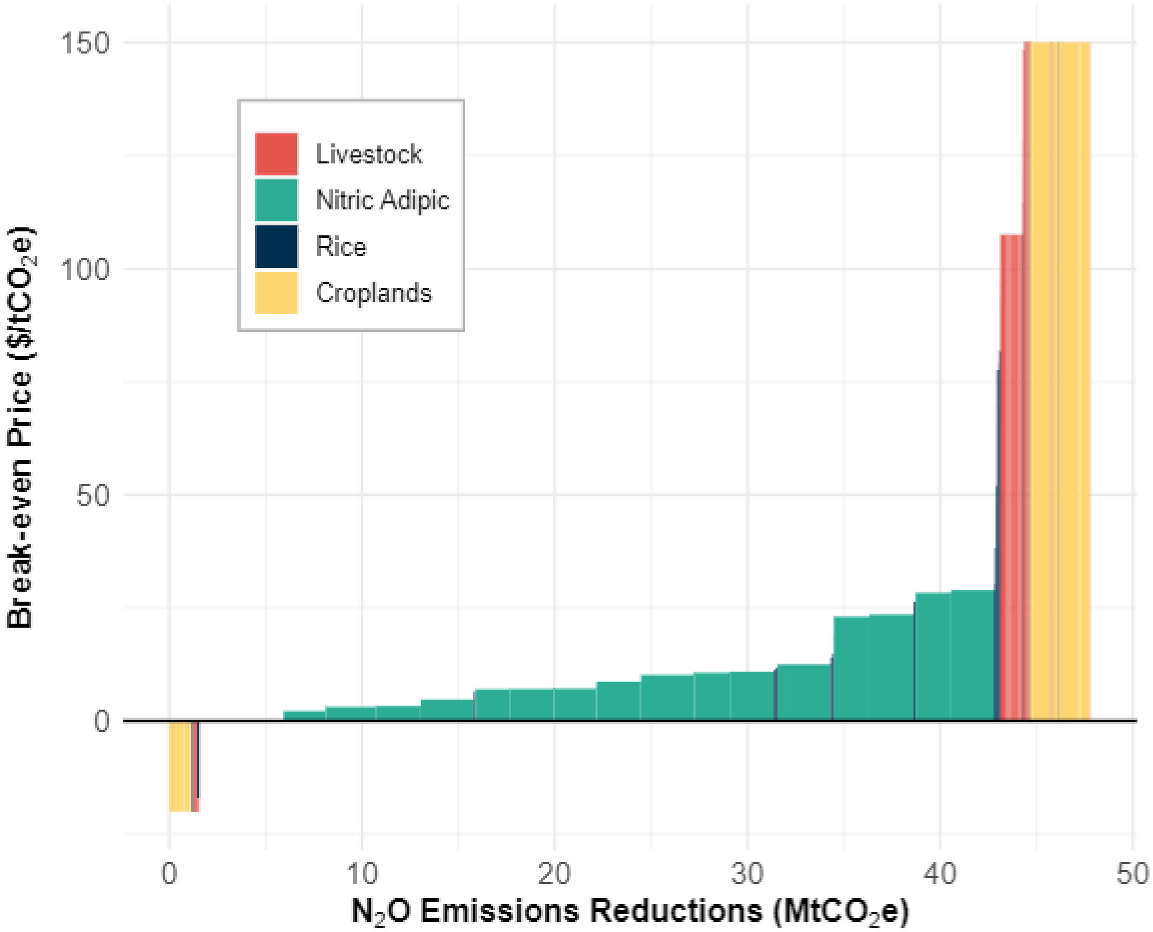

**Figure 15: 2050 Nitrous Oxide Abatement Potential in the United States.** This figure shows sources of nitrous oxide abatement potential in 2050 in the United States. This marginal abatement cost curve indicates the price at which nitrous oxide mitigation from various sources of are cost-effective. This figure does not include abatement associated with a reduction of the underlying activities that drive emissions. These additional reductions from activity driver changes are included in the GCAM modeling and reflected in Figure 11. Approximately 1-2 MtCO2e in N2O emissions can be abated at negative cost, primarily from croplands. Approximately an additional 40 MtCO2e can be abated at ~$25/tCO2e or less, primarily from nitric adipic sources. An additional approximately 10 MtCO2e can be abated only at >$100/tCO2e, including from livestock and croplands sources.

**Nitrous oxide mitigation opportunities by sector include:**

- **Agricultural Nitrous Oxide.** Agriculture is the source of over 82% of nitrous oxide emissions. Most $N_2O$ is produced in soils by bacteria through the processes of nitrification and denitrification which occur with fertilizer application. It is also emitted in lesser amounts from livestock waste, rice production, and soil management such as draining, irrigation, and land use change. Nitrous oxide emissions can be mitigated by changing fertilizer management practices to increase the efficiency of plant uptake of nitrogen [35]. Practices include precision agriculture, using nitrification inhibitors, and splitting annual applications into seasonal applications. The mitigation potential from the agriculture sector at $100/t is 8.8 $MtCO_2e$, which is 2.5% of 2030 nitrous oxide emissions from agriculture [36] and remains a small source of mitigation through 2050.

- **Nitric and Adipic Acid Production**. Nitric acid is an inorganic compound used primarily to make synthetic commercial fertilizer. Adipic acid is a white crystalline solid used as a feedstock in the manufacture of synthetic fibers, coatings, plastics, urethane foams, elastomers, and synthetic lubricants. The production of these acids results in nitrous oxide emissions as a by-product. By 2030, about two-thirds of nitrous oxide emissions from this source category are projected to be from adipic acid production driven by high demand growth compared with about one-third from nitric acid production. Abatement measures applicable to nitric acid are characterized by the point in the production process they are implemented, but generally involve catalytic decomposition of the nitrous oxide by-products [35]. Thermal destruction is the abatement option applied to the adipic acid production process. The mitigation potential from nitric and adipic acid production at $100/t is 17.7 $MtCO_2e$, or 62% of total sectoral 2030 nitrous oxide emissions [36] and remains an important source of mitigation through 2050.

### *5.2.3 Fluorinated Gases*

Fluorinated gases (F-GHGs) are anthropogenically-generated and used in a range of applications. Sometimes referred to as “climate superpollutants,” they are highly potent GHGs, capable of trapping hundreds to thousands of times more heat per molecule than carbon dioxide. According to the 2021 Inventory of U.S. Greenhouse Gas Emissions and Sinks [27], most fluorinated gases emitted are hydrofluorocarbons (HFCs). A substitute for ozone-depleting substances, HFCs were initially developed to replace ozone-depleting substances (ODS) in refrigeration, air conditioning, aerosols, fire suppression, and as foam blowing agents. HFC emissions reductions are achievable by preventing or reducing leaks and transitioning to the use of alternatives with low global warming potential (GWP). Figure 16 shows 2050 fluorinated GHG abatement potential by source.

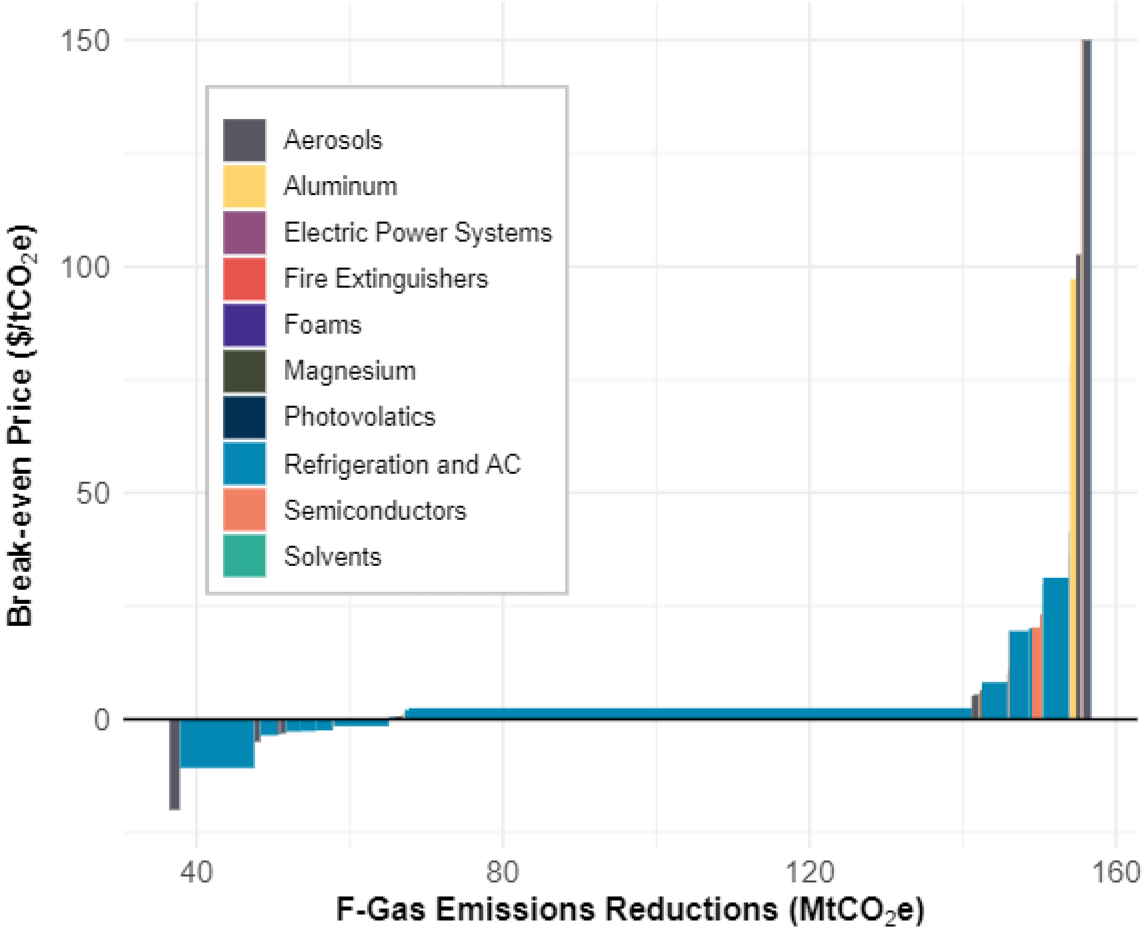

**Figure 16: 2050 Fluorinated GHG Abatement Potential in the United States:** This figure shows sources of fluorinated GHG abatement potential in 2050 in the United States. This marginal abatement cost curve indicates the price at which F-GHG mitigation from sources of are cost-effective. This figure does not include additional abatement that can be achieved by reducing the underlying activities that drive emissions. These additional reductions from activity driver changes are included in the GCAM modeling and reflected in Figure 11. Approximately 70 MtCO2e in F-gas emissions reductions can be accomplished at negative cost, primarily from refrigeration and AC or aerosols. Approximately a further 70 MtCO2e from refrigeration and AC can be accomplished at less than $10/tCO2e. Approximately an additional 15 MtCO2e can be accomplished at less than $35/tCO2e, including from aerosols, refrigeration and AC, and semiconductors. Approximately an additional 5 MtCO2e can only be accomplished at ~$100/tCO2e or higher, including from aluminum and aerosols.

Under the American Innovation and Manufacturing (AIM) Act of 2020, in September 2021 the EPA finalized a rule that phases down HFCs through an allowance allocation and trading program. The AIM Act, along with this rule, provides the domestic legal framework to implement the phasedown of HFCs outlined in the Kigali Amendment to the Montreal Protocol, which 124 countries have joined to date. The phasedown will effectively decrease the production and import of HFCs in the United States by 85% by 2036 on the same step-down schedule as laid out in the Kigali Amendment and is expected to result in reductions of more than 4.5 billion metric tons of carbon dioxide-equivalent by 2050.

Achieving significant HFC reductions by 2050 will rely on a three-pronged approach. First, phase down the production and import of HFCs. Second, address the existing stock of refrigerators and air conditioners, which already contain HFCs and have potential to leak into the atmosphere over the coming decades. Third, deploy the next generation of low-GWP alternatives to existing HFCs. Additional RD&D support to ensure new alternatives to HFCs continue to enter the market may also be important, including both new molecules and new uses for existing alternatives. Combining these approaches, the mitigation potential of HFCs at less than $100/t is 84 $MtCO_2e$, which is 39% of total 2030 sectoral emissions, and remains an important source of mitigation through 2050.

### 5.2.4 Black Carbon

Black carbon (soot) is not a GHG, but a powerful climate-warming aerosol [1] that is a component of fine particulate matter ($PM_{2.5}$) that enters the atmosphere through the incomplete combustion of fossil fuels, biofuels, and biomass [46]. The Arctic is particularly vulnerable to warming from black carbon. Black carbon is also a local air pollutant, contributing to major health impacts that disproportionately affect low-income and marginalized communities [47]. Transitioning from fossil fuel combustion for electricity and transport (on-road and off-road) to cleaner alternatives is key to reducing black carbon emissions in the United States. Flaring in the oil and gas sector is an additional source of black carbon. The EPA estimates that U.S. black carbon emissions have been reduced significantly since 2013 primarily due to reductions in the road and off-road transport sectors, largely through policies and strategies to reduce the emissions from mobile diesel engines. Strengthening particulate matter standards and addressing legacy diesel vehicles and emissions associated with ports, including from ships, port equipment, and trucks, would further contribute to meeting national climate, health, and climate justice goals.

### Box 5: Non-$CO_2$ Breakthrough Technologies: Reducing Methane from Enteric Fermentation

While many low-cost abatement opportunities exist today for non-$CO_2$ emissions—and are reflected in this analysis—some specific applications do not have current, low-cost mitigation opportunities. A renewed focus on research and development for these remaining non-$CO_2$

emission processes could potentially provide significant benefits as well as dramatically lower the costs of reductions. While not required to achieve our 2050 net-zero goal, such advances could provide valuable additional flexibility in how that goal could be achieved.

One example of this kind of positive breakthrough may be emerging. Without a technological advance, there is limited methane abatement potential from enteric sources—cattle, sheep, and goats—which produce methane as part of their digestive process. While improving productivity can, to a limited extent, help reduce methane emissions per pound of beef or gallon of milk, it does not provide a route to major reductions. However, recent research suggests that new technologies might be able to offer greatly increased effectiveness. New discoveries of low-cost feed additives indicate the possibility that these would unlock large additional potential emissions reductions. Examples of these additives include red algae (*Asparagopsis*) and a compound, 3-Nitrooxypropanol (3-NOP).

EPA and other researchers are collecting information to assess these technologies. *Asparagopsis*, 3-NOP, and other technologies may increase non-$CO_2$ GHG mitigation. The science and economics of *Asparagopsis* is far from settled, with important remaining questions surrounding the costs to grow, harvest, and process *Asparagopsis* into feed; to assess scalability to produce marketable quantities (or directly synthesize bromoform); and to assess the long-term tolerance of cattle and the applicability to different production and regulatory systems. If national-scale developments prove technically and economically feasible, *Asparagopsis* could potentially decrease livestock emissions by as much as 160 $MtCO_2e$ (60%) in 2030. 3-NOP has shown strong potential for methane reduction across multiple trials, with over 45 peer-reviewed papers examining numerous aspects of the potential impacts of this additive. 3-NOP has been shown to be effective in reducing enteric emissions by about one-third in dairy cows and up to 70% in beef finishing trials without unacceptable side-effects. More innovation and testing are needed to further develop these solutions and bring them to market.

# Chapter 6: Removing Carbon Through 2050 and Beyond

## 6.1 The Necessity of $CO_2$ Removal to Reach Net-Zero

Efficiency, electrification of end uses, decarbonization of the electricity sector, and reduction in non-$CO_2$ emissions are the most important levers for decarbonizing the U.S. economy and will be the emphasis of the overall strategy to reach net-zero by 2050. However, as mentioned in previous sections, some activities will be difficult to decarbonize completely by 2050. Because of this, removals of $CO_2$ from the atmosphere will be critical to enable the United States to reach net-zero by 2050 and achieve net negative emissions thereafter. This implies an important role for the land sector, which can increase natural carbon dioxide removal and storage from the atmosphere, as well as a role for technologies including advanced carbon dioxide removal (CDR) technologies. Carbon dioxide removal technologies will only deliver desired societal and environmental benefits if their deployment is well-designed and well-governed. Figure 17 shows the range of outcomes for mitigation pathways as well as removals pathways to achieve net-zero by 2050.

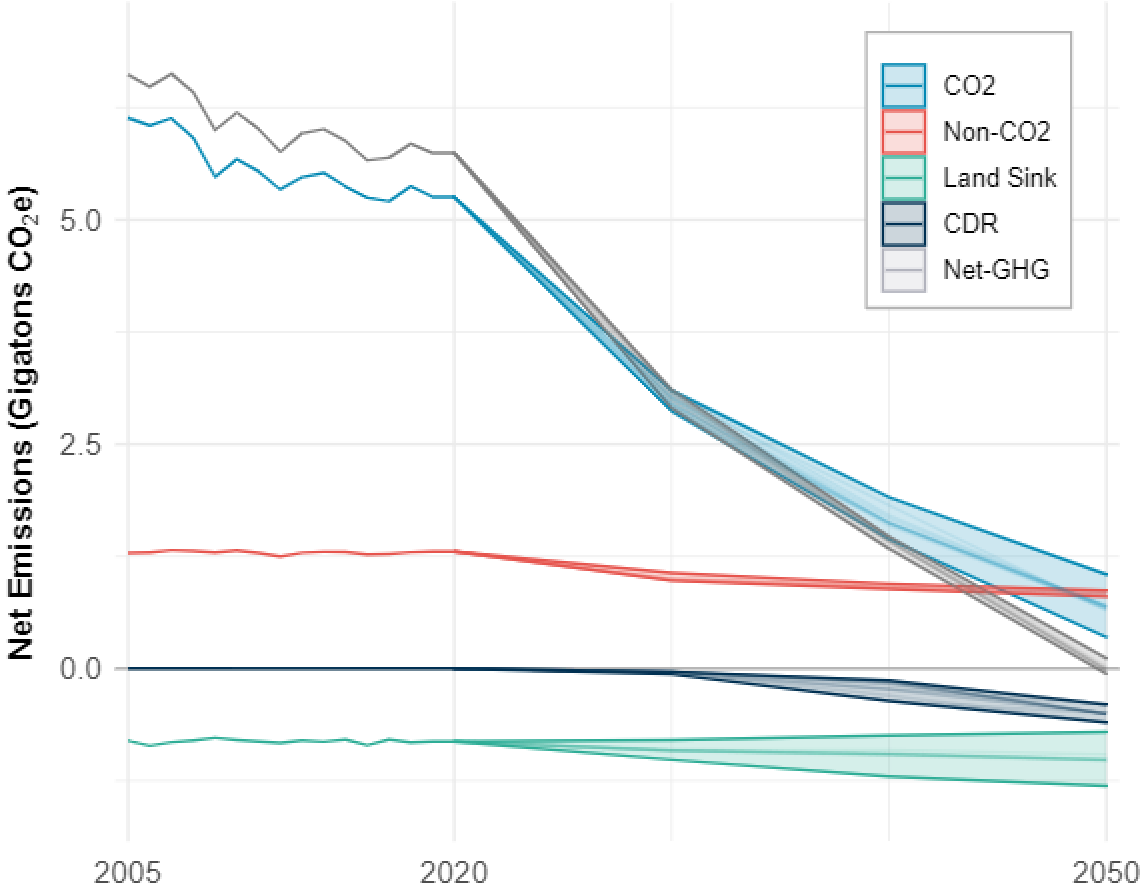

**Figure 17: Balancing Emissions Reductions and Removals to Reach 2050 Net-Zero.** This figure shows the range of outcomes for mitigation pathways as well as removals

pathways to achieve net-zero by 2050. Some sources of non-$CO_2$ emissions, and potentially some $CO_2$ emissions, cannot be reduced to zero, and these must be balanced by $CO_2$ removals. $CO_2$ removals can happen through land sinks, such as forest growth and soil carbon sequestration, or through carbon dioxide removal technologies such as direct air capture or carbon capture and sequestration in industry or electricity generation. Note: Historical data in this figure are from the U.S. GHG Inventory (2021). Historical CO2 emissions decreased from approximately 6.25 GtCO2e in 2005 to approximately 5.1 GtCO2e in 2020. Projected CO2 emissions decrease to roughly 1 GtCO2e in 2050. Historical non-CO2 emissions remained roughly steady at approximately 1.25 GtCO2e from 2005 to 2020. Projected non-CO2 emissions decrease to roughly 1 GtCO2e in 2050. Historical land sink removals remained roughly steady at approximately -0.8 GtCO2e from 2005 to 2020. Projected land sink removals range from approximately -0.7 GtCO2e to -1.25 GtCO2e in 2050. Historical CDR removals were zero from 2005 to 2020. Projected CDR removals increase to approximately -0.25 GtCO2e in 2040 and approximately -0.5 GtCO2e in 2050. Overall, historical net GHG emissions decreased from approximately 6.5 GtCO2e in 2005 to approximately 5.8 GtCO2e in 2020. Projected net GHG emissions fall to approximately 2.7 GtCO2e by 2030 and 0 by 2050.

## 6.2 Maintaining and Enhancing $CO_2$ Removal through the U.S. Land Carbon Sink

U.S. lands provide myriad social, economic, and environmental benefits. The United States has 8% of the world's forests (310 million ha) and 8% of global agricultural lands (400 million ha) [48]. These lands provide essential ecological, economic, and non-monetary social services, and will also be critical in supporting economy-wide decarbonization over the next 30 years and beyond.

Our lands, and human activities on those lands, emit $CO_2$ to the atmosphere through land conversion, soil degradation, and forest loss and degradation, but also remove it via photosynthesis and store it as carbon in trees, other vegetation, soils, and products. For the last several decades, U.S. lands have been a net carbon sink, meaning more $CO_2$ is sequestered than emitted annually from the land sector. This historic trend was due in part to millions of acres shifting into forest from other uses and the conservation and continued regrowth of trees on already forested lands, much of which had been deforested before the early 1900s [49]. Today's forest sink is still increasing but at a decreasing rate [27]. In 2019, the U.S. land carbon sink yielded net $CO_2$ removals of 813 $MtCO_2e$, offsetting approximately 12.4% of economy-wide GHG emissions [27].

Though the overall U.S. lands net carbon sink has been relatively stable for recent decades, the future of that sink is uncertain [50], and several challenges exist to bolstering it and expanding it significantly. Substantial forested lands, including large portions of our Western public lands, now have older forests which sequester less $CO_2$ and are more vulnerable to natural disturbances [51]. Moreover, increased levels of disturbances—fires, insects, diseases, droughts, and storms—are expected in the future, along with other potential ecosystem changes such as $CO_2$ fertilization, due to climate change. These changing environmental conditions will also dictate the future degree of mitigation and adaptation capabilities and opportunities [52]. These factors are already having an impact: total carbon removal in the land use, land use change, and forestry (LULUCF) sector has decreased by approximately 11% since 1990 [27]. In addition, U.S. lands include diverse ecosystems which complicates efforts at comprehensive and timely data collection, as well as monitoring and verification of baseline emissions, sequestration, and GHG outcomes of mitigation activities. In addition, the land base is finite in terms of its ability to continue to provide food, fiber, and essential ecosystem and biodiversity services while also supporting potentially increased levels of carbon-beneficial biomass for energy production and carbon removal strategies through bioenergy and CCS. In addition, $CO_2$ removals via natural systems can be more variable than those in other sectors or technologies, as they are subject to reversals, e.g., from natural disturbances like fires, storms, and pests or from individual landowners changing land management practices. Also, with respect to policies, U.S. lands are held and managed for different objectives by a range of different stakeholders that operate under different legal, social, and environmental norms. Achieving land sector goals necessitates coordination and cooperation with millions of private landowners, private sector corporations, and non-governmental organizations, as well as Tribal, local, state, and federal government agencies.

These challenges may be counterbalanced, at least in part, by changes in the economy, policy actions, and investments. Achieving significant land carbon benefits by 2050 and beyond requires targeted, science-based action in the near term and over the next several decades. These actions must not only work to enhance our land carbon sink but also ensure our lands continue to provide a host of other benefits, including provision of goods, jobs, ecosystem services, recreational and spiritual spaces, and biodiversity preservation. For example, public and private investments in natural climate solutions (e.g., augmented federal programs, private entities' involvement in land conservation, and offset markets) can increase acreage, productivity, and overall health of U.S. forested lands [52] [54]. Strengthening existing and supporting new emerging timber markets, especially in the fast-growing climes of Southeast United States, can also help maintain and expand forested lands [55]. Policies, incentives, and investments that can support an enhanced sink through activities such as reforestation and soil carbon retention will be central. Low- or zero-carbon biomass for bioenergy and BECCS applications can also contribute to emissions reductions. These policies and programs must include safeguards to minimize issues such as potential reversals and leakage to the extent possible, and include efforts to bolster our ability to monitor, track, and verify emissions reductions at different scales.

Specific areas of focus include:

- **Forests.** GHG benefits in the relative near term can come from activities such as avoided forest land conversion to other uses. Some forest sector actions, such as longer harvest rotations or increased carbon storage in harvested wood products and substitution of more fossil-intensive construction materials with wood products, can yield both near- and long-term benefits [56]. There are considerable opportunities for reforestation in the United States [57], potentially up to 133 million acres [58]. Other activities like afforestation, improved forest management, and reduced natural disturbances (e.g., avoided forest fires via fuel treatments such as thinning and prescribed fires) can offer incremental near-term net carbon benefits and may yield substantial benefits in the long term [59].
- **Agricultural Lands**. There are potential substantial GHG mitigation and increased removal opportunities on U.S. croplands and grasslands via activities that conserve and/or increase soil carbon and employ innovative lands management approaches such as agroforestry, rotational grazing, reduced tillage, residue management, and more.
- **Bioenergy.** Biomass is a key component of efforts to decarbonize the energy sector, as studies have shown that higher levels of biomass availability and use can offer lower-cost mitigation than decarbonization strategies without biomass (e.g., [60] [61]). Bioenergy can be particularly useful in deep decarbonization scenarios, as it can be used to decarbonize energy use in multiple sectors through a range of different energy pathways (e.g., liquid fuel, biogas, electricity, and hydrogen production), and it can be used in combination with CCS to further reduce GHG emissions [9]. Efforts aimed at employing biomass use for energy should include safeguards to ensure actual emissions reductions to the atmosphere and reflect consideration of the many non-carbon consequences of large-scale biomass production and use (e.g., competition with food production and biodiversity and broader ecosystem impacts).

## 6.3 Assessing Potential Land Sector Pathways

The LTS pathways explored for this study include varying degrees of private and public investment in natural climate solutions in both forestry and agriculture, such as improved forest management, fire reduction activities, afforestation, and improved agricultural soil management. To better reflect the uncertainties associated with estimating the complex carbon dynamics of different terrestrial ecosystems and related market interactions, and the potential extent of land use change between sectors, the U.S. LULUCF projections through 2050 are presented as a range, as seen in Figure 18. This range was developed via a collaborative multi-agency effort using different models reflecting alternate modeling techniques. The analysis is based on several sectoral lands models including the Global Timber Model (GTM), the Forestry and Agriculture Sectoral Optimization Model with Greenhouse Gases (FASOM-GHG), three U.S. Forest Service models (the Resources Planning Act (RPA) Forest Dynamics model, the RPA Land Use Change model, and the Forest Resource Outlook model), and USDA agricultural soil carbon projections, to provide a range of potential land sink projections in 2050. As shown in Figure 18, there is a significant range of possible land sector pathways which could enable the United States to meet its net-zero goal by 2050.

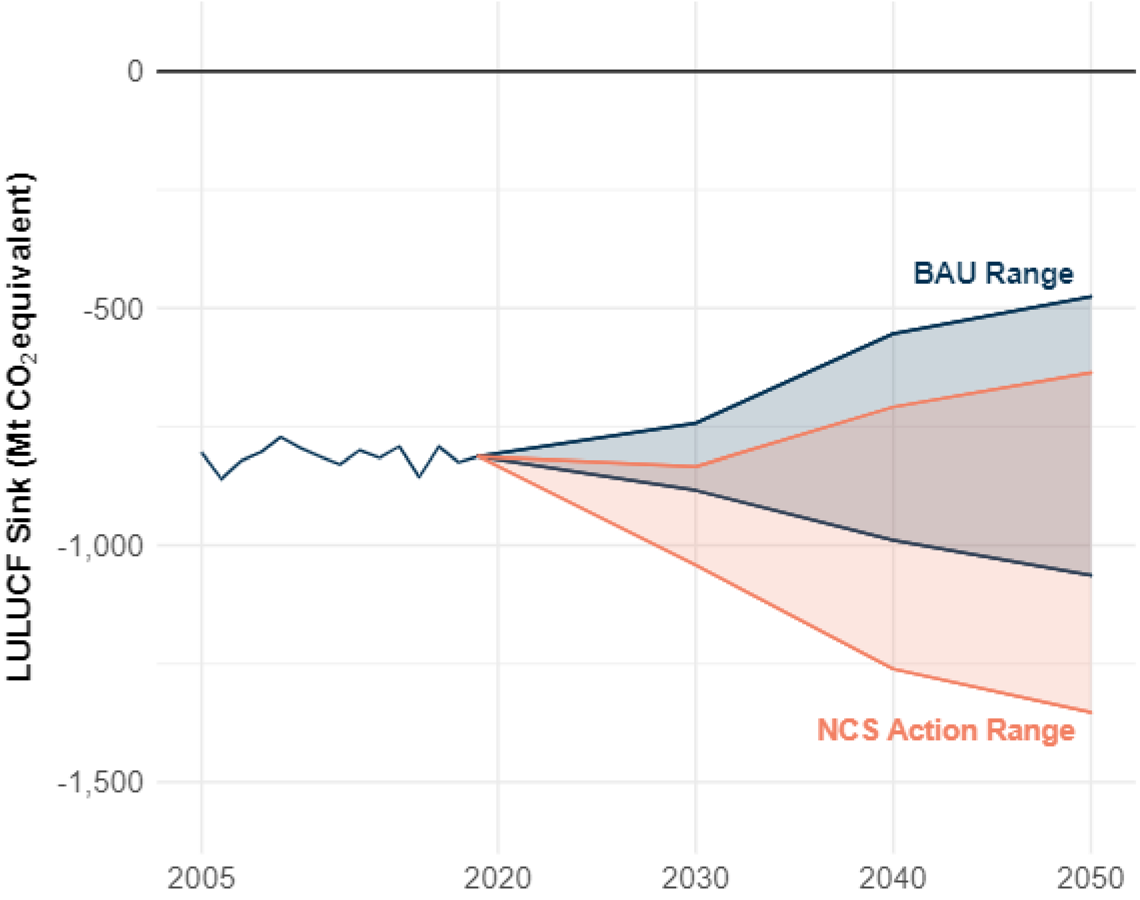

**Figure 18: Land Use, Land Use Change, and Forestry CO$_2$ Business as Usual and LTS Action Projections with Uncertainty Ranges**. There is a range of possible CO$_2$ outcomes for both the reference case and the Long-Term Strategy action case. Historic values are from the U.S. GHG Inventory [27] and projected values are derived from a range of land sector models. Estimates include forest ecosystem carbon pools, harvested wood products carbon storage, and land use and land use conversion fluxes across land types. Historical LULUCF removals remain generally steady at approximately -750 MtCO2e from 2005 to 2020. BAU LULUCF removals by 2050 range from approximately -500 MtCO2e to

-1,050 MtCO2e. NCS Action Range LULUCF removals by 2050 range from approximately -600 MtCO2e to -1,300 MtCO2e.

## 6.4 CO2 Removal Through Engineered Approaches

In addition to the land sector $CO_2$ reduction potential, technological $CO_2$ removal options could be deployed over coming decades to support the net-zero emissions goal. While some technologies for such activities do exist, advanced CDR technologies are today in various stages of development.

At this early stage, it is difficult to estimate exactly which combinations of technologies might be most achievable and appropriate in terms of deployment, but potential strategies include:

- **Biomass carbon removal and storage**. This is a carbon dioxide removal approach where $CO_2$ is produced from the combustion, gasification, or other conversion of low- or zero-carbon biomass, for example to generate electricity or produce hydrogen, and the resulting $CO_2$ emissions are captured and then stored in a manner that prevents it from reentering the atmosphere. Specifically, the captured $CO_2$ emissions are compressed into a fluid and transported to a specified site, where they are injected into deep, underground geological formations, such as former oil and gas reservoirs or deep saline formations for long-term storage. CDR efforts using biomass as an input, such as biomass use for energy with CCS, should include safeguards to ensure actual emissions reductions to the atmosphere (e.g., including, to the extent possible, robust GHG accounting), and reflect consideration of the many non-carbon consequences of large-scale biomass production and use (e.g., competition with food production and biodiversity and broader ecosystem impacts) [61].
- **Direct Air Capture and Storage (DACS)**. This is a technology that captures $CO_2$ emissions directly from ambient air (instead of from point sources, such as power plants or industrial facilities), via solvent, solid sorbent, or mineral processes. The captured $CO_2$ is then either compressed and sequestered permanently in a geological setting or converted into a usable material such as a synthetic aggregate in concrete production.
- **Enhanced mineralization**. This is a CDR approach that accelerates natural geologic processes around mineral reactions with $CO_2$ from the ambient air, leading to permanent carbon storage through carbonate rock. There are several types of mineralization processes: in situ (e.g., $CO_2$ reactions in geologic formations underground), ex situ (e.g., $CO_2$ reactions that involve extraction, transport, and grinding of minerals), and surficial (e.g., ambient weathering using $CO_2$-enriched fluids and on-site minerals like mine tailings). Research and development for enhanced mineralization is still early, but the potential capacity of $CO_2$ mineralization could be quite high [62].

- **Ocean-based CDR**. This is a CDR approach that removes dissolved $CO_2$ from the ocean. Ocean-based approaches include nature-based approaches (e.g., kelp afforestation), engineered approaches (e.g., electrochemical $CO_2$ capture from seawater), or a combination of the two (e.g., growing macroalgae and sinking it to the sea floor). Ocean-based CDR is in early stages of research and development and merits closer study.

The early stages of these potential removal strategies present some visible challenges to large scale deployment by 2050. For example, there is currently no large-scale proof of concept for DAC technology or bioenergy with carbon capture and storage, making it difficult to determine how well the technology can scale up and what the true cost and adverse impacts of the technology are at large scale. In parallel, some technical obstacles remain. Research to date indicates that DAC requires high energy use for each metric ton of $CO_2$ removed. Other technologies, such as enhanced mineralization, are still in nascent stages of research and development, so the potential magnitude of reductions and the timeframes over which these technologies might deliver reductions is unknown. Other uncertainties associated with large-scale deployment of some technologies like BECCS could have broader upstream GHG and other environmental implications (e.g., life-cycle GHG outcomes of biomass production).

Addressing these challenges and uncertainties will require a substantial and integrated research, development, and deployment strategy. As one step towards the development and deployment of new approaches to CDR, Congress recently created the Carbon Dioxide Removal Task Force to “establish a research, development, and demonstration program…to test, validate, or improve technologies and strategies to remove carbon dioxide from the atmosphere on a large scale” [63]. However, additional actions will be needed to understand and innovate on CDR options, to reduce uncertainties, and to ensure sustainable outcomes.

# Chapter 7: Benefits of Climate Action Through 2050

## 7.1 The benefits from a transformed, net-zero economy

Bold and timely climate action towards net-zero will help the United States and the world avoid the worst impacts of climate change—and provide a transformative boost to the U.S. economy and the health and well-being of all Americans. Reductions in fossil fuel combustion and reductions in non-CO2 emissions will improve air quality and reduce the dangerous risks of climate change. The expansion of new industries will create high-quality jobs, maintain economic competitiveness, and enable sustainable, broad-based economic growth. The benefits from this transformation are not constrained by political borders: U.S. action and ambitious action from other countries will have positive spillover effects, including driving down the cost of carbon-free technologies and reducing the costs of climate induced disasters and conflicts around the world, particularly for lowest-income nations that are least able to adapt.

In addition to the economic gains, action to meet the net-zero goal will, combined with global efforts, allow the United States to avoid the worst impacts of climate change, which are already being felt. For example, air pollution kills thousands of people in the United States annually [64] and millions worldwide, particularly in the lowest-income countries, and ongoing international conflicts are exacerbated by climate change [65]. The longer action is delayed, the faster the transition must be, potentially causing severe disruption [66]. Moreover, delay incurs more severe consequences such as changed weather regimes (including new extremes [67]), higher sea level rise, greater ocean acidification [68], and a higher likelihood of reaching catastrophic damages or "tipping points" and potentially irreversible ecological impacts. These impacts have health and economic costs for all, but they are borne unequally, with greater consequences for low-income countries globally and communities of color, low-income communities, and indigenous communities within the United States [69]. For example, Black children are 34-41% more likely to live in areas with the highest projected increases in asthma diagnoses due to climate-driven changes in particulate air pollution [68]. These impacts are addressed more completely in the National Climate Strategy [2].

## 7.2 Improvements in Public Health

Climate-driven changes in weather, human activity, and natural emissions are all expected to impact future air quality across the United States [70]. Acting now on climate change and decarbonizing our energy sector will result in vastly cleaner air, immediate and long-term improvements in public health, and ecological benefits throughout the United States. These benefits arise from several sources.

*Reducing GHGs causes reduction in pollutants harmful to health, well-being, and productivity.* Reducing GHGs to net-zero by 2050 will simultaneously reduce other pollutants, including particulate matter (PM), ozone and PM precursors, nitrous oxides ($NO_x$), sulfur dioxide ($SO_2$), and other air toxics. These benefits will be more significant in communities overburdened by air pollution. Ozone and PM are air pollutants that adversely affect human health and are monitored and regulated with national standards [71]. Human exposures to these pollutants have been associated with premature death, hospital admissions, and respiratory ailments, among others. A total of 60,600 deaths in the United States in 2019 alone were attributable to PM and ozone exposure [72]. The energy sector accounts for 80% of emissions of $NO_x$ and 96% of $SO_2$ [70]. As the economy transitions to carbon-free energy, reductions in air pollution are also expected to increase productivity of the workforce due to health improvements. Beyond the traditional focus on mortality impacts, there is emerging evidence that minor health impacts from air pollutants can also adversely affect educational attainment and reduce labor productivity, e.g., fewer tasks completed and fewer hours worked [73]. Such improvements would be important because climate projections show a direct impact of future extreme temperatures reducing hours worked in the economy [74].

*Reducing climate change severity saves lives and improves health.* Climate change threatens the health and well-being of Americans through catastrophic events; increases in heat-related illnesses and deaths; increases in vector-, food-, and water-borne disease; and reduced food and water quality. In addition to immediate fatalities associated with the events themselves, extreme weather events can exacerbate underlying medical conditions and disrupt critical health care, resulting in potentially lasting consequences. Furthermore, temperature increases have been linked to increases in premature death due to exposures to both cold and heat extremes; additionally, heat exposure has led to increases in emergency room visits and hospital admissions for heat-related illnesses such as cardiovascular and respiratory conditions, kidney failure, and preterm birth, among others [75]. There are large disparities in urban heat environments in many U.S. cities that put lower-income people and people of color at higher risk of heat exposure [76]. Changes in temperature and rainfall patterns have been implicated in the spread of some infectious diseases in some areas, including mosquito-borne Zika and West Nile viruses, by creating conditions that promote the expansion, abundance, and activity of certain disease vectors [77] [78]. Waterborne diseases have been associated with excessive rainfall as well as drought conditions. Water temperature increases have contributed to the growth of toxic algal blooms and harmful pathogens (e.g., *Salmonella* and *Campylobacter*), the presence of which can adversely affect food security and availability [75]. As for air pollution, the benefits of action to reduce impacts will be strongest in communities that are historically disadvantaged, low-income, and/or lack access to health services and prevention and are therefore most vulnerable to climate change [68]. For example, Hispanic and Latino individuals are 25-43%

more likely to currently live in areas with the highest projected labor hour losses in weather-exposed industries due to increases in high-temperature days.

## 7.3 Avoiding Costly Climate Impacts

Avoiding climate change will provide immediate and sustained benefits to the economy across several categories. Global emissions reductions can substantially reduce the damages of climate change in the United States [79]. One estimate shows reduced monetary damages from a subset of climate change impacts of $49 billion/year in 2050 and up to $388 billion/year in 2090 to the U.S. economy in 1.5°C-compatible scenarios compared to a reference scenario, from factors such as fewer deaths, less damage to infrastructure, and fewer lost wages.[6] Similarly, Figure 19 shows the large and increasing benefits that accrue over time to the overall economy from a low-emissions pathway.[7] This analysis is only a lower-bound estimate as it does not include a comprehensive accounting of all potential impacts such as other health effects, effects on managed and unmanaged ecosystems, some indirect effects, and social impacts.

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[6] The temperature and radiative forcing for the two scenarios are calculated from the median over an ensemble of 600 MAGICC v7.5.1 runs selected to match assessed proxy ranges [112]. For the 1.5°C scenario, global mean temperature reaches 1.5°C in 2100 with a corresponding radiative forcing of 2.45 $Wm^{-2}$ and 3.8°C in 2100 with a corresponding radiative forcing of 7.60 $Wm^{-2}$ for the Reference scenario. Descriptions of future population, GDP, the transformation of global temperature change to continental U.S. temperature change, estimation of sea level rise, and other parameters and assumptions can be found in [111]. This framework includes impact estimates that employ a variety of assumptions regarding adaptive responses to climate impacts. The general adaptation scenarios considered in the analyses do not capture the complex issues that drive adaptation decision-making at regional and local scales. Adaptation and scenario assumptions used in this analysis: High Tide Flooding and Traffic impacts assume reasonably anticipated adaptation measures; Rail, Roads, Electricity Transmission and Distribution Infrastructure, and Coastal Properties assume reactive adaptation; Extreme Temperature Mortality assumes cities in cooler climates will adapt and become more resilient similar to present day cities in warm climates; and Ozone and $PM_{2.5}$ Mortality uses 2011 emissions of co-emitted pollutants. The rest of the sectors do not explicitly model adaptation.

[7] Damages, and therefore avoided damages, increase over time due to the increasing divergence in global mean temperature change between the two scenarios along with growing populations; more valuable potentially vulnerable infrastructure; and higher valuation of avoided mortality.

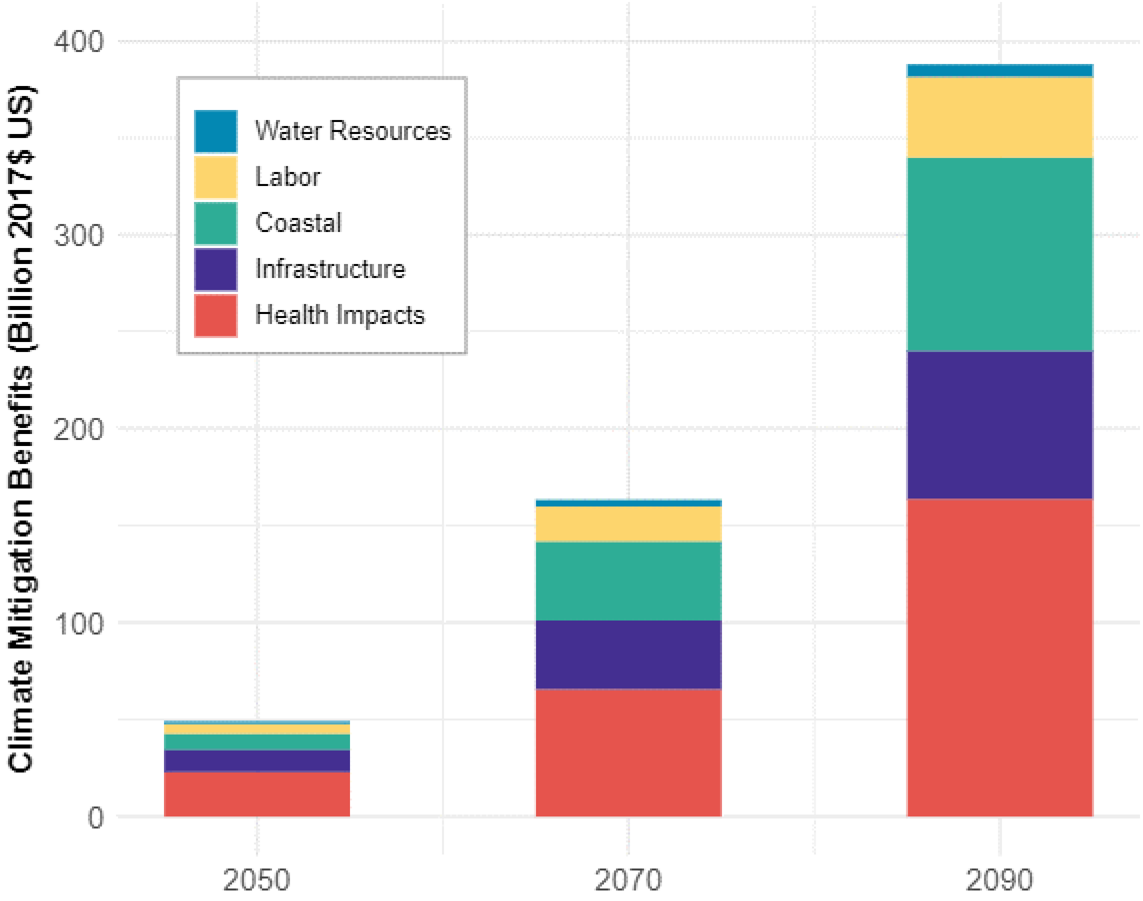

**Figure 19: Projected Annual Benefits of Climate Mitigation for Select Years.** Benefits from keeping to a 1.5$^{o}$C trajectory grow significantly over time. U.S. annual economic impacts for a subset of sectors for the Reference minus 1.5°C scenario.[8] Impacts presented in billions of $2017. Annual benefits of climate mitigation grow from approx. $50 billion 2017USD in 2050 to approx. $160 billion 2017USD in 2070 and to nearly $400 billion 2017USD in 2090. In 2050, health impacts make up roughly half of annual benefits, with infrastructure and coastal benefits making up the next largest categories. In 2070, health benefits make up approximately two-fifths of annual benefits, coastal benefits make up slightly more than one-fifth, infrastructure benefits make up slightly less than one-fifth, and labor makes up the majority of remaining emissions, with only a small share of water resource benefits. These proportions remain similar in 2090.

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[8] 17 U.S. sectors are represented in this figure. Health impacts consist of the following sectors: extreme temperature mortality, ozone and PM2.5 mortality, valley fever, wildfire health effects, and suppression and southwest dust health effects. Coastal impacts consist of the following sectors: coastal property, hightide flooding and traffic, and tropical storm wind damages. Infrastructure consists of the following sectors: rail and road infrastructure, electricity demand and supply, electricity transmission and distribution, and urban drainage. Water resources consist of the following sectors: water quality, winter recreation, and inland flooding. Lastly, the labor sector represents lost wages.

## 7.4 Enhanced Climate Security

There is a growing body of evidence that climate change can exacerbate conflict and reduce global security. Climate change is a national security threat because it is globally destabilizing, changes military operating conditions, and demands new missions [80]. This means that mitigating the risk of climate change not only delivers ecological, public health, and economic benefits, but also enhances national and global security. By acting early and leading by example, the United States can build confidence in global efforts to reduce the risk of climate change [81]. The risks of a changing climate can make existing conflict more violent, lead to instability, and, through more erratic weather, affect the ability of the military to respond to security concerns. The U.S. National Intelligence Estimate assessment is that "climate change will increasingly exacerbate risks to U.S. national security interests as the physical impacts increase and geopolitical tensions mount about how to respond to the challenge" [82].

Extreme weather and conditions increasingly attributed to climate change already impact U.S. infrastructure, through the effects of sea level rise, storms, and wildfire. The U.S. Department of Defense calls climate change a "top management challenge" because of the threat to operational security and to the physical infrastructure of installations [83], and finds that climate change is reshaping the geostrategic, operational, and tactical environments with significant implications for U.S. national security and defense [6]. It can also impact military readiness by diverting military assets and personnel to assist with disaster recovery, storms, and wildfire impact [84].

Experts agree that climate-related events (droughts, storms, wildfires, and flooding) are already contributing to conflict [85]. While the main conflict drivers have been related to low socioeconomic development, low state capability, intergroup inequality, and a history of conflict, these drivers can be exacerbated by disruption related to climate change [86]. Clear causal relationships between climate change and specific conflicts are the subject of ongoing research, but drought, floods, and other disasters related to climate change have been associated with large-scale displacement of people and, in some cases, this has led to political instability and conflict.

Climate change is related to both short-term phenomena such as extreme weather events and long-term impacts such as rising sea levels and persistent drought. All of these can affect the lives and potentially the movements of large numbers of people in a way that can increase stresses within and between countries. Tropical storms, which are expected to become more severe as climate continues to change (and have already become more severe in the Atlantic Basin), already can displace large populations. Hurricane Katrina, for example, traumatically displaced tens of thousands of people from the city of New Orleans. In a country with lower capacity to address such crises, a similar event could create climate refugees and cause instability. Continued, more frequent, or more severe drought is also an expected result of climate change. In agricultural societies, severe drought can exacerbate stresses. Drought contributed to the current civil war in Syria, causing internal destabilization as well as political stresses in neighboring countries due to the resulting refugee crisis [87]. The impacts of long-term changing sea level have already led to climate refugees, including in parishes in southern Louisiana [88]—and this can be disruptive across the world. For example, a further sea level rise of six inches (15 cm) could displace millions from the Nile Delta in Egypt [89]. Instability in strategically important regions, even far from the United States, is a national security concern.

Societies can respond to crises like drought and water stress by strengthening political relationships that can benefit mutual security [90], but, in particular for vulnerable societies, the impacts of climate change may result in increased conflict. Actively working to mitigate climate change along with helping communities to build resilience and adapt may reduce the risks of these conflicts.

## 7.5 Building a Stronger U.S. Economy

The revolution in climate solutions has already begun. The fastest-growing power generation technologies are solar and wind, with a record-setting 35 GW of deployment in 2020, accounting for about 80% of new capacity [91]. Globally, the zero-emissions vehicle share of new car sales is expected to rise from 2% today to nearly 30% by 2030 [92], with significantly higher numbers in the United States in line with reaching 50% new car sales. In these and many other sectors, the transition to carbon neutrality will accelerate for compatibility with international climate targets [93], representing rapidly expanding new markets in the United States and globally.

The economic opportunity of decarbonization is immense. The United States is well-positioned to incubate new innovators and firms, with a well-trained workforce and institutions that have enabled global leaders in information technology, biotechnology, pharmaceuticals, and other industries [94]. Moreover, a unique endowment of natural resources makes geographic regions of the country well-suited to be hubs of a wide range of carbon-free activities [40]. The United States can lead in the clean technologies for the 21st century, manufacturing crucial technologies like batteries, electric vehicles, and heat pumps, without sacrificing critical worker protections or a fair distribution of benefits of economic activity.

Because innovation is cumulative and because many environmental technologies have returns to scale, investing early in the development of new technologies [95] will boost innovation in climate solutions and make the pathway to carbon neutrality more economically and politically feasible [96] [97]. Smart public investments in innovation stimulate private investment and economic growth and can help establish new (and often unforeseen) productive industries in the process [98] [99] [100]. One recent study finds social returns from investments in research and development are as much as four times larger than private returns [101], and an analysis of data on 16 advanced countries between 1980 and 1998 found that a 1% increase in public research and development investment generated an extra 0.17% in long-run output [102]. The benefits of accelerating innovation will spill over to our international partners, including to developing countries which will be hit hardest by climate damages and can least afford to take actions in response.

Although the overall economy will benefit from the transition to carbon neutrality, certain fossil fuel-dependent sectors and regions will have a more difficult transition. Some communities are already experiencing economic challenges from the declines in fossil fuel-related employment [103], while others (predominantly low-income communities, communities of color, and indigenous communities) are experiencing disproportionate impacts of climate disasters and air pollution. A comprehensive policy strategy can support American workers and firms through the transition, creating high-quality jobs throughout the country, including in historically marginalized communities and in regions that have lost major employers and taxpayers.

# Chapter 8: Accelerating Global Climate Progress

With our ambitious NDC target to cut emissions in half or more by 2030, and our goal for net-zero emissions no later than 2050, the United States has committed to sustained investment in a vibrant clean economy that will propel global climate action while improving social, economic, and health equity at home.

This report has presented the U.S. Long-Term Strategy to achieve these ambitious goals. The road ahead to 2050 contains opportunities, uncertainties, and challenges. The opportunities are clear and broad ranging, and collectively offer a pathway to reinventing and reinvigorating the American economy to be equitable, globally competitive, and supportive of global climate and sustainability goals. It will rely on American innovation and partnerships across all of society, including Tribal and subnational governments; private sector businesses, industry, and investors; non-governmental organizations and cultural institutions; universities, research organizations, and educational institutions; and our people. Together, we can meet the challenges in developing and deploying new clean technologies at scale. We can discover new and creative ways to provide better services and products with lower climate footprints. And we can develop, train, and educate workers for productive and healthier work in new and fast-growing industries. Undoubtedly, the U.S. roadmap will evolve as we learn more about the potential for new technologies in diverse applications, and as new policy platforms are developed over time. The United States intends to regularly review and update this Long-Term Strategy as needed to consider such developments and the latest science.

Given the rapid pace of action in the United States and other leading countries, if other major economies adopt similar levels of ambition, the world can keep a safer 1.5°C future within reach. For its part, the United States currently emits 11% of annual global GHGs (second to China, which emits 27% of the global total), so eliminating U.S. emissions by 2050 will make an important direct contribution to reaching our shared global climate goals. However, others must step up with both long-term and short-term ambition, and many are already doing so. To date, at least 63 countries representing over half current global emissions have committed to net-zero GHG emissions targets. Many more, representing over 70% of global emissions, are in diverse stages of identifying and committing to similar net-zero targets by mid-century [104] [105] [106]. These commitments matter: achieving near-net-zero emissions globally by 2050 will dramatically improve our chances of limiting global warming to 1.5°C.

However, while the rapid expansion of 2050 targets and long-term strategies is encouraging, commitments to act by 2030 are also critical. Countries representing well over half of the global economy, including nearly all the G7 countries, have already put forward strong 2030 NDCs.

Leadership and action by these countries will support development of new and more affordable climate technologies and support enhanced diplomatic momentum to encourage global action toward reaching sufficient levels of near-term action.

But the United States, EU, UK, Japan, Canada, Republic of Korea, South Africa, and other ambitious major economies cannot do it alone. Strong 2030 NDCs will be required by all G20 economies to cut global emissions by at least 40% by 2030. Enhanced action by all G20 members to adopt high ambition 2030 NDCs and mid-century net-zero commitments could reduce warming by over 0.5°C and keep 1.5°C within reach [107]. Globally, this is the moment for all the world's major economies to act to rapidly reduce emissions to meet ambitious 2030 NDC targets and to develop and communicate strategies to achieve ambitious 2050 net-zero goals.

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