CLIMATE INNOVATION

PATHWAYS TO 2050

ALTERNATIVE SCENARIOS FOR DECARBONIZING THE U.S. ECONOMY

C2ES CLIMATE INNOVATION 2050

by

Robert Lempert
Benjamin L. Preston
RAND Corporation

Jae Edmonds
Leon Clarke
University of Maryland
Pacific Northwest National Laboratory

Tom Wild
University of Maryland

Matthew Binsted
Pacific Northwest National Laboratory

Elliot Diringer
Brad Townsend
Center for Climate and Energy Solutions

May 2019

PATHWAYS TO 2050

ALTERNATIVE SCENARIOS FOR DECARBONIZING THE U.S. ECONOMY

by

Robert Lempert
Benjamin L. Preston
RAND Corporation

Jae Edmonds
Leon Clarke
University of Maryland
Pacific Northwest National Laboratory

Tom Wild
University of Maryland

Matthew Binsted
Pacific Northwest National Laboratory

Elliot Diringer
Brad Townsend
Center for Climate and Energy Solutions

May 2019

ACKNOWLEDGEMENTS

C2ES would like to thank The Bernard and Anne Spitzer Charitable Trust, the William and Flora Hewlett Foundation, the Energy Foundation, and the Intel Corporation for their support of this work.

C2ES is also grateful to the following companies for their valuable contributions to the scenario development process that resulted in this report:

ABB Inc.
AECOM
ArcelorMittal
Arizona Public Service Corporation
BASF
Berkshire Hathaway Energy
BHP
BP
Dow
Duke Energy
Entergy
Exelon Corporation
Intel Corporation
Johnson Controls
LafargeHolcim USA
Mars, Incorporated
Microsoft
National Grid
Novartis
Pacific Gas and Electric Company
Toyota Motor North America

Matthew Binsted's contributions were supported by the Global Energy Technology Strategy Program at the Pacific Northwest National Laboratory.

As a fully independent organization, C2ES is solely responsible for its positions, programs, and publications. For further information, please visit www.C2ES.org/Funding/GuidingPrinciples. A company's participation in this project does not represent an endorsement of this report or its findings.

CONTENTS

FIGURES

I. INTRODUCTION

Climate change is among the most profound challenges of all time, confronting individuals, businesses, and governments across the globe. Meeting this challenge requires a sweeping, sustained effort over the coming decades. To successfully orient the global economy toward the goal of climate protection will require strong leadership from two indispensable forces: the United States, the world's leading economy, and the private sector—foremost for its power to innovate.

The Center for Climate and Energy Solutions (C2ES) is working to help illuminate and confront this looming long-term challenge through Climate Innovation 2050. This multi-year initiative brings together leading companies across key sectors to develop viable pathways for decarbonizing the U.S. economy. As an initial step, C2ES led a group of companies in a collaborative exercise examining potential scenarios for achieving mid-century decarbonization goals. This scenario exercise aimed to build a common understanding—benefitting both these firms and broader societal efforts—of the potential for alternative pathways to deep decarbonization in the United States and to highlight important commonalities and differences among such paths. This report presents the resulting scenarios and the insights drawn from them.

The scale and the broad contours of the decarbonization challenge are addressed at the global level by the long-term goals of the Paris Agreement, which include achieving global greenhouse gas (GHG) neutrality in the second half of the 21st century. For the purposes of the scenario development undertaken here, we chose a corresponding benchmark for the United States: an 80 percent reduction from 2005 levels in economy-wide emissions by 2050.

Achieving climate neutrality requires a broad array of social, economic, and technological transformations—in essence, reinventing the ways we power our homes and economies, move people and goods from place to place, and manage our lands. Previous analyses point to five core imperatives: decarbonizing the world's power supply; switching to electricity and other low-carbon fuels in the transportation, industry, and buildings sectors; increasing energy efficiency in each of those sectors; increasing carbon sequestration; and reducing emissions of non-carbon climate pollutants.[1]

Many decarbonization scenarios to date have focused primarily on the technological dimensions of these challenges.[2] This collaborative scenario exercise closely examined social and policy dimensions as key drivers of change as well, including the roles played by policy-makers, businesses, and consumers. Among the key takeaways:

- Decarbonizing the U.S. economy requires fundamental shifts in the ways we generate energy, produce goods, deliver services, and manage lands.
- These fundamental shifts can be achieved through a host of alternative pathways reflecting different drivers, different contingencies, and different societal choices.
- Decarbonization requires that action accelerates quickly and that everyone plays their part—policymakers at all levels, investors, entrepreneurs, consumers, voters, and companies across key sectors of the economy.
- The success of any pathway hinges on high levels of public support, expressed through stronger demand for effective policies and/or low-carbon goods and services.
- Decarbonization requires a broad suite of policies that drive investment and action by setting goals, targeting resources, providing incentives, and ensuring a level playing field.
- Technological innovation can greatly facilitate decarbonization but, without adequate policy drivers, is not sufficient to achieve it.
- The private sector is an essential partner in any decarbonization pathway, and timely business leadership can help ensure choices that are beneficial for both companies and society as a whole.
- Sectoral responses are highly interdependent—the pathway chosen by one sector may enhance or constrain the decarbonization options of others.

This current scenario exercise—undertaken in partnership with the RAND Corporation and the Joint Global Change Research Institute, a partnership between the Pacific Northwest National Laboratory and the University of Maryland—can help advance collective understanding in a number of ways. Unlike most previous scenario exercises, it is directly informed by the insights and perspectives of more than 20 leading companies in sectors critical to decarbonizing the U.S. economy, including electric power, transportation, oil and gas, manufacturing, and high-tech. By deepening understanding of the relevant challenges and opportunities, this exercise helps to inform the long-term decision-making of participating companies and, hopefully, the business community at large.

For Climate Innovation 2050, the insights drawn from this exercise provide a critical foundation for the next stage of the initiative—working with companies to outline a comprehensive strategy for putting the United States on the path to climate neutrality.

The following sections describe the scenario development process, present the three final scenarios and accompanying modeling results, outline broad and sector-by-sector takeaways, and offer brief conclusions. Appendices provide further detail on the scenario development process, the quantitative modeling assumptions and results, the baseline scenario, and the model employed.

II. A SCENARIOS APPROACH TO CLIMATE PLANNING

Scenarios are descriptions of plausible future worlds. They are a common tool used by researchers, governments, and businesses to explore the future implications of human actions for society, the economy, and the environment, as well as the relative benefits and adverse consequences of different policy and technology choices. This study uses scenarios to demonstrate the potential for alternative pathways to substantially decarbonizing the U.S. economy by 2050 and to highlight important commonalities and differences among such paths to aid decision-makers in the public and private sectors in pursuing deep decarbonization goals.

This study builds on previous energy and climate scenario efforts by various national and international agencies and organizations. These include the U.S. Energy Information Agency's *Annual Energy Outlook* and the International Energy Agency's *World Energy Outlook*.[3] Scenarios were fundamental to the federal government's development of the U.S. Mid-Century Strategy for Deep Decarbonization.[4]

Similarly, scenarios are routinely used within companies to support strategic planning. Shell, a pioneer in scenario analysis, published the *New Lens Scenarios* in 2013 outlining technology and economic pathways to net-zero carbon emissions by the end of this century. More recently, Shell published *Shell Scenarios: Sky*, describing a pathway for delivering on the goals of the Paris Agreement.[5] Similar scenarios have been developed by other energy companies and trade associations including ConocoPhillips, IPIECA, and BP.[6]

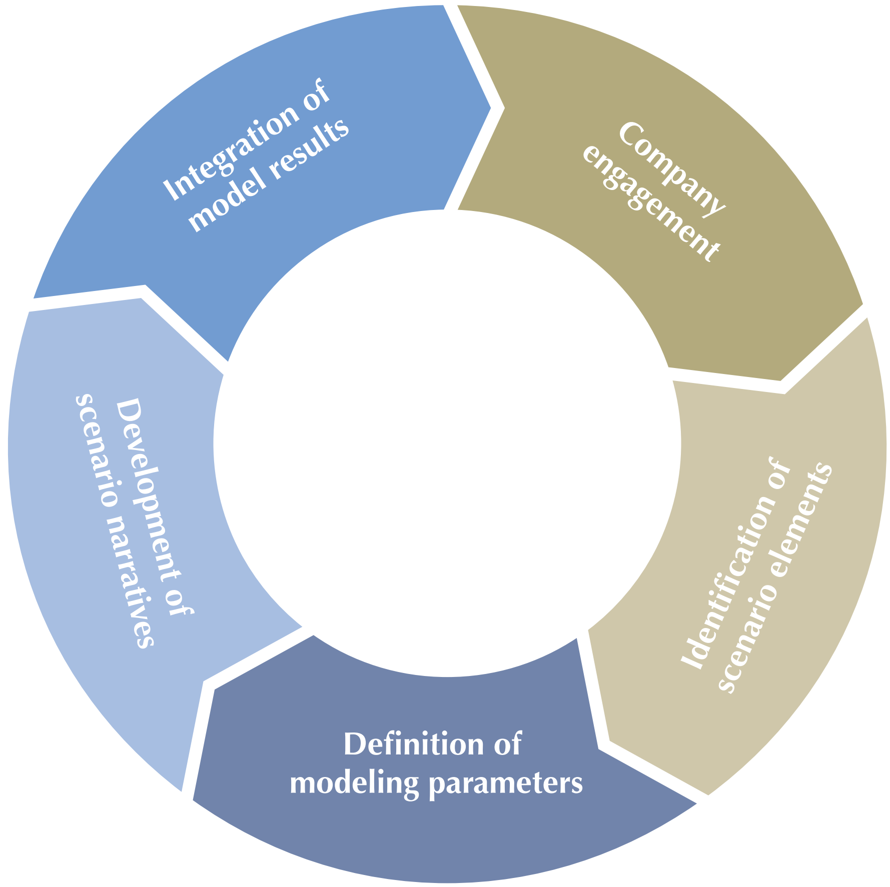
Scenario processes are also commonly used to bring together a wide variety of expert and lay perspectives to collectively identify drivers or key factors that shape the future and examine current data, knowledge, and understanding around these drivers. Such participatory processes help to enhance the relevance of the resulting scenarios to particular communities of stakeholders and decision-makers and to build common understanding around issues relevant to these groups. This can include a better understanding of stresses or shocks that could shape future outcomes, or social, economic, technology, or policy developments that cannot be easily forecast based on current trends. These qualities make scenarios particularly useful for exploring alternative pathways for achieving climate neutrality.

Climate Innovation 2050 engaged a wide range of leading companies and experts in the research community to apply a scenarios approach in order to envision plausible pathways to decarbonizing the U.S. economy (see **Figure 1**). Scenarios were developed through an iterative approach employing structured decision analysis frameworks and integrated modeling. Through a series of workshops, businesses representing key sectors enabling decarbonization shared their perspectives and experiences with climate policy development and implementation. (See **Appendix A** for details of the scenario development process.) Key objectives included:

- Illustrating alternative pathways to mid-century decarbonization goals
- Deepening collective understanding of opportunities and challenges in reaching these goals
- Illuminating critical interrelationships among sectors and actors
- Enlisting the perspectives and expertise of businesses toward the development of successful decarbonization strategies

A first round yielded three scenarios, each with a dominant set of actors or drivers: federal policy, state policy, and voluntary consumer and company action. Modeling revealed that none of these initial scenarios achieved an 80 percent reduction in U.S. GHG emissions by mid-century. In a second iteration, the scenario narratives assumed a more ambitious response across a wider array of actors. This included the introduction of a broader set of policy and technology responses implemented by a broader set of actors, which, when modeled, successfully achieved an 80 percent reduction in all scenarios.

FIGURE 1: **Process for developing Climate Innovation 2050 scenarios.**



Scenarios were developed through multiple iterations among researchers and business representatives, with the learning and feedback from each iteration used to refine the evolving scenarios. See Appendix A for more detail on the scenario development process.

III. ALTERNATIVE PATHWAYS TO 2050

The process described above led to a final set of scenarios representing three plausible pathways to reducing U.S. GHG emissions 80 percent below 2005 levels by 2050:

- **A Competitive Climate:** Strong international pressure in the form of carbon tariffs and growing recognition of the competitive benefits of low-carbon innovation lead to a strong, early U.S. federal response, including an economy-wide price on carbon.
- **Climate Federalism:** Responding to economic opportunities and intensifying climate-related disasters, a growing number of U.S. states implement ambitious climate policies, leading to calls from business for a more harmonized national response.
- **Low-Carbon Lifestyles:** Increased urbanization, generational shifts, and technological breakthroughs lead to strong market demand for low-carbon consumption products and services, along with the emergence of innovative low-carbon business models.

The three scenarios have important commonalities reflecting the fundamental physical requirements for decarbonizing a thriving economy. Achieving such a dramatic reduction in GHG emissions requires significant effort across all major sectors of the economy. In broad strokes, it requires decarbonizing the power sector; substituting electricity and biofuels for fossil fuels in transportation, buildings, and industry; increasing end-use energy efficiency; increasing carbon sequestration; and reducing the emissions of non-carbon climate pollutants.

While the three scenarios share these important commonalities, they also describe significantly different, plausible pathways to deep decarbonization by 2050. The scenarios differ in their mix of policies and the central technology innovations they require. Each scenario involves a distinct process of social transformation with different actors driving near-term change, different reasons for growing public support, and different mechanisms for enticing late adopters to join the transformation to a low-carbon society.

The United States, of course, does not act in isolation. To address the global context, all three scenarios assume that other countries achieve the 2050 GHG reduction targets reflected in the Sustainable Development scenario developed by the International Energy Agency (a 67 percent reduction from 2005 levels in countries belonging to the Organisation for Economic Co-operation and Development (OECD) and a 40 percent reduction in non-OECD countries).[7]

The remainder of this section provides a more detailed description of the scenarios, including modeling outputs.

Table 1 summarizes the scenarios' key elements. See also **Appendix B**, which identifies the quantitative assumptions used in modeling the scenarios; **Appendix C**, which describes a reference scenario used for comparative purposes; and **Appendix D**, which describes the version of the Global Change Assessment Model employed.

Partial modeling results, presented in **Figures 2 through 7**, include:

- Net GHG emissions
- Cumulative net GHG emissions
- GHG emissions by sector
- Primary energy consumption
- Negative emissions
- Carbon price revenues

A COMPETITIVE CLIMATE

A restructuring of the world trading system leads to the proliferation of aggressive carbon tariffs and new carbon-based trading partnerships as a central part of many nations' decarbonization strategies. The U.S. federal government, in partnership with the business community, responds with an aggressive clean energy drive tinged with economic nationalism and garnering strong public support. The new, comprehensive federal policy includes a strong national carbon price in 2022, along with ambitious clean power and vehicle efficiency standards. Increased federal RDD&D funding and large national markets speed innovations in and deployment of large-scale technologies including nuclear, carbon capture and storage, grid-scale battery storage, and cellulosic biofuels.

TABLE 1: Key elements of the Climate Innovation 2050 scenarios.

	A COMPETITIVE CLIMATE	CLIMATE FEDERALISM	LOW-CARBON LIFESTYLES
Overarching Drivers of Change	• Strong international pressure in the form of carbon tariffs, and growing recognition of the competitive benefits of low-carbon innovation, lead to a strong federal response, including an economy-wide price on carbon	• Responding to economic opportunities and intensifying climate-related disasters, a growing number of states implement ambitious climate policies, leading to calls from business for a more harmonized national response	• Increased urbanization, generational shifts, and technological breakthroughs lead to new low-carbon consumption patterns and the emergence of innovative low-carbon business models
Federal Government	• Implements economy-wide carbon price starting 2024 • Implements more rigorous vehicle emission standards • Makes strong investment in low-carbon research, development, demonstration, and deployment (RDD&D)	• Implements economy-wide carbon price starting 2031	• Is supportive, but plays no proactive leadership role
State and Local Governments	• Most states implement ambitious complementary policies, including building codes, transportation policies, and clean energy standards in the electric power sector	• Carbon trading expands on the east and west coasts through 2030 • Complementary policies are implemented after 2031, including clean energy standards and more stringent building codes	• Carbon trading expands on the east and west coasts through 2030 • Highly urbanized states support cities' ambitious policies, including by offering land-based sequestration incentives • Cities make large investments in public transit, implement more stringent building codes, and implement zero-emissions vehicle mandates for ride-sharing services
Businesses	• Driven by export opportunities, companies invest heavily in low-carbon technologies • Companies engage in closer collaboration on RDD&D with the federal government	• Facing a fractured regulatory landscape, companies push for a federal response to level the playing field	• New business models (e.g., "sharing economy," distributed power generation) transform key sectors • The power sector voluntarily reduces emissions by 85% by 2050 • Finance favors low-carbon over high-carbon investments
Consumers	• Consumers are willing to pay more for domestically produced low-carbon products	• Consumer preference for electric vehicles increases	• Improved carbon accounting and transparency enable consumers to easily act on growing preference for low-carbon products • Dietary and other behavioral shifts occur (e.g., beef consumption decreases)
Technology	• Federal RDD&D support lowers costs for nuclear, carbon capture and storage, grid-scale battery storage, and cellulosic biofuel	• Low-carbon investment favors domestic technologies, including hydrogen and nuclear energy • With lower incentives for innovation, more low-carbon technologies are imported	• Consumer demand and new, technology-enabled business models drive rapid electrification, greater efficiency in buildings and industry, and improved renewables integration
Rest of the World	• Countries achieve International Energy Agency Sustainable Development Scenario targets in 2050 (OECD countries, 67% below 2005; non-OECD countries, 40% below 2005)		

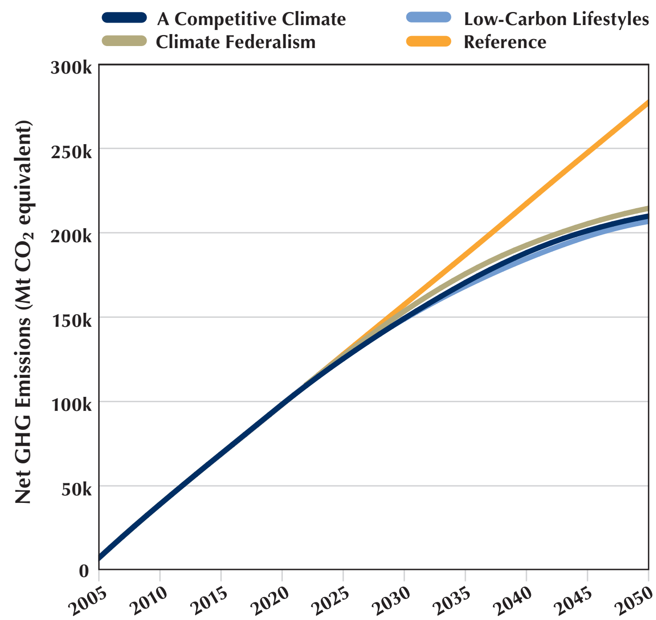
Appendix B contains the quantitative assumptions used in modeling the scenarios.

Net U.S. GHG emissions are reduced 80 percent below 2005 levels by 2050. Cumulative emissions are 24 percent lower than the reference case in 2050. Negative emissions from land system sequestration and biofuels deployed in combination with carbon capture and storage offset 41 percent of U.S. emissions (see **Figures 4 and 6**). Transportation is responsible for the largest share of remaining emissions (more than 40 percent of net GHG emissions in 2050), followed by industry and buildings.

Specific components of *A Competitive Climate* include:

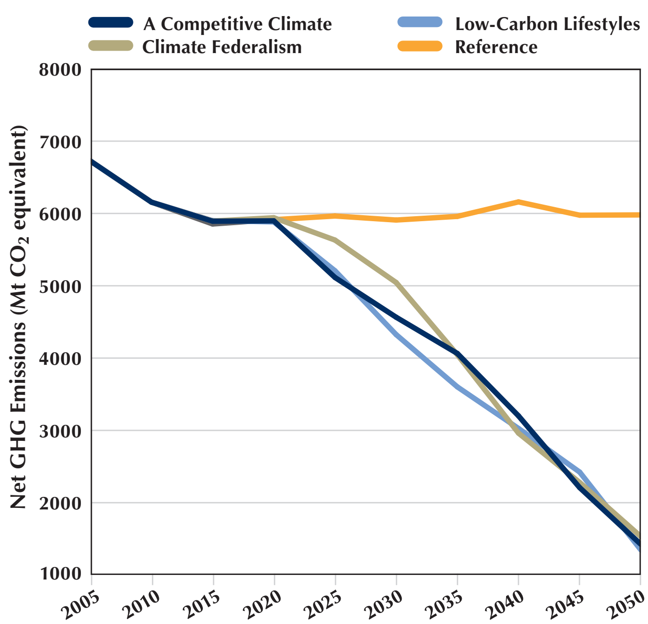
- **Federal:** In response to international and domestic pressures, the federal government moves aggressively to reduce emissions and dominate global clean tech markets. This agenda includes targeted regulations such as aggressive GHG standards for passenger vehicles, a significant boost in RDD&D investment, and a carbon price starting at $40/ton in 2024 and rising 8 percent per year. Carbon price revenues peak at over $350 billion per year around 2040. The federal government uses these revenues to fund strong investments in low-carbon RDD&D and to enhance regional and income equity in the clean energy transition. Federal policy favors policy certainty for business, a single national market, and greater regional equity.
- **State/Local:** Complementing federal efforts, a growing number of states and cities pursue policies promoting energy efficiency and low-carbon deployment, including ambitious clean energy standards in the power sector, stronger building and energy-efficiency standards, and innovative forms of financing efficiency and energy switching. The federal response, however, limits the diversity of policy environments across the United States.
- **Companies:** Responding to policies, public interest, and market opportunities, companies increasingly decarbonize their operations, invest in low-carbon research and development (R&D), and build brands around decarbonization. Firms actively support federal clean energy policy and seek export opportunities. A harmonized national policy, however, provides fewer market opportunities for unexpected new technologies and thus unplanned creative destruction.
- **Consumer:** Growing climate concern and a patriotic interest in winning the clean tech "race" drive rising consumer preference for low-carbon goods

FIGURE 3: Cumulative net GHG emissions.



This figure shows that cumulative GHG emissions through 2050 vary marginally across the three scenarios

Figure 2: Net GHG emissions.



This figure illustrates the emissions path each scenario takes to an 80 percent reduction by 2050.

Note: Figures 2-4 include carbon dioxide (CO_2) emissions from energy and industry, CO_2 emissions from land-use change, and the non-CO_2 emissions of CH_4, N_20, and fluorinated gases.

and reduce consumers' resistance to low-carbon infrastructure (e.g., pipelines, high-voltage DC transmission, advanced nuclear). Federal policies aimed at equity ease any public resistance to the clean energy transition.

- **Technology:** Public and private R&D investments produce breakthroughs across a range of technologies—many with export potential—including advanced nuclear, grid-scale energy storage, cellulosic biofuels and bioenergy with carbon capture and sequestration, carbon capture, and 3D manufacturing. The unified national response is particularly favorable to large-scale technologies such as advanced nuclear and carbon capture and storage.

CLIMATE FEDERALISM

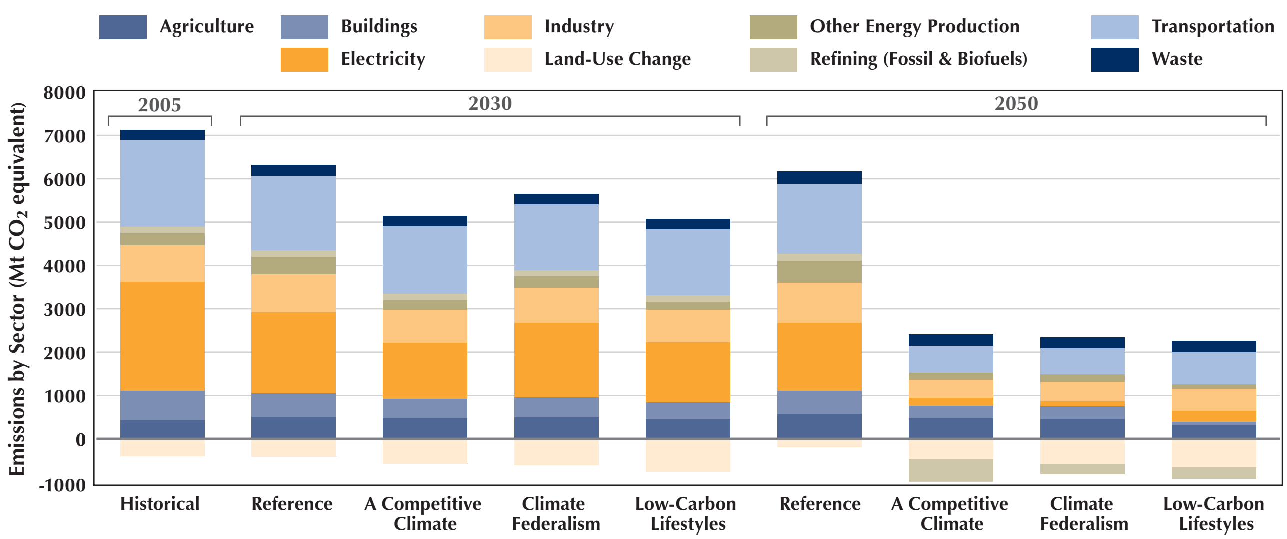
A growing number of states take increasingly aggressive action to reduce GHG emissions, driven both by their own unique economic opportunities and by their citizens' escalating concern with the impacts of climate-related disasters. States' efforts create a successful but increasingly fragmented regulatory and policy landscape that persists for about a decade. The patchwork of markets increases costs for U.S. firms, so businesses and investors force a more unified federal response by the early 2030s, which includes an aggressive national carbon price. But business must still contend with the legacy patchwork of differing state policies.

The United States achieves net emission reductions close to 80 percent by 2050. Emission reductions begin more slowly than in *A Competitive Climate*, then accelerate more quickly, with cumulative emissions in 2050 roughly 2 percent higher. Negative emissions, achieved almost entirely through the use of biofuels, offset 35 percent of total U.S. emissions. High use of solar and wind help to significantly reduce power-sector emissions. Increased deployment of both battery-electric vehicles and fuel-cell electric vehicles reduce emissions from transportation, although the sector's total emissions remain relatively high.

Specific components of the *Climate Federalism* scenario include:

- **Federal:** The federal government plays only a modest role in climate policy throughout the 2020s, focusing mainly on emissions-reducing regulations in the power sector and transportation. Its response subsequently grows with increasing public concern, rising disaster relief costs, and private sector

FIGURE 4: GHG emissions by sector.



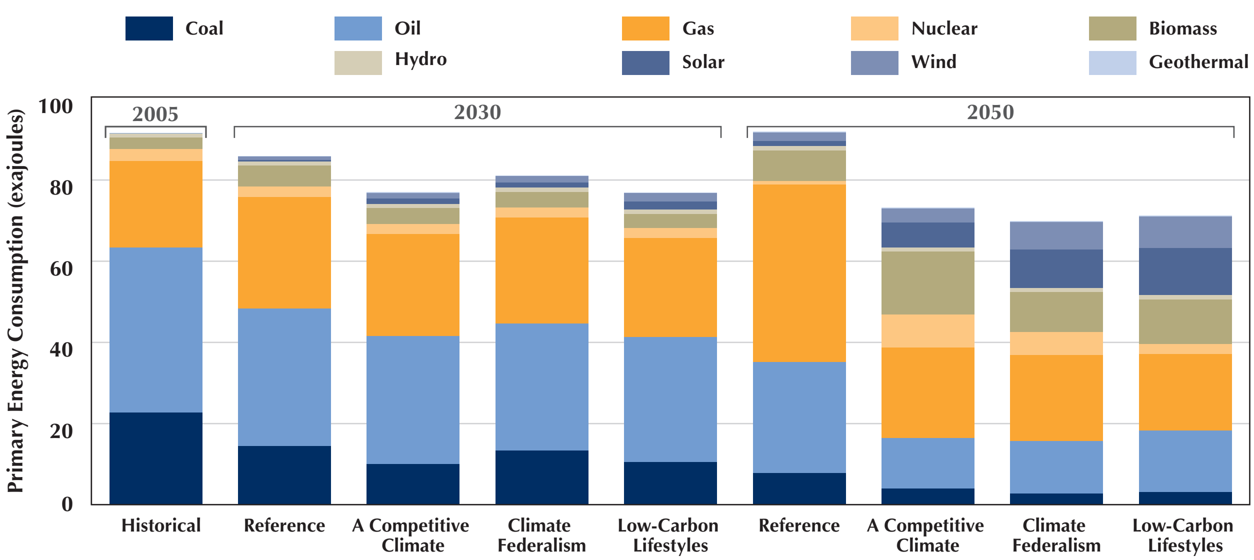
This figure shows the size and source of emissions and negative emissions for each scenario in 2030 and 2050.

Note: *Bars below the 0-emissions line indicate net negative emissions in a given sector and year. See Box 1 for a fuller description of negative emissions in these scenarios.*

calls for harmonization. The federal government implements economy-wide carbon pricing in 2031 that starts at $50/ton and rises 10 percent per year. Carbon price revenues peak at $330 billion/year around 2045 and are used by the federal government to help states and localities manage the growing impacts from climate change and to enhance regional and income equity in the clean energy transition.

- **State/Local:** A growing number of states, seeking to seize economic opportunities and supported by public concern with worsening climate impacts, pursue aggressive early action. This includes expanding carbon markets and implementing ambitious clean energy standards and other climate-relevant policies. By 2025, most of the U.S. population lives in states with a carbon price, linked to either the Northeast's Regional Greenhouse Gas Initiative or California's cap-and-trade system. While there are some attempts to coordinate policies among states, such as linking carbon markets, each state fashions a policy mix most suited to its own circumstances. This fosters numerous opportunities for policy experimentation and learning but increases costs for business.
- **Companies:** Firms actively engage with the new market opportunities offered by state policies and work with states to shape policies that favor innovation. Insurers, faced with rising risks, restrict coverage in impact-prone areas, and the financial industry favors low-carbon over high-carbon investment. Other companies reduce risk (financial, market, policy, physical) by decarbonizing, managing supply chains, increasing R&D, and capitalizing on emerging market opportunities. Expanding low-carbon business communities in each state encourage state action but create barriers to a truly unified national market when the federal government finally becomes engaged in the 2030s.
- **Consumers:** Public concern rises most quickly in coastal states, driving stronger state action and consumer preference for low-carbon goods. As climate impacts are felt in other regions, and the economic benefits of a low-carbon transition become more evident, support emerges for a national response.
- **Technology:** Numerous decarbonization efforts blossom, and the many experiments speed both technological and social innovation, which often favor smaller-scale systems such as renewables and

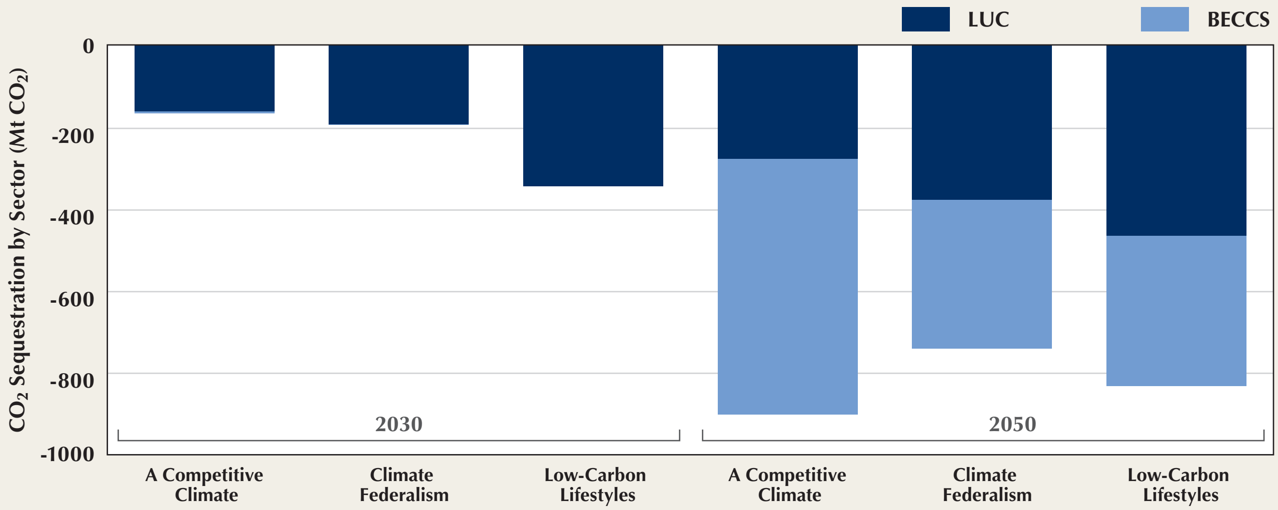
FIGURE 5: Primary energy consumption.



This figure shows the levels and sources of primary energy consumed in each scenario in 2030 and 2050.

Note: *Primary energy consumption reflects the embodied energy of raw energy resources (i.e., before any processing) for hydrocarbon fuels (coal, oil, gas, biomass). For nuclear energy and renewable energy sources (solar, wind, hydro, geothermal), primary energy consumption reflects the electricity generated from these resources.*

BOX 1: Negative emissions by sector for selected years.



"Negative emissions" result from activities that remove CO_2 from the atmosphere, which can offset emissions to the atmosphere from other activities. Most analyses suggest that achieving mid-century decarbonization goals will require such negative emissions to offset emissions from sectors that are especially difficult to decarbonize. This figure shows the levels and sources of negative emissions in each scenario in 2030 and 2050. The sources of negative emissions in these scenarios are land-system CO_2 sequestration (LUC) and bioenergy with carbon capture and sequestration (BECCS). Negative emissions from land-system CO_2 sequestration are calculated as the change in these emissions relative to the reference scenario, as the U.S. land system is a net sink (sequesters more carbon than it releases) even in the reference scenario. In these scenarios, BECCS is available in the electricity and refining sectors, and is primarily deployed in refining. BECCS is not deployed in the reference scenario.

distributed generation in the power sector. Hydrogen power finds enough niche markets that major advances are made. However, many low-carbon technologies (e.g., solar, storage, electric vehicles, appliances) are imported due to lack of federal RDD&D investment and states' willingness to pursue their climate goals with the assistance of foreign suppliers. Climate impacts and the need for cyber-risk management lead to widespread grid modernization and building retrofits and replacement.

LOW-CARBON LIFESTYLES

Increased urbanization, generational shifts, and technological breakthroughs drive new low-carbon consumption patterns and favor radically new business models. Improved carbon accounting enables ubiquitous supply chain transparency, allowing consumers to express their preferences for low-carbon products and services. Cities, driven by climate as well as non-climate concerns, become early drivers of climate-related policy. Leading firms create new models in energy and transportation, based on distributed power and ubiquitous ride-sharing, which speeds turnover of legacy capital stock and includes decarbonization as one of many co-benefits.

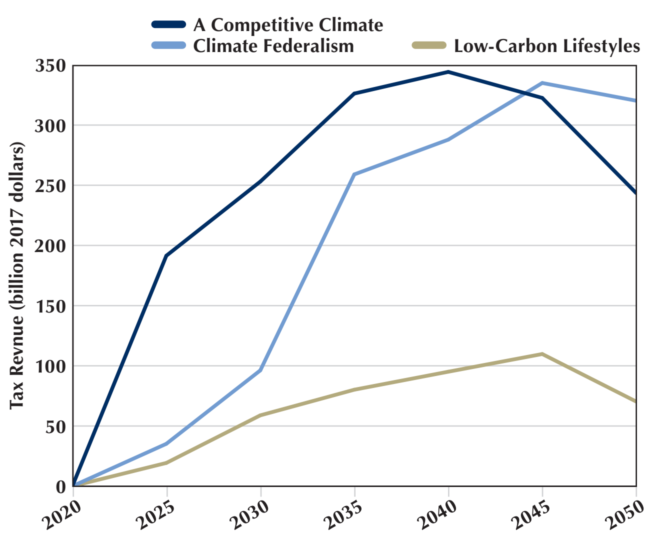
While commercial pressures both from within and from outside the United States force widespread decarbonization in all sectors and all parts of the country, regional equity suffers from the lack of any coordinated national response that enables burden sharing among regions. The federal government plays largely a supporting role, although it begins to engage with the growing regional inequities in the 2030s and 2040s.

Nationally, net GHG emissions drop to 80 percent below 2005 levels by 2050, with cumulative emissions at mid-century slightly lower than in the other two scenarios. Most of the economy becomes electrified, in particular buildings, where almost no fossil-fuel use remains in 2050. Transportation emissions decrease through a mix of battery-powered vehicles and expanded use of public transit, but fossil fuels still provide over half of all energy in transportation. Renewables account for well over two-thirds of the nation's electricity. Energy use in industry remains relatively high, with industry accounting for nearly 40 percent of total U.S. emissions. Negative emissions are large, offsetting 40 percent of U.S. emissions through a mix of biofuels and enhanced land-based sequestration.

Specific components of the *Low-Carbon Lifestyles* scenario include:

- **Federal:** Polarization between urban and rural states stymies federal action for a decade or more, limiting it to moderate RDD&D support, minimal power and transportation regulation, and facilitating actions such as software interoperability standards. Urban states secure federal policies that facilitate ambitious state and local action. No federal carbon price exists, but exporting firms face carbon tariffs in other countries.
- **State/Local:** Cities take aggressive, paradigm-shifting actions that reduce emissions while producing other benefits (such as reduced traffic congestion and improved energy efficiency), including carbon pricing, updates to zoning and building codes, mandates for zero-emission vehicles in ride-sharing services, and expanded mass transit. Many of these policies are coordinated across cities, facilitated by multi-city partnerships. Highly urbanized states adopt supporting policies such as clean energy standards, providing regulatory environments for the new business models that encourage innovation and guide them in socially beneficial directions (e.g., using ride sharing and autonomous vehicles to enhance rather than replace public transportation). About half of the states expand or launch carbon markets. In the California market, prices start at $15/ton in 2020 and rise 7.5 percent per year. The Northeast's Regional Greenhouse Gas Initiative expands to be economy-wide, with prices starting at $10/ton in 2020 and rising 9 percent per year. Revenues to state governments peak at around $100 billion/year in the 2030s. A significant fraction of these funds flows toward carbon sequestration in the land-use sector.
- **Companies:** Responding to reduced consumption and enabled by software advances, companies pursue new business models attuned to increasingly dense, urban environments, including expanded ride sharing, radically transparent green branding, and marketing of low-carbon products. Utilities voluntarily reduce power sector emissions by 90 percent by 2050, the finance sector increasingly shifts billions of dollars to low-carbon investments, and industry achieves high levels of energy efficiency and electrification.
- **Consumers:** Consumers increasingly demand a wide range of low-carbon products and services, favoring low-carbon diets, mass transportation, and a software-enabled sharing economy. U.S. firms aggressively invest to meet this demand. U.S. beef consumption drops by 50 percent by 2050. Consumers' willingness to pay small price increases for a low- or zero-carbon supply chain on consumer goods such as automobiles results in very high effective carbon prices for many firms in the industrial sector, helping to speed investment in low-carbon supply chains.
- **Technology:** Rapid advances in new technologies offer a wider range of low-carbon options and

FIGURE 6: Carbon price revenues.



This figure shows the level of government revenues generated by federal and/or state-level carbon pricing in each scenario, from 2020 to 2050. Some revenues are directed to RDD&D, resilience, incentives for land-based sequestration, and transition assistance for disadvantaged households and regions.

Note: *The carbon prices are assumed to be revenue-neutral for government; modeling did not consider the macroeconomic or distributional effects of revenue recycling.*

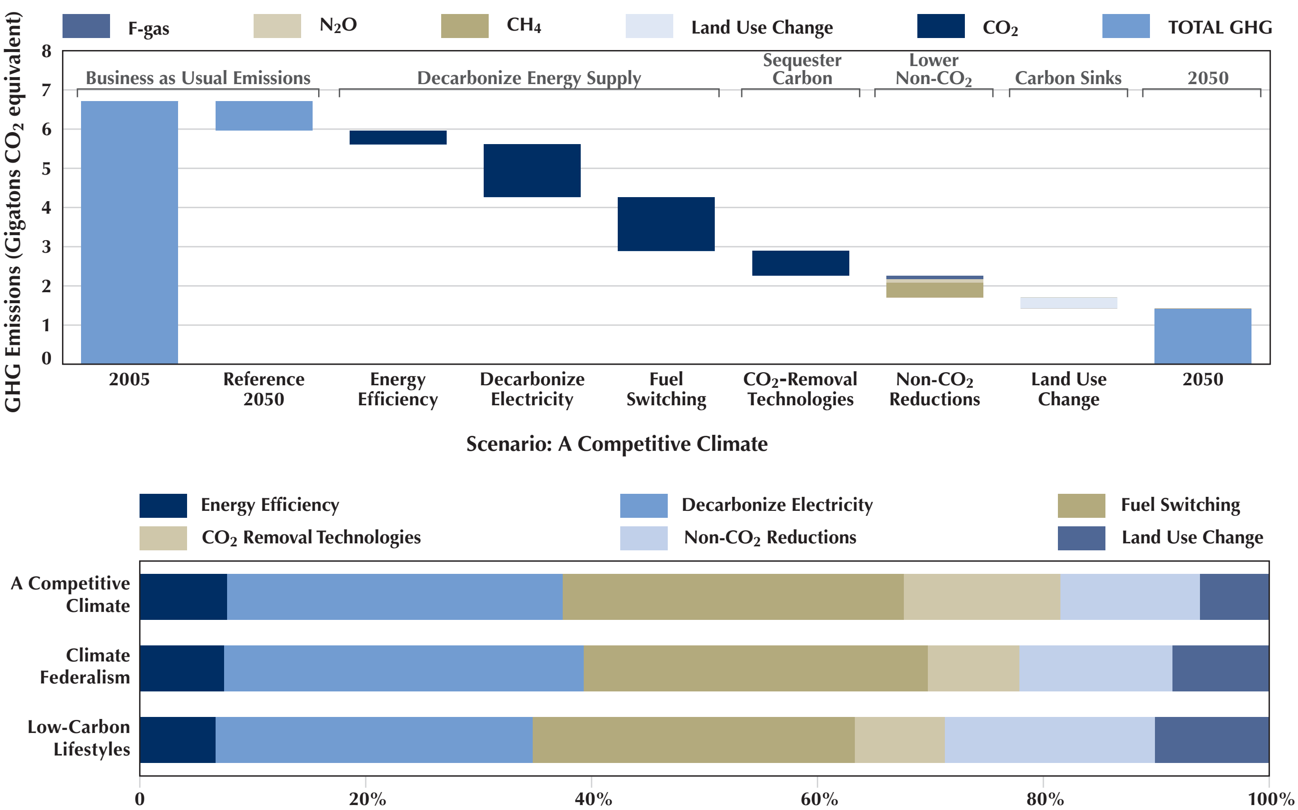
enable new business models. Advances in artificial intelligence, 3D printing, supercomputing, and blockchain technologies enable materials and process breakthroughs, autonomous vehicles, precision carbon accounting, and improved supply chain management. Reduced costs for renewables and nuclear power support the rapid electrification of transportation and buildings, while intelligent efficiency produces systems-level energy savings and improved demand flexibility, thereby reducing back-up requirements for intermittent power sources.

IV. KEY TAKEAWAYS

Considering any individual scenario provides a rich opportunity for improved understanding of potential drivers and uncertainties and of the policies and other tools available to effect change. However, each scenario is merely one hypothetical future, and the richest insights derive from looking across a range of scenarios to tease out the broader lessons that emerge. While no single analysis can produce definitive conclusions, a close consideration of the three scenarios that emerged in this collaborative exercise, alongside the broader literature available on decarbonization challenges, leads to a set of overarching takeaways.

Decarbonizing the U.S. economy requires certain fundamental shifts in the ways we generate energy, produce goods, deliver services, and manage lands. Consistent with a broad range of previous analyses, the scenarios presented above illustrate that achieving climate neutrality will necessitate changes across virtually every facet of the economy. Although the specific nature of these changes varies among scenarios, together they reinforce the conclusion that certain fundamental shifts are essential: decarbonizing the world's electric power supply; switching to electricity and other low-carbon fuels in the transportation, industry, and buildings

FIGURE 7: Key elements of decarbonization.



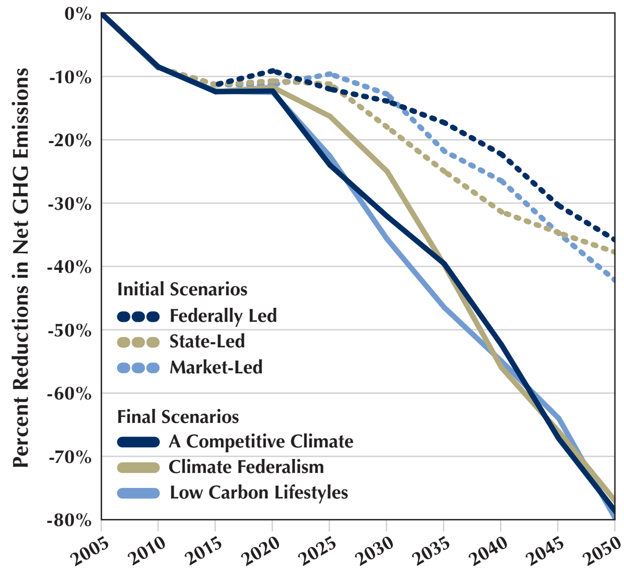
The top figure illustrates, in the case of *A Competitive Climate*, the relative contributions of different emissions-reducing strategies toward an 80 percent reduction in 2050. The lower figure shows that the relative contributions of these strategies are roughly similar across all three scenarios.

sectors; increasing energy efficiency in each of these sectors; increasing carbon sequestration; and reducing non-carbon climate pollutants such as methane.

These fundamental shifts can be achieved through a host of alternative pathways reflecting different drivers, contingencies, and societal choices. The United States can decarbonize by mid-century by following any one of a number of technology and policy trajectories. That multiple pathways exist offers both reassurance and challenges. On the one hand, multiple pathways may make reaching the decarbonization goal more likely because no single technological, political, or societal failure can block progress. The inability to reach consensus regarding one pathway—such as a top-down federal price signal—will not preclude successful decarbonization along other routes. On the other hand, this wide range of potential pathways means there is also significant uncertainty about which policies or technologies are best to pursue, and which will prove most successful. This uncertainty can, in turn, inhibit investment in transformative technologies and business models and be an obstacle to achieving the broad political consensus needed to reorient the economy toward climate neutrality (see **Figure 7**).

Decarbonization requires that action accelerates quickly and that everyone plays their part—policy-makers at all levels, investors, entrepreneurs, consumers, voters, and companies across key sectors of the economy. This reflects both the breadth and the scale of the decarbonization challenge: all sectors and actors need to make substantive contributions to achieving climate neutrality. While the scenarios envision different sets of actors driving change initially, any pathway that relies too heavily on a single actor or set of actors (e.g., the federal government, or climate-progressive states, or a minority of companies) is unlikely to succeed (see **Figure 8**). Rather, we must work all of the "levers" to achieve an 80 percent reduction—policy at multiple levels, private innovation and investment, business leadership, and the engagement of the public at large. And while all of these levers are important, some may be especially critical to success. For example, all three scenarios include some form of carbon price—either an actual carbon price set by policy action or a shadow price set by societal preferences. In addition, all of the scenarios imply significant investment in innovation to accelerate technological change.

FIGURE 8: Importance of broad-based action.



This figure shows the GHG emissions reductions achieved through 2050 in both the initial and the final sets of scenarios. Dashed lines correspond to the initial scenarios, while solid lines correspond to the final scenarios presented in this report.

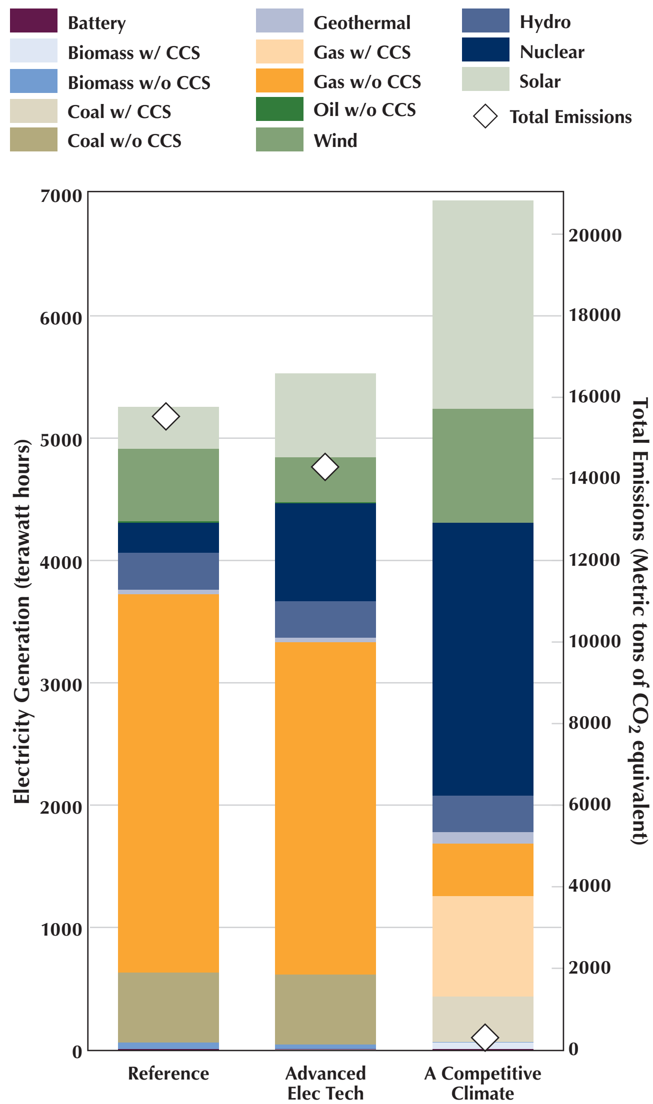
Note: A Competitive Climate *most closely corresponds to the earlier* Federally Led *scenario;* Climate Federalism *to* State-Led*; and* Low-Carbon Lifestyles *to* Market-Led

Success hinges on a high level of public support, expressed through stronger demand for effective policies and/or low-carbon goods and services. This support manifests differently in the three scenarios. For example, interest-group politics are more essential for delivering the strong policy responses seen in *A Competitive Climate* and *Climate Federalism*. *Low-Carbon Lifestyles*, by contrast, depends on more diffuse societal support communicated via consumer preferences. This underscores the importance of exploring how different policy framings and incentives can generate public support. For example, some co-benefits of climate policy may be perceived as having a higher value to society than the direct benefits of avoided emissions. Stronger public support will not necessarily arise on its own—business and political leaders, civil society organizations, and the media all have a role to play in generating public awareness and support.

Decarbonization requires a broad suite of policies that drive investment and action by setting goals, targeting resources, providing incentives, and ensuring a level playing field. Achieving an 80 percent reduction by mid-century will require effective policies at all levels of government. Among the suite of policy choices, a top-down mechanism such as carbon pricing stands virtually alone in its ability to orient and drive efforts across sectors and society. In contrast, a patchwork of policies can lead to emissions leakage between sectors and/or states. In *Low-Carbon Lifestyles*, for instance, the lack of an economy-wide carbon price leads to increases in building and industry emissions, as rising demand for electricity drives up electricity prices relative to direct fossil-fuel combustion. Even with a strong national framework, however, targeted interventions also are needed at the state and local levels. For example, state governments are often the implementing authority for federal policies and investments, and local governments have a critical hand in areas such as building codes. In addition, policies will be needed to assist industries and communities that will be economically disadvantaged in the low-carbon transition.

Technological innovation can greatly facilitate decarbonization, but without adequate policy drivers, is not sufficient to achieve it. Innovation in low-carbon technologies, and the policy structures that enable their cost-effective deployment, can not only reduce the costs of decarbonizing but also foster economic growth and competitiveness—important co-drivers for climate efforts. Some sectors, such as power and buildings, already have a wide variety of technology and policy options. Yet others, such as transportation and industry, require more rapid innovation and deployment if substantive reductions in emissions are to be achieved. Some technologies, like carbon capture, contribute to decarbonization by design; some, such as intelligent efficiency, can enable emission reductions across multiple sectors. Other technologies could contribute given the proper policy environment, but could have little benefit, or prove counterproductive, if the appropriate incentives are not in place. For example, autonomous vehicle technologies do not inherently contribute to emissions reduction; therefore, in *Low-Carbon Lifestyles*, autonomous vehicles are coupled to local zero-emission vehicle mandates. In the absence of market drivers, translating low-carbon innovation into technology deployment is contingent on sufficient policy support and demand (see illustration in **Figure 9**).

FIGURE 9: Role of policy in driving technology deployment.



This figure illustrates that advances in low-carbon technologies, in the absence of policies driving their deployment, produce only limited emission reductions. The bars show the level and sources of electricity generation in 2050; the diamonds show the associated GHG levels. The *Advanced Elec Tech* case and *A Competitive Climate* scenario incorporate the same assumptions regarding cost breakthroughs in generation technologies (cost reductions in solar, wind, nuclear, carbon capture and storage, and grid-scale storage). While cost breakthroughs lead to greater deployment of some technologies in the *Advanced Elec Tech* case, emission reductions are modest compared with the same technological advances paired with policies like a carbon price and clean energy standards in *A Competitive Climate*.

The private sector is an essential partner in any decarbonization pathway, and timely business leadership can help ensure choices that are beneficial for both companies and society as a whole. Business leadership manifests differently in each scenario—by supporting early federal action in *A Competitive Climate*, pressing for more harmonized policies in *Climate Federalism*, and innovating new business models in *Low-Carbon Lifestyles*. Early interventions by business can help generate support for policy frameworks that include flexible, cost-effective strategies for achieving climate neutrality.

Sectoral responses are highly interdependent—the pathway chosen by one sector may enhance or constrain the decarbonization options of others. Addressing each sector in isolation is likely to result in inefficiencies, emissions leakage, and higher overall costs. For example, decarbonizing transportation, buildings, and industry is partly to largely dependent on the decarbonization of—and potentially drives much higher demand for—electric power. This increased electrification can, in turn, dramatically affect the fossil fuel sector. These interactions extend to land management as well, as a large increase in the use of biofuels may have significant implications for land use, food production, and food imports and exports. In particular, the negative emissions made possible by coupling biofuels with carbon capture and storage, or through biological pathways such as afforestation and soil carbon enhancement, can ease the demands on sectors where steep emission reductions are especially challenging.

SECTORAL TAKEAWAYS

POWER

The electric power sector represents a lynchpin of decarbonization (**Figure 7**). Other sectors will lean heavily on it as a source of zero- or low-carbon power. This greater reliance on electricity as an end-use form of energy throughout the economy, combined with population and economic growth, could result in greatly increased power demand. Gains in energy efficiency could moderate this growing demand. Grid modernization will play an important role in facilitating both. Relative to other sectors, the power sector has a wide range of low-carbon technology options, from renewables to nuclear to coal and natural gas with carbon capture. These can be advanced through a wide array of policy options, including a carbon price and a clean energy standard incentivizing the full range of technology options.

FIGURE 10: Electricity-sector GHG emissions.

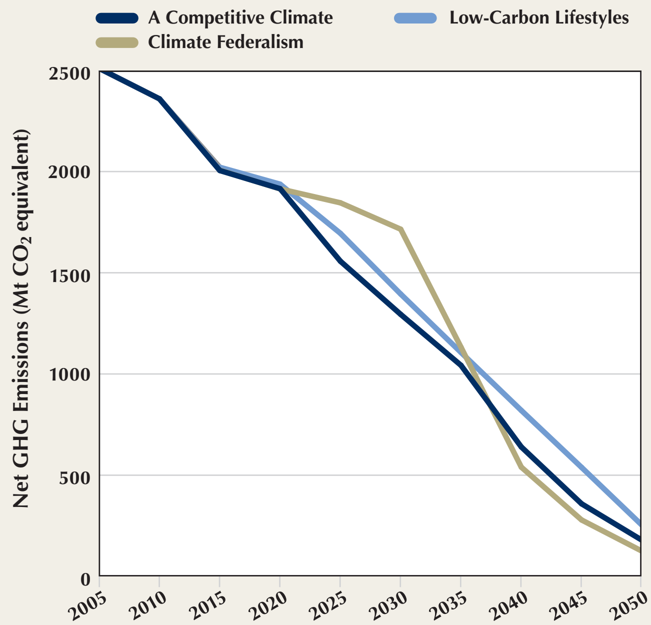
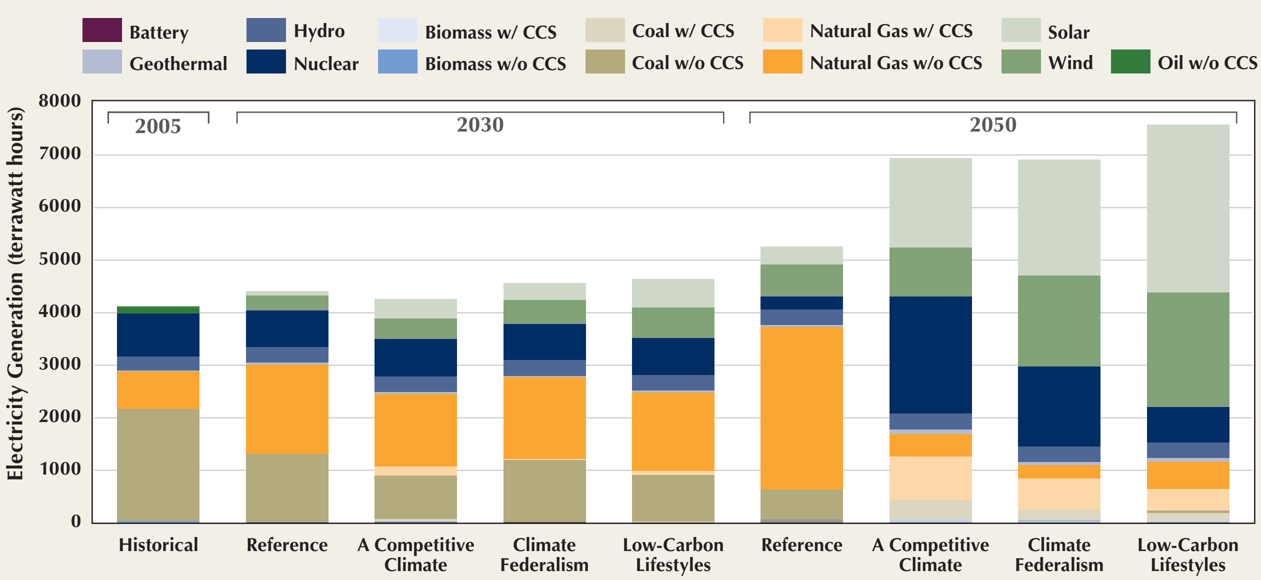


FIGURE 11: Electricity generation by technology.



TRANSPORTATION

The transportation sector is already experiencing rapid changes with the emergence of new technologies and mobility paradigms. Decarbonizing the sector necessitates moving beyond incremental improvements in fuel efficiency to large-scale fuel switching (**Figure 7**). While current trends in road transportation point toward battery-electric vehicles, other technologies including hydrogen and biofuels may also prove important. Growth in autonomy, connectivity, and ride sharing will facilitate business models that provide new mobility options and, potentially, contribute to decarbonization (see *Low-Carbon Lifestyles*). But whether automation and other new mobility options increase or reduce emissions remains uncertain. Policy choices at all levels—local, state, and federal—will play an important role in shaping how these new transportation technologies and mobility paradigms evolve, and their contributions to decarbonization. Policy-makers may need to address looming pathway choices, such as investments in batteries and charging infrastructure and/or hydrogen fuels and biofuels.

FIGURE 12: Transportation-sector GHG emissions.

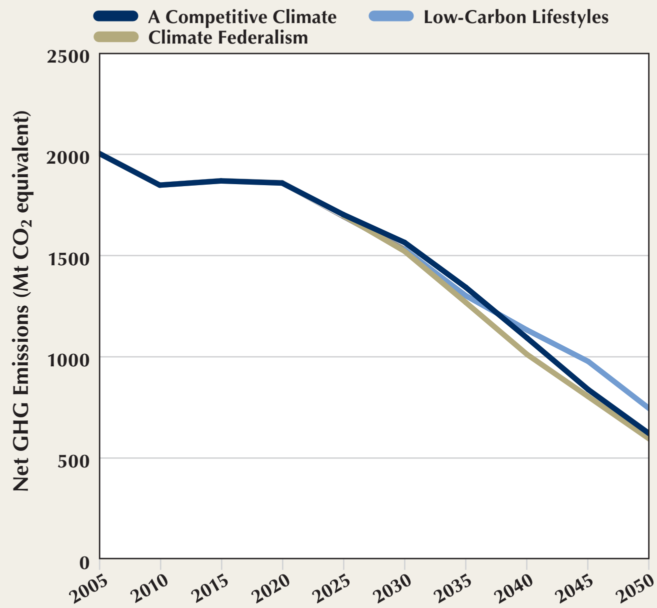


FIGURE 13: Transportation final energy by fuel.

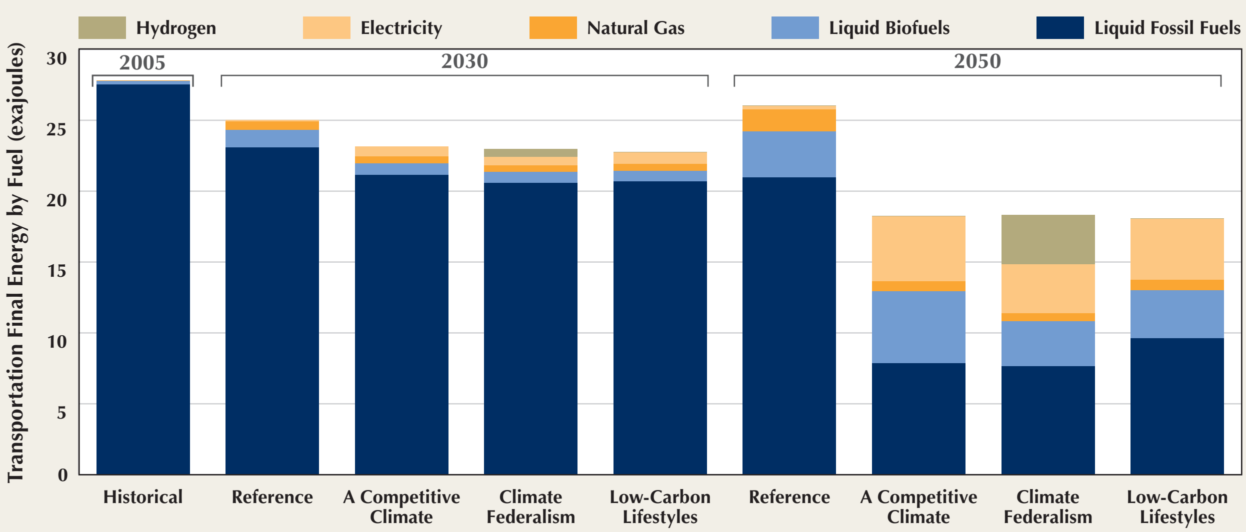
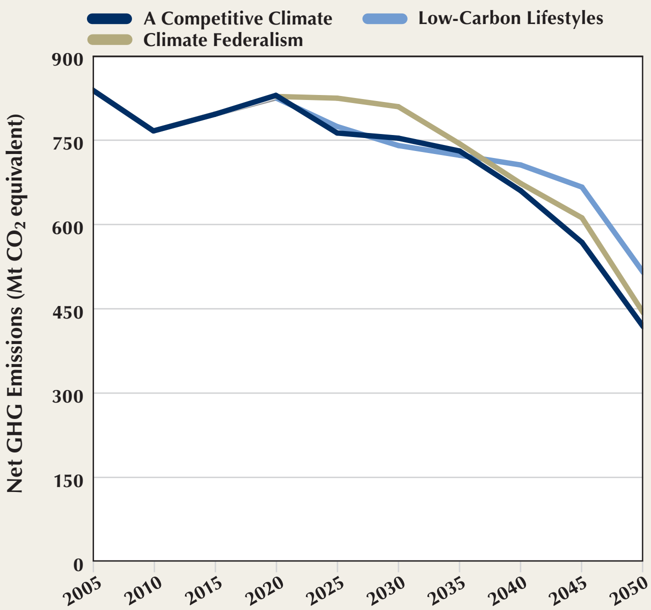
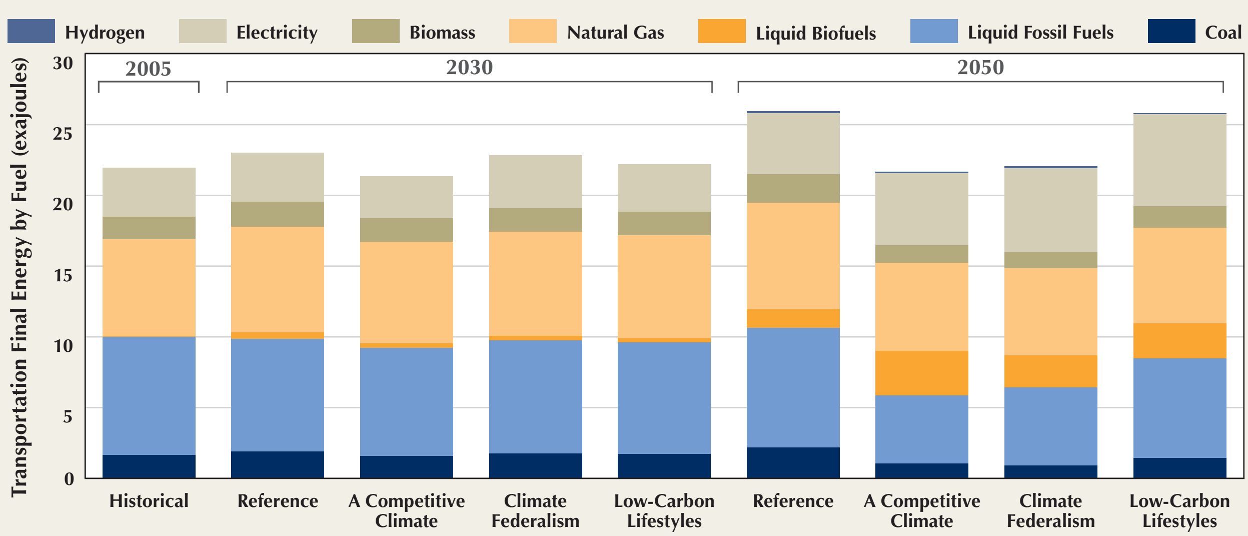


FIGURE 14: Industry-sector GHG emissions.



From a technological standpoint, industry presents diverse and difficult decarbonization challenges. Its many subsectors employ a wide range of industrial processes, many of them highly energy-intensive, heavily reliant on high-carbon feedstocks, or requiring a large, steady supply of thermal energy. From a political economy standpoint, trade-exposed industries—those whose products are internationally traded—face the additional challenge of maintaining their global competitiveness. Key decarbonization strategies could include greater electrification of the sector, carbon capture, and the use of renewable energy where possible for thermal needs. Economy-wide incentives such as a carbon price (included in all three scenarios) or supply chain transparency (in *Low-Carbon Lifestyles*) can drive electrification and other low-carbon shifts. But targeted policies and investments will be needed to generate the particular technology advances that can enable deeper emission reductions across the diverse industrial base. In addition, transition assistance or measures that help shelter U.S. industry from overseas competition may be an essential political ingredient of a comprehensive climate policy.

FIGURE 15: Industry final energy by fuel.



BUILDINGS

The buildings sector is diffuse and diverse. Many policies and design decisions are made at the local level, customized for local tastes and conditions. The slow turnover of building stock and the relatively high rate of existing electrification further reduces opportunities for rapidly reducing emissions across the sector as a whole. At the same time, economic and population growth may drive substantial increases in the total building stock. Efforts to reduce emissions from both existing and new building stock face significant upfront cost hurdles that will need to be addressed. Policies and consumer choices favoring fuel switching and electrification, as well as the integration of digital intelligent-efficiency technologies, can make significant contributions to decarbonization. In addition, taking advantage of digital advances to enhance the integration of distributed energy resources into the broader power grid could also boost system-level efficiency in important ways.

FIGURE 16: Building-sector GHG emissions.

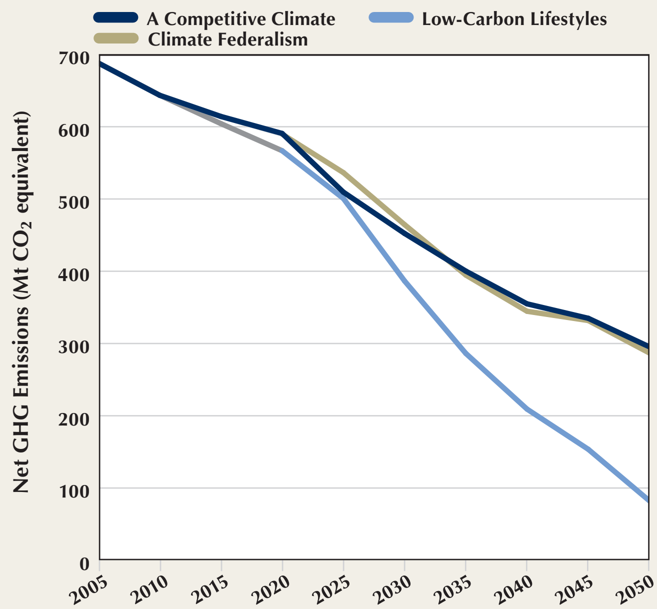
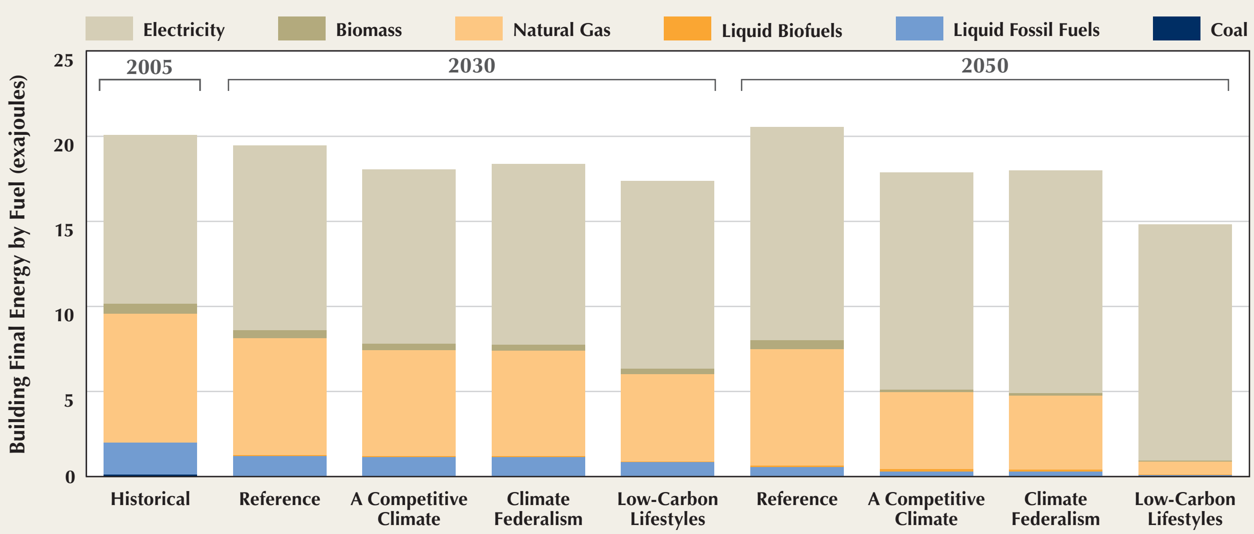


FIGURE 17: Building final energy by fuel.

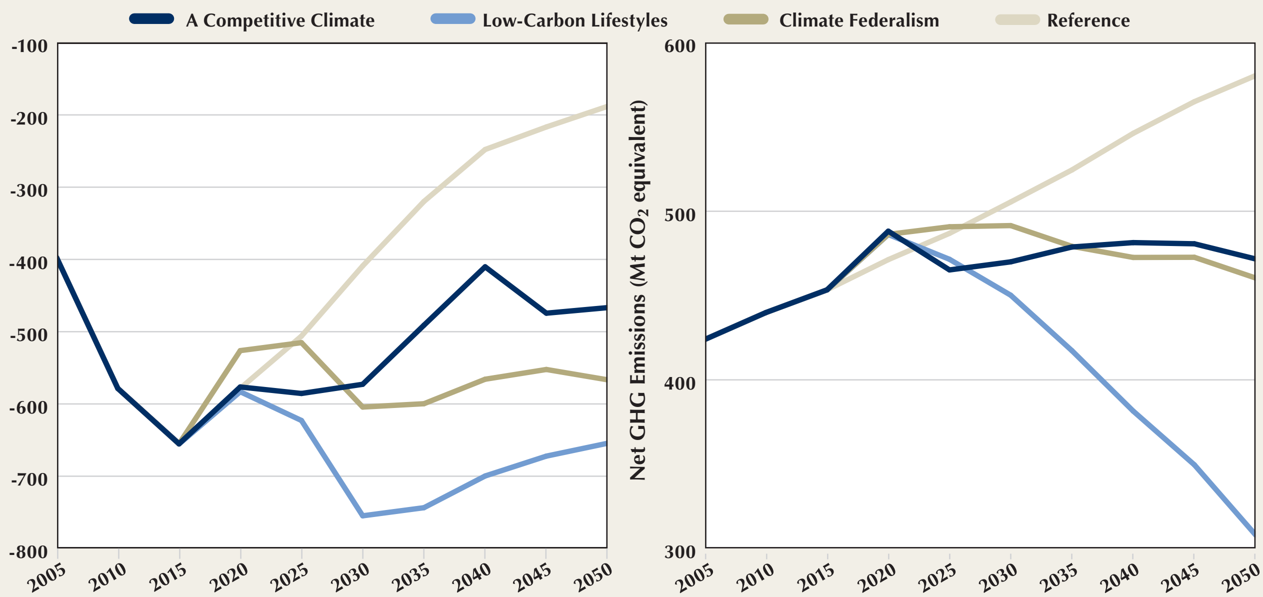


LAND USE

Land use—which includes agriculture and forestry—is unique among sectors in that it can be both a source of emissions and a sink to absorb carbon from the atmosphere. Indeed, all three scenarios rely on enhanced carbon sequestration to produce negative emissions critical to achieving a net 80 percent reduction. This is achieved partly through incentives for afforestation/reforestation and "carbon farming" practices that increase soil sequestration, and partly through the production of cellulosic biofuels linked with carbon capture (see **Box 1** on negative emissions).

Agriculture also has significant non-CO_2 emissions from fertilizer use and livestock production. Similarly, conversion of forested land for settlement or agriculture can produce significant non-energy emissions. However, decarbonization can be furthered through innovations such as feed additives to reduce animal methane and carbon-sequestering fiber crops that replace synthetic fibers. In addition, dietary changes such as lower meat and dairy consumption could reduce the land necessary to support livestock production, as in *Low-Carbon Lifestyles*.

FIGURE 18: Land-use change and agriculture-sector GHG emissions.



Land-use change emissions (left) include changes in terrestrial carbon stocks from conversion of land from one purpose to another (such as conversion of grassland to agricultural land). Agriculture-sector emissions (right) do not include land-use change but include, for example, nitrous oxide (N_2O) emissions from fertilizer application and methane emissions from digestive fermentation in livestock.

V. WHERE WE GO FROM HERE

The scenario development process is, by design, collaborative. It is a collective effort to envision alternative futures, greatly enriched by the range of expertise and diversity of perspectives brought into the conversation. This process—part of C2ES's Climate Innovation 2050 initiative—draws heavily on the combined expertise of C2ES, the RAND Corporation, and the Joint Global Change Research Institute, a partnership between the Pacific Northwest National Laboratory and the University of Maryland. But it was explicitly designed to benefit as well from the perspectives of leading companies across key sectors of the economy—a set of actors whose full engagement is crucial to the success of the U.S. decarbonization effort. It is our hope that by integrating these perspectives, and by looking beyond technology pathways to a wider range of drivers and societal and policy choices, this analysis will deepen and advance this critical debate.

Achieving decarbonization is likewise a collaborative undertaking. Our analysis illustrates that all have a role to play in reorienting the world's largest economy to achieve climate protection—if we are to succeed, this must be an all-in effort. This analysis will provide crucial input for the next phase of Climate Innovation 2050: working with a broad array of companies to sketch the fundamental features of a U.S. decarbonization strategy. C2ES welcomes feedback on this foundational scenario exercise and looks forward to sharing the results of our further endeavors.

APPENDICES

APPENDIX A: HOW THE SCENARIOS WERE DEVELOPED

The scenarios presented in this report were informed by four workshops with a group of company representatives assembled by C2ES. As shown in **Table AA-1**, the workshops were held over the course of a year. They began with a kickoff workshop in which the project team (from C2ES, RAND, and the Joint Global Change Research Institute, a partnership between the Pacific Northwest National Laboratory and the University of Maryland) introduced the effort and developed the design of the scenario development process with the firms. At the second, scoping workshop, the project team presented lessons from previous scenario exercises focused on deep decarbonization. The project team then facilitated a discussion among participants of the key factors they wished to see addressed by the scenarios. At the third workshop, the project team presented initial descriptions (called thumbnails) and modeling of three proposed scenarios. Participants critiqued the initial scenarios and, working in breakout groups, sketched out details of what would become the revised scenarios. In the final, fourth workshop, participants reviewed written descriptions and detailed modeling results for each of the three revised scenarios and provided their final suggestions.

Between the second and third workshop, the project team developed the initial set of scenario narratives and generated integrated modeling results using the Global Change Assessment Model to support each narrative. The material generated in the second workshop informed the team's narrative construction and modeling. The project team also held several conference calls with workshop participants to review draft scenario text and model runs. Between the third and fourth workshops, the project team revised the scenario narratives in response to the participant input at the third workshop and the latest modeling results. The project team also revised the assumptions used in the modeling in order to reach 80-percent emission reductions and improve alignment with the narratives.

The second workshop employed two frameworks—called XLRM and Three Horizons—to help organize the scoping discussions. The use of XLRM helps to organize key factors in a decision-oriented analysis. The four types of XLRM are:[8]

- Policy levers (L), near-term actions that, in various combinations, comprise the alternative strategies that decision-makers want to explore
- Exogenous uncertainties (X), factors outside the control of decision-makers that may nonetheless prove important in determining the success of their strategies
- Measures (M), the performance standards that decision-makers and other interested communities would use to rank the desirability of various scenarios
- Relationships (R), potential ways in which the future evolves, in particular those attributes addressed by the measures

TABLE AA-1: Scenario development process.

DATE	WORKSHOP	ACTIVITIES
• December 2017	• Kick off	• Introduce effort, design scenario development process
• April 2018	• Scoping	• Identify key factors to address with scenarios
• July 2018	• Feedback	• Present initial scenarios and modeling, refine and flesh out scenarios
• November 2018	• Final	• Present revised scenarios, receive final feedback

TABLE AA-2: XLRM factors suggested by participants during the second workshop.

UNCERTAINTY FACTORS	POLICY LEVERS	PERFORMANCE MEASURES
• Public acceptance of new technology • Consumer preferences • Evolution of international trade • Rates of technological change • Rates of infrastructure development • Water availability	• Carbon prices • Liability regime • Regulatory certainty • Education and awareness raising • Monetization of benefits from technology investment • Public investment in innovation • Industry consortiums • Incentives for agricultural sequestration • Promotion of policy co-benefits	• Rate of decarbonization • Economic growth • Avoidance of catastrophic climate change • Ending energy poverty • Regional equity • Appropriate distribution of effort • Technology leadership • Reasonable carbon prices • Industry sustainability • Jobs and employment

The workshop discussion focused on gathering perspectives around the policy levers, uncertainties, and measures. Participant discussions were lightly facilitated, and the project team then organized these discussions into the four XLRM categories. These XLRM factors were used by the project team after the workshop to to develop the initial scenarios and associated social, economic, and technological elements which reflected different combinations of uncertainties, policy approaches, and outcomes.

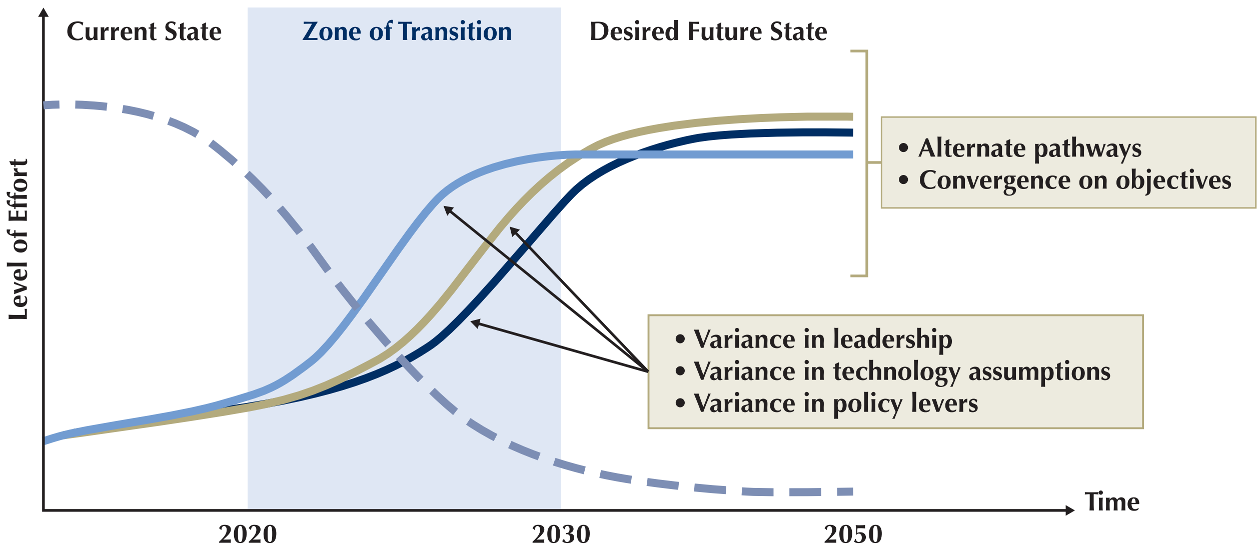
Participants at the second workshop were also shown the Three Horizons framework, as shown in **Figure AA-1**. The horizons represent different periods of decision-making and societal evolution. For example, the first horizon describes the current state of conditions based on present-day values and trends. The third horizon describes the long-term desired future state of the world. Meanwhile, the second horizon represents a transition phase articulating how society shifts from the current state to the desired future state. In particular, Three Horizons was useful in explicitly laying out the sequence of driving forces and other events that might occur as society transitioned from the current fossil fuel–dominated economy to a future state where GHG emissions are reduced by 80 percent by mid-century.

The project team used this framework to help facilitate the workshop discussions by occasionally guiding the discussion to explicitly focus on one or more of the horizons. The project team also used this Three Horizons framework in considering how the driving forces in the various scenarios might play out over time.

To develop the initial scenarios after the second workshop, the project team first articulated the key elements that make up the scenarios and how they varied across three futures representing alternative combinations of policy, technology, and social preferences. One scenario assumed a future where federal interventions in the form of a carbon price drive decarbonization from the top down. The second scenario assumed that interventions would largely be driven at the state level, with federal policy emerging later. A third assumed that decarbonization would largely be driven from the bottom up, based on a combination of consumer demand and technological innovation. Each of these was associated with a different set of policy, technology, and sector responses—a different transitional pathway—in pursuit of an 80 percent reduction by 2050.

For each scenario, elements were articulated to provide more detail regarding the assumed policy environment (local to international), technological innovation and deployment, social preferences, and sectoral responses. Scenario elements were subsequently integrated into broader narrative descriptions of the future.

FIGURE AA-1: Illustration of the three horizons associated with decarbonization pathways.



Each curve represents an alternative pathway for achieving the desired outcome—an 80 percent reduction in emissions by mid-century. Each pathway follows a different trajectory as society transitions toward decarbonization, with each representing a different mix of policy levers and technology options.

Meanwhile, those scenario elements were also used to inform the choice of input parameters for the Global Change Assessment Model (GCAM) in order to generate quantitative model runs consistent with the scenarios. The GCAM team would periodically present the model results to the rest of the project team, which would discuss potential revisions to the assumptions about input parameters in order to move closer to the desired emissions reduction goals while at the same time improving perceived consistency with the emerging scenario narratives. The scenario narratives were also adjusted in light of the model runs.

At the third workshop, the project team presented the initial scenario narratives, model parameters, and model outputs. The participants provided feedback and revisions, both in plenary sessions and breakout groups organized around specific scenarios.

Key critiques of the initial scenarios provided by the participants included the following:

- **Failure to achieve decarbonization objectives:** Modeling revealed that the scenarios, as originally specified, did not achieve an 80 percent reduction by 2050 (particularly the third scenario, which lacked a carbon price), indicating a need for additional interventions in order to achieve decarbonization objectives.
- **Justification for scenario elements:** Company participants noted that scenario narratives should provide plausible justifications for how different policy or technology options emerge. For example, what drives technology innovations, or what triggers aggressive policy action at the federal or state level?
- **Single point of failure:** Initially, each scenario was overly dependent on a single actor. Company participants noted that scenarios dominated by federal, state, and consumer or company action potentially neglect the need for a broader range of actors. For example, aggressive federal action was viewed as being contingent on public support, and public and private investment in technology was seen as important for any decarbonization pathway.

Following the third workshop, the project team made revisions to the scenarios—the narrative descriptions as well as model parameters—to address the above issues. The general framework for the scenarios (different initial driving forces catalyzing the decarbonization transition) remained intact. A broader set of policy and technology options were introduced and implemented by a broader set of actors in order to achieve the 80-percent emissions reduction in each of the three scenarios. This culminated in the final scenarios which were presented at the fourth workshop in November 2018 and are discussed in this report.

These three scenarios represent only a small sample of the multiplicity of plausible pathways into a decarbonized future. The requirement of reaching an 80-percent reduction by 2050 imposed a significant constraint on the set of plausible futures. The project team had to work hard to find combinations of assumptions consistent with this goal. There are certainly other plausible scenarios that this exercise failed to consider—both because it did not explore those combinations of parameter or potential driving forces and associated narratives. Nonetheless, the final three scenarios represent a diverse and suitable foundation to pursue this project's objectives: building a common understanding—benefitting both participating firms and broader societal efforts—of the potential for alternative pathways to deep decarbonization in the United States and highlighting important commonalities and differences among such paths.

APPENDIX B: QUANTITATIVE ASSUMPTIONS USED TO MODEL THE SCENARIOS

TABLE AB-1: Assumptions regarding policies, company actions, and consumer preferences.

	A COMPETITIVE CLIMATE	CLIMATE FEDERALISM	LOW-CARBON LIFESTYLES
Economy-wide Carbon Price	• Starting in 2024: $40/ton, escalating at 8%/year through 2050 ($296 in 2050)	• Starting in 2031: $50/ton, escalating at 10%/year through 2050 ($306 in 2050)	
Subnational Carbon Prices		• California carbon market: $15/ton starting in 2020, escalating to $50 in 2030 ▪ AZ, CA, CO, NM, NV, OR, UT, WA • Regional Greenhouse Gas Initiative (economy-wide): $10/ton starting in 2020, escalating to $40 in 2030 ▪ 2020: CT, DE, IL, MA, MD, ME, NC, NH, NJ, NY, RI, VA, VT ▪ 2025: above plus FL, GA, KS, LA, MN, NE, PA, SC	• California carbon market: $15/ton starting in 2020, escalating to $131 in 2050 ▪ 2020: CA, CO, OR, WA ▪ 2025: above plus AZ, NM, TX, UT • Regional Greenhouse Gas Initiative (economy-wide): $10/ton starting in 2020, escalating to $133 in 2050 ▪ 2020: CT, DE, IL, MA, MD, ME, NC, NH, NJ, NY, RI, VA, VT ▪ 2025: above plus FL, MN, OH, PA
Land Use Change Mitigation	• Incentive for carbon sequestration in the land sector equivalent to 15% of economy-wide carbon price	• Incentive for carbon sequestration in the land sector equivalent to 15% of economy-wide carbon price	• Incentive for carbon sequestration in the land sector equivalent to 25% of California carbon market price
Electric Power	• 100% clean energy standard (by 2050): AZ, CA, CO, CT, DC, DE, HI, IA, ID, IL, KS, MA, MD, ME, MN, NC, NE, NH, NJ, NM, NV, NY, OR, PA, RI, SC, VA, VT, WA • 80% clean energy standard (by 2050): FL, GA, MI, OH, TX, UT, WI • 60% clean energy standard (by 2050): ▪ AK, AL, AR, IN, KY, LA, MO, MS, MT, ND, OK, SD, TN, WV, WY	• 80% clean energy standard (by 2050): ▪ AK, IA, ID, MO, ND, OH, SD, TX	• Utilities respond to investor pressure and commit to reducing emissions by 90% nationally by 2050 • Lower cost of financing for low- and zero-carbon technologies • Increased finance cost for fossil technologies without carbon capture and storage
Buildings			• Residential floor space decreases by 6% relative to reference scenario (2050) • Commercial floor space decreases by 10% relative to reference scenario (2050)
Industry			• Industrial emissions face 12% of international CO_2 price ▪ $16/ton in 2030, escalating to $19/ton in 2050 ▪ Refining and cement exempted

	A COMPETITIVE CLIMATE	CLIMATE FEDERALISM	LOW-CARBON LIFESTYLES
Transportation	• Federal Corporate Average Fuel Economy (CAFE) and GHG standards: ▪ Light-duty vehicles: 62.5 mpg in 2050 (52.8 mpg on-road performance) ▪ Freight: 12.2 mpg in 2050	• Pre-2030: California standards adopted nationwide: ▪ Light-duty vehicles: 46.29 mpg by 2030 (38.6 mpg on-road performance) ▪ Freight: 8.93 mpg by 2030 • Post-2030: Federal Corporate Average Fuel Economy (CAFE) and GHG standards: ▪ Light-duty vehicles: 51 mpg by 2050 (42.3 mpg on-road performance) ▪ Freight: 10.45 mpg by 2050	• Federal Corporate Average Fuel Economy (CAFE) and GHG standards: ▪ Light-duty vehicles: 46.29 mpg by 2030, 51 mpg by 2050 (38.6, 42.3 mpg on-road performance) ▪ Freight: 8.93 mpg by 2030, 10.45 mpg by 2050 • Increasing subsidy for public transit (bus, passenger rail), reaching 25% of non-fuel costs in 2050 • Zero-emission-vehicle fleet procurement (increased preference for zero-emission trucks and busses)
Consumer Preferences			• \$15/ton shadow price on CO_2 emissions from all sectors starting in 2031, escalating to \$31 in 2050 • Diet: beef consumption decreases by 50% relative to reference levels
Biomass Availability (US)	• Limited to ~1 billion tons in 2050	• Limited to ~670 million tons in 2050 (1/3 less biomass is available than other scenarios)	• Limited to ~1 billion tons in 2050
International Policy	• Countries achieve International Energy Agency Sustainable Development scenario targets in 2050 (OECD countries, 67% below 2005; non-OECD countries, 40% below 2005)		

TABLE AB-2: Technology assumptions.

	A COMPETITIVE CLIMATE	CLIMATE FEDERALISM	LOW-CARBON LIFESTYLES
Nuclear Power	• 50% reduction in capital cost (2015-2050)	• 50% reduction in capital cost (2015-2050)	• Reference assumptions [~13% reduction in capital cost (2015-2050)]
Wind and Solar Power	• ~30% (wind) and ~70% (solar) reduction in capital cost (2015-2050)	• ~60% (wind) and ~80% (solar) reduction in capital cost (2015-2050)	• ~60% (wind) and ~80% (solar) reduction in capital cost (2015-2050) • Lower backup requirements for intermittent renewables, reflecting increasing flexibility of demand response
Power-Sector Carbon Capture and Storage (CCS) (Gas, Coal, Syngas)	• ~40%/~75% reduction in capital cost of CCS component (2015-2050)	• Reference assumptions [~30%/~50% reduction in capital cost of CCS component (2015-2050)]	• Reference assumptions [~30% /~50% reduction in capital cost of CCS component (2015-2050)]
Grid-scale Battery Storage	• 50% reduction in capital cost (2015-2050)	• 50% reduction in capital cost (2015-2050)	• Reference assumptions [~35% reduction in capital cost (2015-2050)]
Cellulosic Biofuels	• 50% reduction in non-fuel cost by (2015-2050)	• Reference assumptions [~5% reduction in non-fuel cost (2015-2050)]	• Reference assumptions [~5% reduction in non-fuel cost (2015-2050)]
Hydrogen Production	• Reference assumptions [~15% reduction in non-fuel cost for most technologies (2015-2050); ~30% reduction for electrolysis]	• 40% reduction in non-fuel cost for most production technologies (2015-2050); 50% reduction when paired with carbon capture and storage	• Reference assumptions [~15% reduction in non-fuel cost for most technologies (2015-2050); ~30% reduction for electrolysis]
Carbon Capture and Storage (Refining, Cement, Nitrogen Fertilizer, Hydrogen Production)	• 50% cost reduction of carbon capture and storage component in these applications	• Reference assumptions [no cost reduction for carbon capture and storage component in these applications]	• Reference assumptions [no cost reduction for carbon capture and storage component in these applications]
Industry	• Increased industrial efficiency	• Increased industrial efficiency	• Increased industrial efficiency • Increased ability to electrify industrial energy use
Transportation	• Light-duty battery-electric vehicles have cost parity with internal combustion engines by 2035 • Heavy-duty battery-electric vehicles have cost parity with internal combustion engines by 2050	• Light-duty battery-electric vehicles have cost parity with internal combustion engines by 2035 • Heavy-duty battery-electric vehicles have cost parity with internal combustion engines by 2050 • Fuel-cell electric vehicles have cost parity with internal combustion engines by 2035	• Light-duty and heavy-duty battery-electric vehicles have cost parity with internal combustion engines by 2035 • 10% increase in speed of public transit, and 10% decrease in speed of light-duty-vehicle transit (by 2050, relative to reference) • 25% increase in light-duty vehicle load factor (reflecting increased use of ride-sharing services)
End-use Energy Efficiency	• Increased stringency of residential and commercial appliance standards and building codes; lower cost and increased performance for equipment and appliances; increased availability of efficient technologies; improved performance of new residential shell technology; increased consumer adoption of high-efficiency products*	• Same as *A Competitive Climate*	• Same as *A Competitive Climate*, plus increased electrification of building end-uses, in particular (i) electric heat pumps and resistance heaters, (ii) LED lighting, and (iii) electrical cooking in residential and commercial applications**

* Iyer et al. (2017).

** Ibid.

APPENDIX C: REFERENCE SCENARIO

There are many ways in which the U.S. energy system might evolve over the coming decade. The reference scenario in this report is intended as a counterfactual storyline against which these alternative scenarios can be compared. Broadly, the Global Change Assessment Model (GCAM)-USA reference scenario assumes that historical trends continue in the near term due to inertia in the system and continuation of current policies. However, in the long term, the reference scenario assumes that outcomes are largely driven by economic forces.

The reference scenario assumes a growing U.S. economy, with a population reaching nearly 400 million by mid-century. This economic and population growth results in rising service demands in all end-use sectors. The reference scenario assumes a continuation of current energy efficiency policies (e.g., building efficiency standards) but still sees increasing final energy demands due to growing service demands with no expansion or strengthening of existing efficiency policies.

The reference scenario also assumes increases in electricity demand over the coming century, including modest growth over the next decade due to increased electrification in the industrial, buildings, and transportation sectors. This departs from recently observed flat electricity demand, in part because the reference scenario assumes no expansion or increased stringency of demand-side policies (e.g., building efficiency and fuel economy standards). From an electricity supply perspective, the reference scenario assumes that increasing shares of natural gas and renewables are deployed to meet the growing demand for electricity. The reference scenario also includes state-specific assumptions about retirements of coal and nuclear plants based on the age structure of those power generation fleets. The reference scenario assumes no new deployment of coal-fired power plants without carbon capture and storage throughout the United States, consistent with recent historical trends and the current Clean Air Act Section 111 (b) New Source Performance Standards for carbon dioxide emissions from new steam-generating electricity generation units. The reference scenario also assumes rather limited deployment of nuclear technologies in the near term, reflecting the common understanding that deployment of nuclear technologies is constrained by economic, institutional, and social factors including concerns regarding nuclear waste disposal, safety, and security.

From an emissions perspective, economy-wide GHG emissions in the reference scenario are relatively flat from 2015 to 2050, with a reduction in carbon dioxide emissions (driven largely by the natural retirement of aging coal-fired power plants) offset by growing non-carbon dioxide emissions.

APPENDIX D: THE GLOBAL CHANGE ASSESSMENT MODEL

The Global Change Assessment Model (GCAM) was employed to provide the scientific and technical quantification of the scenarios described in this report. GCAM is a global, long-term, multi-sector human-Earth systems model that captures key interactions between the global economic, energy, land, and climate systems.[9] The version of the model utilized for this report is based on GCAM version 4.1 and includes subnational detail in the United States (GCAM-USA).[10]

The three scenarios in the report describe three alternative pathways each of which could deliver an 80 percent reduction in U.S. GHG emissions in 2050 relative to 2005. The scenarios are much more than the numerical quantifications; they include narrative descriptions of the state of the world and the United States that in turn are translated into quantifications. GCAM-USA provides a consistent accounting tool for quantifying and exploring these scenarios throughout their development. The model tracks physical and financial flows, supplies of and demands for commodities, and prices paid for each market transaction, ensuring that there is no double-counting or leakage. As with any quantified scenario, the scenarios in this report are a product of both the model (GCAM-USA) and the assumptions that go into that model. The quantitative model outputs are contingent on the exogenous assumptions provided to the model. These assumptions are critically important in shaping the quantified scenario and thus must be based on a well-formed narrative framing. Below we provide an overview of the GCAM-USA model, its assumptions, and additional information about the scenario quantifications.

Detailed documentation for GCAM version 4.2 model can be found at http://jgcri.github.io/gcam-doc/v4.2/toc.html, and a description of GCAM-USA is at http://jgcri.github.io/gcam-doc/gcam-usa.html. What follows is a short nsummary of some key features of GCAM-USA.

GCAM is global in scope and divides the world into 32 geopolitical regions, of which the United States is one. Key model inputs include socioeconomic assumptions (population and labor productivity) for each region and representations of resources, technologies, and policies. GCAM operates in five-year time steps from 2010 (final calibration year) through 2100 by solving for the equilibrium prices and quantities of various energy, agricultural, and emissions markets in each time period and region. Activity in the energy, agriculture, and land-use systems produces emissions of 16 GHGs tracked endogenously within the model.

GCAM-USA divides the United States into 51 regions representing the 50 U.S. states and Washington, DC, each of which is modeled explicitly. GCAM-USA is embedded within the global GCAM model; therefore, GCAM-USA represents interactions between the United States and the rest of the world through global markets, and conditions in the United States are internally consistent with international conditions. The use of GCAM-USA also allows state-level policies and actions to be represented. These state-level regions contain more detailed representations of features previously modeled at the national level, including socioeconomics, energy transformation, carbon storage, renewable resources, electricity markets, and consumer end-use energy demands. GCAM-USA also captures interactions between state-level actions and policies and actions in other states and at national scales.

The energy system in GCAM includes detailed regional representations of resource availability and extraction for both depletable primary resources (coal, natural gas, oil, and uranium) and renewable energy sources (bioenergy, hydropower, solar, and wind). The model also includes representations of the processes that transform these resources to final energy carriers (electricity, refined liquids, refined gas, coal, commercial bioenergy, hydrogen) and the technologies that deliver energy services demanded by end users in the buildings, transportation, and industrial sectors. The deployment of technologies in GCAM depends on relative costs and is achieved using an implicit probabilistic formulation that is designed to represent decision-making among competing options when only some characteristics of the options can be observed. The model tracks investments in energy systems and gives priority to the utilization of existing plant and equipment as long as that existing infrastructure can cover its operating costs.

The agriculture and land-use module of GCAM represents competition for land across various uses including food crops, biomass, forests, pasture, grassland, shrubs, desert, tundra, and urban land. The energy system, agriculture, and land-use systems are linked through bioenergy and fertilizer. The energy system determines the demand for bioenergy, and the agriculture and land-use systems determine the supply. Conversely, the agriculture and land-use system determines the demand for fertilizers and the energy system determines the supply.

The scale of human activity in each region of the model is determined by the population in that region and labor productivity. Other input assumptions such as available resources (e.g., fossil fuels, wind, solar insolation, uranium, arable land area) and technology options and characteristics are inputs to a GCAM scenario.

GCAM solves energy, economy, and land markets simultaneously. The GCAM solver finds a set of market prices that equates supplies and demands for all commodities in all sectors and all countries simultaneously. Emissions of GHGs, aerosols, and short-lived climate pollutants are determined by combining emissions coefficients with levels of associated activities. Carbon dioxide is the most important GHG that humans emit at present, but all emissions that affect the Earth's energy balance are important. GCAM tracks all climate-related gases and uses Hector, a reduced-form climate model, to estimate climate change associated with changes to the atmosphere that are caused by human emissions. For specific geographic sub-regions, GCAM provides a carbon dioxide-equivalent value of all human emissions by multiplying each emission type by a carbon dioxide-equivalent value based on 100-year global warming potential coefficients.

REFERENCES

BP. 2019.Energy Outlook. London, United Kingdom. https://www.bp.com/en/global/corporate/energy-economics/energy-outlook.html.

Calvin, Katherine, Pralit Patel, Leon Clarke, Ghassem Asrar, Ben Bond-Lamberty, Ryna Yiyun Cui, Alan Di Vittorio, Kalyn Dorheim, Jae Edmonds, Corinne Hartin, Mohamad Hejazi, Russell Horowitz, Gokul Iyer, Page Kyle, Sonny Kim, Robert Link, Haewon McJeon, Steven J. Smith, Abigail Snyder, Stephanie Waldhoff, and Marshall Wise. 2019. "GCAM v5.1: Representing the Linkages between Energy, Water, Land, Climate, and Economic Systems." Geoscientific Model Development Discussions 12: 677–698. https://doi.org/10.5194/gmd-12-677-2019.

"Carbon Scenarios." 2019. ConocoPhillips. Accessed May 9, 2019, http://www.conocophillips.com/environment/climate-change/climate-change-strategy/carbon-scenarios/.

International Energy Agency. 2018. World Energy Outlook. Paris, France. https://www.iea.org/weo.

"Sustainable Development Scenario." International Energy Agency. 2019. Accessed May 9, 2019. Accessed May 20, 2019, https://www.iea.org/weo/weomodel/sds.

IPIECA. 2016. Low-Emissions Pathways - IPIECA Workshop Summary. London, United Kingdom. http://www.ipieca.org/media/2802/low-emissions_pathways_workshop_summary_2016.pdf.

Iyer, G., C. Ledna, L. Clarke, H. McJeon, J. Edmonds, M. Wise, and P. Kyle. 2017. GCAM-USA Analysis of U.S. Electric Power Sector Transitions. Richland, WA: Pacific Northwest National Laboratory. https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-26174.pdf.

Joint Global Change Research Institute. 2019. "GCAM v4.2 Documentation." Accessed May 9, 2019, http://jgcri.github.io/gcam-doc/v4.2.

Lempert, Robert J., Steven W. Popper, and Steven C. Bankes. 2007. Shaping the Next One Hundred Years: New Methods for Quantitative, Long-Term Policy Analysis. Santa Monica, CA: RAND. https://www.rand.org/content/dam/rand/pubs/monograph_reports/2007/MR1626.pdf.

"Shell Scenarios." 2019. Royal Dutch Shell. Last Modified April 25, 2019, https://www.shell.com/energy-and-innovation/the-energy-future/scenarios.html.

Weyant, John, Leon Clarke, and Allen Fawcett (eds.). 2014. "Energy Modeling Forum 24: U.S. Technology and Climate Policy Strategies." The Energy Journal 24(Special Issue 1). https://emf.stanford.edu/publications/emf-24-us-technology-and-climate-policy-strategies.

White House Council on Environmental Quality. 2016. United States Mid-Century Strategy for Deep Decarbonization. Washington, DC: White House. https://unfccc.int/files/focus/long-term_strategies/application/pdf/mid_century_strategy_report-final_red.pdf.

Williams, J.H., Benjamin Haley, and Ryan Jones. 2015. Policy Implications of Deep Decarbonization in the United States. San Francisco, CA: Energy and Environmental Economics, Inc. http://deepdecarbonization.org/wp-content/uploads/2015/11/US_Deep_Decarbonization_Policy_Report.pdf.

U.S. Energy Information Administration. 2019. Annual Energy Outlook 2019. Washington, DC. https://www.eia.gov/outlooks/aeo/pdf/aeo2019.pdf.

ENDNOTES

1 White House (2016); Williams, Haley, and Jones (2015); Weyant, Clarke, and Fawcett (2014).

2 Ibid.

3 U.S. Energy Information Agency (2019); International Energy Agency (2018).

4 White House (2016).

5 Shell Scenarios (2019).

6 Carbon Scenarios (2019); IPIECA (2016); BP (2019).

7 International Energy Agency (2018).

8 Lempert, Popper, and Bankes (2007).

9 Joint Global Change Research Institute (2019); Calvin et al. (2019).

10 Calvin, et al. (2019).

The Center for Climate and Energy Solutions (C2ES) is an independent, nonpartisan, nonprofit organization working to forge practical solutions to climate change. We advance strong policy and action to reduce greenhouse gas emissions, promote clean energy, and strengthen resilience to climate impacts.

C2ES CLIMATE *INNOVATION* 2050

3100 Clarendon Blvd., Suite 800
Arlington, VA 22201
P: 703-516-4146
F: 703-516-9551

WWW.C2ES.ORG

CENTER FOR CLIMATE AND ENERGY SOLUTIONS

PATHWAYS TO 2050: ALTERNATIVE SCENARIOS FOR DECARBONIZING THE U.S. ECONOMY