United States Mid-Century Strategy
FOR DEEP DECARBONIZATION

NOVEMBER 2016

Contents

Abbreviations & Acronyms

ARPA-E	Advanced Research Projects Agency–Energy
BAU	business as usual
BECCS	Carbon beneficial forms of biomass used for bioenergy combined with carbon capture and storage
BEV	battery electric vehicle
BLM	Bureau of Land Management
BR	Biennial Report
BT	Billion-Ton Report
Btu	British thermal unit
CAFE	corporate average fuel economy
CCAC	Climate and Clean Air Coalition
CCS	carbon capture and storage
CCUS	carbon capture, utilization, and storage
CEQ	Council on Environmental Quality
CH_4	methane
CHP	combined heat and power
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
COP	Conference of the Parties
DOD	United States Department of Defense
DOE	United States Department of Energy
DOI	United States Department of the Interior
DOS	United States Department of State
DOT	United States Department of Transportation
EC-LEDS	Enhancing Capacity for Low Emission Development Strategies
EIA	United States Energy Information Administration
EOP	Executive Office of the President
EPA	United States Environmental Protection Agency
EV	electric vehicle
FCEV	fuel cell electric vehicle
FIA	Forest Inventory and Analysis
FWS	United States Fish and Wildlife Service
GCAM	Global Change Assessment Model

GDP	gross domestic product
GHG	greenhouse gas
GTM	global timber model
GW	gigawatts
GWP	global warming potential
HCFC	hydrochlorofluorocarbon
HDV	heavy-duty vehicle
HFC	hydrofluorocarbon
HUD	United States Department of Housing and Urban Development
HWP	harvested wood products
IFM	improved forest management
IPCC	Intergovernmental Panel on Climate Change
kt	kiloton
kWh	kilowatt-hour
LDV	light-duty vehicle
LEDS	low emission development strategies
LULUCF	land use, land-use change, and forestry
MAC	marginal abatement cost
MCS	Mid-Century Strategy
MELs	miscellaneous electric loads
mpg	miles per gallon
MSW	municipal solid waste
Mt	million metric tons
MW	megawatts
N_2O	nitrous oxide
NASA	National Aeronautics and Space Administration
NDC	nationally determined contribution
NEMS	National Energy Modeling System
NEPA	National Environmental Policy Act
NF_3	nitrogen trifluoride
PFC	perfluorocarbon
R&D	research and development
RD&D	research, development, and demonstration
RDD&D	research, development, demonstration, and deployment
REDD+	reducing emissions from deforestation and forest degradation
ROOTS	rhizosphere observations optimizing terrestrial sequestration
RPS	renewable portfolio standard
SF_6	sulfur hexafluoride
SNAP	Significant New Alternatives Policy
TERRA	Transportation Energy Resources from Renewable Agriculture
UNFCCC	United Nations Framework Convention on Climate Change
U.S.	United States
USDA	United States Department of Agriculture
USFAS	United States Forest Assessment System
USFS	United States Forest Service
USGCRP	United States Global Change Research Program
USGS	United States Geological Survey

Executive Summary

Human activities, particularly CO_2 emissions from fossil fuel combustion, have driven atmospheric greenhouse gas (GHG) concentration levels higher than at any time in at least 800,000 years (IPCC 2013). As a result, the Earth has warmed at an alarming rate over the past century, with average temperatures increasing by more than 0.8°C (1.5°F) (NCA 2014). The consequences are already severe. Heat waves and droughts are more common, wildfire seasons are longer and fires larger and more costly, and extreme weather is becoming more intense and unpredictable. Left unchecked, from 2000 to 2100, global average temperature increases of 2 to 5°C (3.6 to 9°F) and sea level rise of two to four feet are likely, and much larger increases are possible (USGCRP 2014, IPCC 2013). Climate change will reduce long-run economic growth and jeopardize national security.

With the adoption of the Paris Agreement in December 2015, the world took a decisive step toward avoiding the most dangerous impacts of climate change. The Paris Agreement aims to hold the increase in the global average temperature to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels. Consistent with this objective, Parties aim to balance GHG emissions sources and sinks in the second half of this century or, in effect, achieve net-zero global GHG emissions. Countries have submitted near-term targets to address GHG emissions, called "nationally determined contributions" or NDCs, and will review and extend these targets every five years. The Paris Agreement further invited countries to develop by 2020 "mid-century, long-term low greenhouse gas emission development strategies." This document answers that call, laying out a strategy to deeply decarbonize the U.S. economy by 2050.

THE UNITED STATES MID-CENTURY STRATEGY

As the world's largest economy and second largest GHG emitter, the United States plays an important role in the global response to climate change. Before President Obama entered office, forecasts projected that U.S. emissions would grow indefinitely. Instead, carbon pollution from energy is down 9 percent since 2008. The economy has grown by 10 percent over this period, proving that emissions reductions can co-exist with a strongly growing economy. The United States has set targets to reduce GHG emissions in the range of 17 percent in 2020 and 26-28 percent in 2025, with both goals defined relative to 2005 levels. As described in the U.S. Second Biennial Report (DOS 2016), the United States is on track to achieve its 2020 target and has laid the foundation for achieving its 2025 target. Individual U.S. states have also taken important actions to reduce GHG emissions, such as California's economy-wide Global Warming Solutions Act and the nine-state Regional Greenhouse Gas Initiative that addresses power sector emissions in the Northeast, as well as renewable portfolio standards in 29 states and energy efficiency resource standards in 20 states.

At the same time, the United States recognizes the need for deeper emissions reductions to constrain global temperature increases. In 2009, the United States joined the "Group of Eight" nations in calling for global emissions reductions of 50 percent by 2050, including reductions of 80 percent or more by developed countries. The U.S. NDC to the Paris Agreement noted that a 26-28 percent reduction in 2025 is consistent with a straight-line emissions reduction pathway to economy-wide emission reductions of 80 percent or more by 2050. In keeping with these previously stated objectives, the United States is presenting a mid-century strategy (MCS) that envisions economy-wide net GHG emissions reductions of 80 percent or more below 2005 levels by 2050.

The United States MCS charts a path that is achievable, consistent with the long-term goals of the Paris Agreement, and an acceleration of existing market trends. It will require increasingly ambitious decarbonization policies and support for continued innovation. The pace of emissions reductions will need to double after 2020 to achieve the 2025 target, and the United States will need to sustain that accelerated pace through 2050.

The MCS demonstrates how the United States can meet the growing demands on its energy system and lands while achieving a low-emissions pathway, maintaining a thriving economy, and ensuring a just transition for Americans whose livelihoods are connected to fossil fuel production and use. It also shows how the momentum of technological progress created by global commitments to low-carbon innovation and policies will enable increasingly ambitious climate action from all countries.

DEVELOPING A VISION FOR 2050

The mid-century vision described in this report is grounded in decades of research and analysis by the U.S. government. It draws heavily on peer-reviewed academic literature and is informed by a wealth of studies on the decarbonization of energy systems and land sector carbon dynamics. The MCS was informed by the input received at a series of stakeholder listening sessions with non-governmental and private sector organizations in the summer of 2016 and by ongoing collaboration with Canada, Mexico, and other nations that are developing mid-century strategies.

Underpinning the MCS vision is a set of low-GHG pathways developed using up-to-date data and modeling of the energy and land sectors. We explore numerous pathways due to uncertainties related to technologies, economic conditions, and social dynamics over the coming decades. We envision flexible policies that support a broad portfolio of existing and emerging low-GHG technologies and enable shifts in course as technologies evolve over time.

The purpose of the MCS analysis is not to predict near-term policymaking, model the future U.S. energy and land sectors with precision, or encompass the full range of possible low-GHG pathways, but rather to describe key opportunities and challenges associated with our illustrative pathways, and highlight findings that are robust across scenarios. The MCS scenarios include numerous pathways to an 80 percent reduction below 2005 levels in 2050 (including an "MCS Benchmark" scenario that we use as a basis for discussion and comparison throughout this report), and a "Beyond 80" scenario that shows deeper emissions reductions enabled by the innovation prompted by greater global climate action.

DRIVING DOWN NET GHG EMISSIONS

Achieving deep economy-wide net GHG emissions reductions will require three major categories of action:

I. **Transitioning to a low-carbon energy system**, by cutting energy waste, decarbonizing the electricity system and deploying clean electricity and low carbon fuels in the transportation, buildings, and industrial sectors;

II. **Sequestering carbon through forests, soils, and CO_2 removal technologies**, by bolstering the amount of carbon stored and sequestered in U.S. lands ("the land sink") and deploying CO_2 removal technologies like carbon beneficial bioenergy with carbon capture and storage (BECCS),[1] which can provide "negative emissions"; and

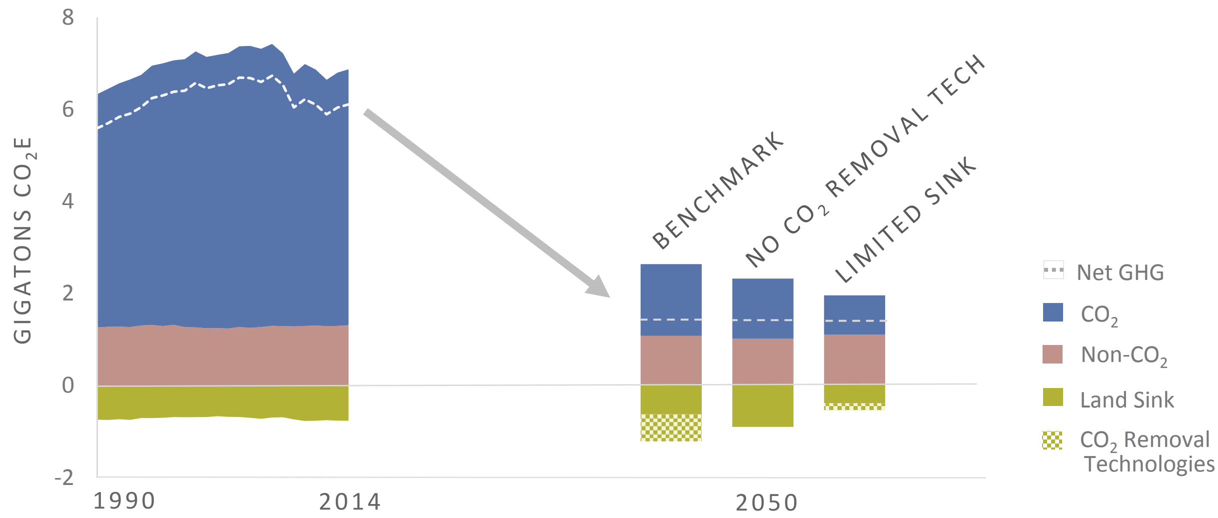
III. **Reducing non-CO_2 emissions**, such as methane, nitrous oxide, and fluorinated gases, which result mainly from fossil fuel production, agriculture, waste, and refrigerants.

Figure E1 displays three illustrative pathways for achieving 80 percent GHG emissions reductions by 2050. All three portray the transformation to a low-carbon energy system, with reductions in energy system CO_2 emissions of 74 to 86 percent across scenarios. Greater success in delivering negative emissions through the land sector sink and CO_2 removal technologies eases the burden on GHG emissions reductions in other sectors. However, since the potential for increased land sector carbon sequestration remains uncertain and the economic viability of negative emissions technologies remains to be demonstrated, we also plan for outcomes in which our ability to achieve negative emissions is limited. The success of the MCS is therefore not contingent upon the successful emergence of BECCS or any other single technology.

In this report, we outline the critical technologies and strategies required for achieving at least 80 percent reductions by 2050, highlighting in each area how the United States can cost-effectively accelerate innovation, drive down emissions, and maintain and enhance the land sink. A significant portion of this report is devoted to the actions needed in the land sector, including the development of carbon-beneficial forms of biomass and negative emissions technologies, because they have not received as much in-depth treatment elsewhere.

[1] Throughout this and other chapters when we refer to biomass or bioenergy used under the Mid-Century Strategy, we are indicating only those sources of biomass that result in net reductions of CO_2 emissions to the atmosphere, or "carbon beneficial forms of biomass."

FIGURE E1: U.S. NET GHG EMISSIONS UNDER THREE MCS SCENARIOS



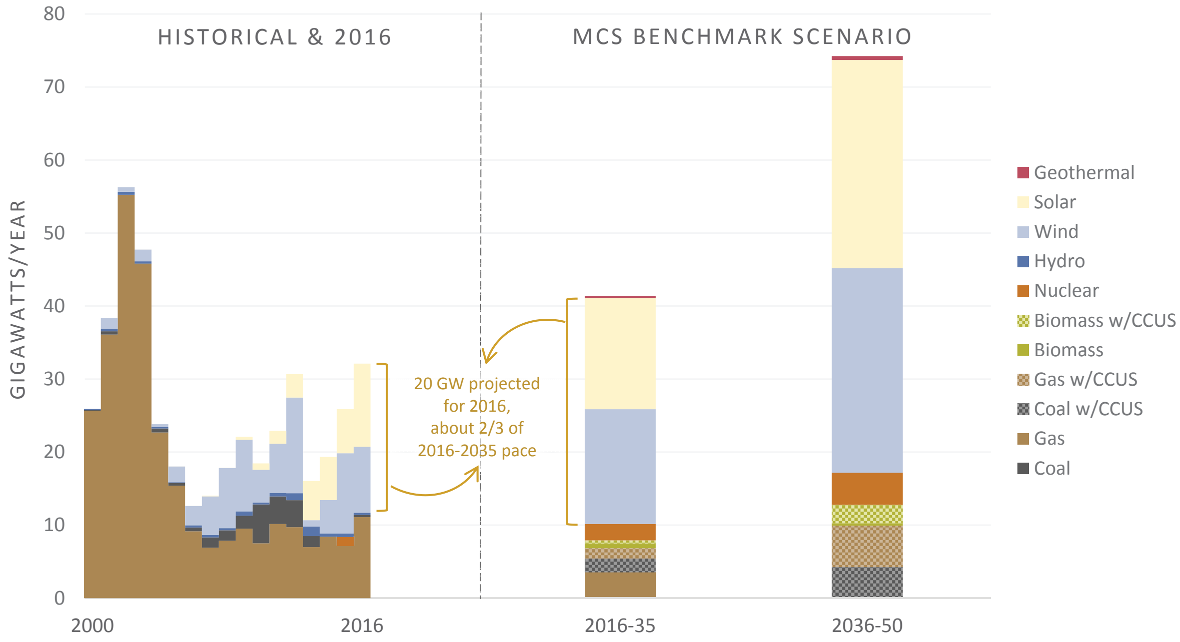
Multiple pathways to 80 percent GHG reductions by 2050 are achievable through large reductions in energy CO_2 emissions, smaller reductions in non-CO_2 emissions, and delivering negative emissions from land and CO_2 removal technologies. Note: "No CO_2 removal tech" assumes no availability of negative emissions technologies like BECCS.

TRANSITION TO A LOW-CARBON ENERGY SYSTEM

The energy system—including electricity, residential and commercial buildings, industry, and transportation—is responsible for about 80 percent of U.S. GHG emissions. The MCS envisions deep emission reductions through the following three levers:

- **Cutting energy waste:** Energy efficiency improvements enable the energy system to provide the services we need with fewer resources and emissions. Over the past several years, the United States has demonstrated that programs and standards to improve the energy efficiency of buildings, appliances and vehicles can cost-effectively cut carbon pollution and lower energy bills, while maintaining significant support from U.S. industry and consumers. Technological advancements will further expand the opportunities for cost-effective energy efficiency improvements. "Smart growth" strategies can also reduce the country's structural energy needs, for example, through improved urban design that supports alternative transit options. In the MCS Benchmark scenario, primary energy use declines by over 20 percent between 2005 and 2050.
- **Decarbonizing the electricity system:** By 2050, nearly all fossil fuel electricity production can be replaced by low carbon technologies, including renewables, nuclear, and fossil fuels or bioenergy combined with carbon capture, utilization and storage (CCUS). Current electricity grids can handle near-term rapid expansion of variable energy sources like solar and wind, and with additional flexibility through, for example, demand response, electricity storage, and transmission improvements, variable renewables have the potential to provide the majority of our electricity by mid-century (NREL 2012). Figure E2 shows the annual average additions in electricity generating capacity in the MCS Benchmark scenario. The corresponding electricity generation mix in 2050 includes significant contributions from renewables (55 percent), nuclear (17 percent), and fossil fuels with CCUS (20 percent). While public policies will help to achieve this mix, existing market trends toward lower cost clean electricity will also play a critical role.
- **Shifting to clean electricity and low-carbon fuels in transportation, buildings, and industry:** The vast majority of energy for transportation is currently provided by petroleum, while the industry and buildings sectors are powered by a mix of fuels including natural gas, coal, petroleum, and electricity. With a clean electricity system comes opportunities to reduce fossil fuel usage in these sectors: for example, electric vehicles displace petroleum use and electric heat pumps avoid the use of natural gas and oil for space and water heating in buildings. The electricity generating capacity additions displayed in Figure E2 are therefore needed not only to decarbonize the electricity sector but also to electrify the buildings, transportation, and industrial sectors. Other low-carbon fuels like hydrogen and carbon-beneficial forms

FIGURE E2: AVERAGE ANNUAL CAPACITY ADDITIONS BY FUEL, HISTORICAL AND MCS BENCHMARK SCENARIO



Note: 2016 data are AEO 2016 reference case projections (EIA 2016a; MCS analysis).

of biomass will also play an important role, particularly for energy uses that are difficult to electrify, such as aviation, long-haul trucking, and heat production in certain industrial sectors. In the MCS Benchmark scenario, direct fossil fuel use (i.e., not including electricity generated using fossil fuels) decreases by 58 percent, 55 percent, and 63 percent in buildings, industry, and transportation, respectively, from 2005 to 2050.

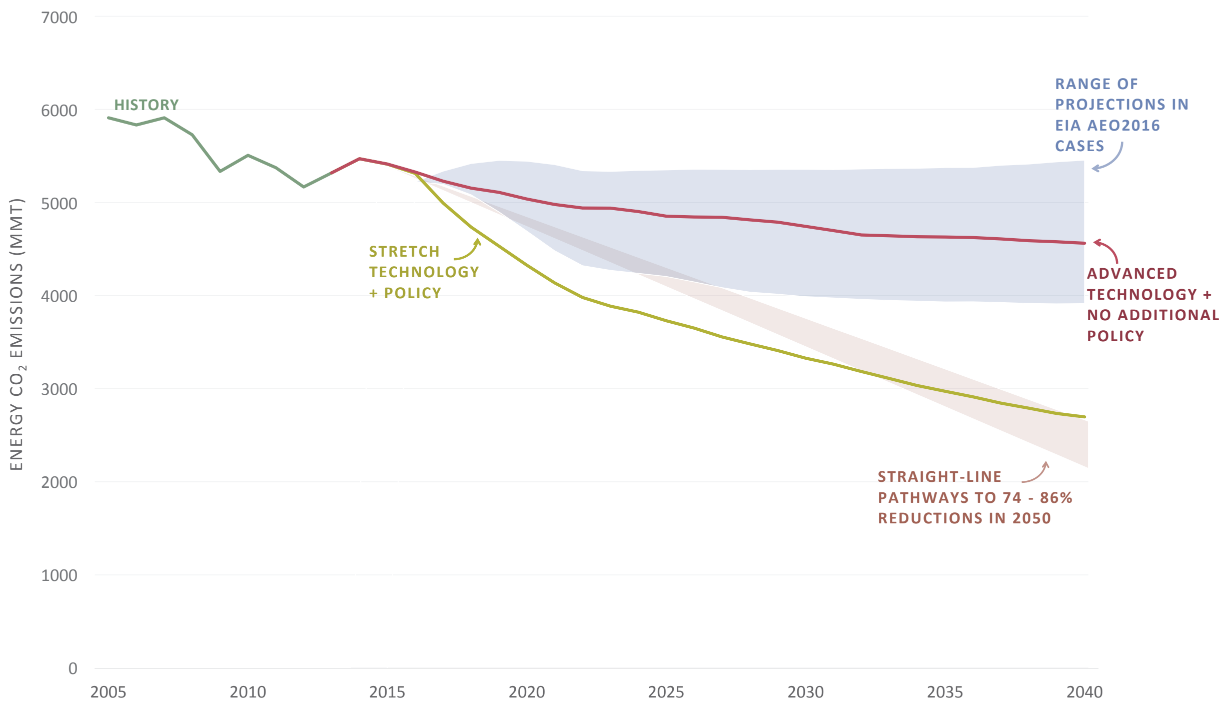
The United States will achieve this energy transformation by (1) rapidly scaling investment in low-carbon innovation to deliver lower-cost technology options and (2) implementing decarbonization policies that continue to drive the deployment of efficient, low-carbon energy technologies.

U.S. government-funded research, development, and demonstration (RD&D) has played a foundational role in spurring technological advances throughout the last century. With the full power of U.S. RD&D efforts unleashed on clean energy technologies, consistent with the Mission Innovation commitment to double clean energy RD&D spending, we can develop new technologies that will increase the pace and reduce the costs of decarbonization. In addition, potential high impact technologies such as CCUS, advanced nuclear, and second generation biofuels are in early stages of development or commercial deployment; to achieve meaningful scale by mid-century, deployment programs may be needed to bring the first set of commercial-scale facilities to market.

Figure E3 shows that energy CO_2 emissions under current near-term policies[2] (blue shading) are not yet on a pathway to 80 percent reductions in net GHG emissions (red shading), confirming that longer-term and more ambitious policies are needed to achieve our mid-century goals. Modeling tools commonly utilize carbon prices as a proxy for a range of potential decarbonization policies.[3] An analysis of the U.S. energy system by the Department of Energy shows that combined with successful innovation policies (including the Mission Innovation commitment), an effective carbon price that starts at $20 per metric ton in 2017 and increases steadily over time would be sufficient to put energy CO_2 emissions on a pathway largely consistent with the MCS vision (Figure E3). The actual costs of emissions reductions could be higher or lower, depending on the rate of technological progress, the deployment of complementary policies, and numerous other factors.

[2] The range of projections under current policies is from the U.S. EIA's Annual Energy Outlook 2016, which only includes policies finalized as of late 2015. For example, it includes vehicle GHG emissions/fuel economy standards through 2025. EIA's model is currently being updated to include years 2040 to 2050.
[3] The technological progress embedded in the model inputs also assumes sustained investment in RDD&D and other complementary policies to bring down technology costs.

FIGURE E3:
ENERGY CO_2 EMISSIONS UNDER CURRENT AND EXPANDED AMBITION POLICIES



Modeling by the U.S. Department of Energy in National Energy Modeling System. "Advanced Technology + No Additional Policy" assumes technologies achieve current DOE program goals. "Stretch Technology + Policy" assumes (1) carbon price of $20 per metric ton, starting in 2017 and increasing at 5 percent per year; (2) additional support for technological progress (such as through Mission Innovation). MCS scenarios in GCAM that achieve 80 percent reductions in economy-wide net GHG emissions show energy CO_2 reductions of 74 to 86 percent.

Combined with market trends, federal sector-specific regulations such as emissions standards for power plants, fuel economy standards, and appliance efficiency standards have achieved substantial emissions reductions. Future administrations have authority under existing statutes to continue using similar tools with increasing ambition which, along with expanded action at the local, state and regional level, could build a pathway to 80 percent emissions reductions or more. A key priority for future policymakers is a transition to efficient carbon pricing over time, either by further optimizing an increasingly ambitious state/local/sectoral approach, or by moving to an economy-wide policy mechanism. Carbon pricing will enable cost-effective emission reductions through market forces that encourage the development and deployment of the most cost-effective low carbon solutions across the economy. In any scenario, the United States will need complementary policies as well, including programs and standards that encourage cost-effective energy efficiency improvements and infrastructure investments that support the emergence of low carbon solutions.

SEQUESTERING CARBON THROUGH FORESTS, SOILS, AND CO_2 REMOVAL TECHNOLOGIES

U.S. landscapes will play an increasingly important role in supporting economy-wide decarbonization over the next 30 years. Some land uses and activities emit CO_2 to the atmosphere and others remove it by sequestering CO_2 in trees, plants, soils, and products. In aggregate, U.S. lands have been a net "carbon sink" (more CO_2 is sequestered than emitted) for the last three decades, largely due to millions of acres shifting into forest from other uses and the continued growth of trees on already forested lands (Oswalt et al. 2014). In 2014, the U.S. land carbon sink sequestered nearly 0.8 Gt of CO_2, offsetting 11 percent of economy-wide GHG emissions (EPA 2016).

With early and sustained effort, maintaining and enhancing the land carbon sink beyond today's levels could offset up to 45 percent of economy-wide emissions in 2050, with U.S. forests playing a central role. Using three distinct land sector models and multiple scenarios, we find that this objective could be achieved by expanding U.S. forests by 40-50 million acres over the next 20-35 years. This would recover one-third of U.S. forestland lost since 1850. U.S. forests expanded by nearly 1 million acres annually over 1987-2012 (Figure E4), with federal agencies supporting tree planting on over 300,000 acres annually over 2006-2011 (Oswalt et al. 2014). An expansion of resources for these efforts will be needed if the country is to maintain the

FIGURE E4:
HISTORICAL FOREST EXPANSION COMPARED TO POTENTIAL MCS FOREST EXPANSION

Note: Historic data from 1800 to 2007 based on Kellogg (1909) and Oswalt et al. (2014). To account for uncertainty in observed forest expansion after 2007, this figure shows an average annual increase in forest area from 2007-2012 that reflects a longer-term average trend based on three separate data sources, including the FIA (1987-2007) as found in Oswalt 2014, the 2007 USDA Major Land Use Database (1992-2007) (Nickerson et al. 2011), and the 2015 FAO Global Forest Resources Assessment (1990-2015) (FAO 2016). The resulting average annual increase for the 2007-2012 period is 1.2 million acres/year. 2017-2035 projection based on analysis of forest expansion that could support the MCS Benchmark scenario. Forest expansion is assumed to occur before 2035 in order to achieve desired 2050 carbon sink levels.

current strength of its annual forest carbon sink. Additional forestry activities also contribute to emissions reductions, like increasing carbon storage levels in working forests and using wood to offset fossil fuel-intensive products.

Emerging research also points to the opportunity to significantly increase carbon stored in cropland and grassland soils, creating potential to enhance agricultural productivity while generating a carbon sink of hundreds of millions of tons of CO_2 annually by 2050. Breakthrough innovations to increase soil mass and depth of commodity crops could massively expand U.S. soil carbon sink potential to multiple gigatons of carbon sequestration by mid-century, while also helping to improve soil quality, water and nutrient retention, and crop yields, all with minimal competition for land use.

U.S. cropland, pasture, and forests can also support biomass supply to help decarbonize the energy sector, including delivering negative emissions through BECCS. New policies and programs will be required to ensure that biomass production is balanced with other critical priorities, including a robust land carbon sink, thriving wildlife habitat, sufficient food production, and other key land-based services. For the U.S. MCS, we find that biomass production in the range of 1 billion dry tons can be consistent with all of our land sector objectives, assuming efficient land management. Carbon accounting protocols based on the most up-to-date science

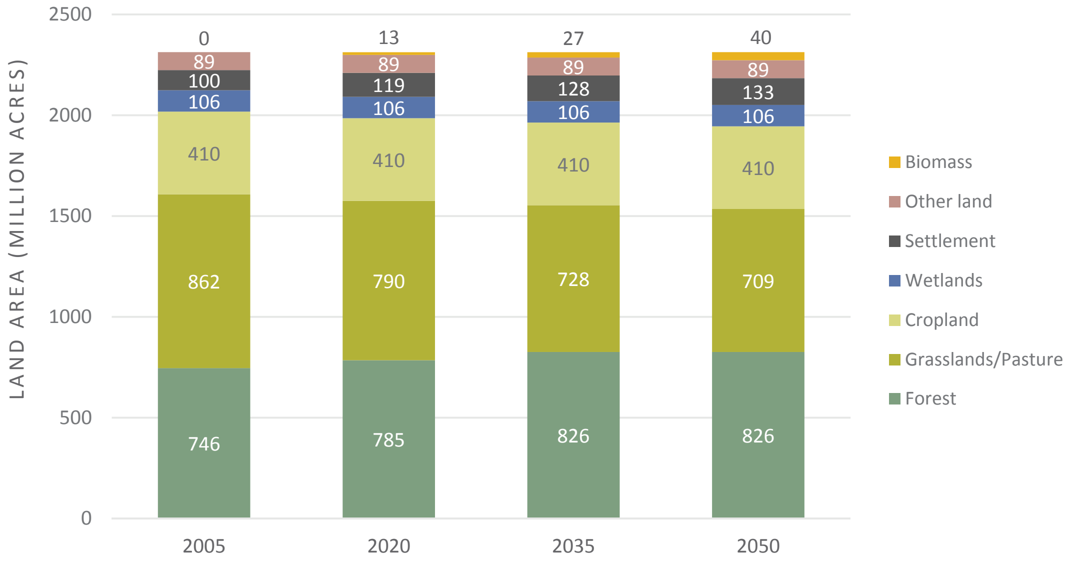
BOX E1: THE ROLE OF CO_2 REMOVAL TECHNOLOGIES

In addition to the land carbon sink, CO_2 removal technologies can capture atmospheric CO_2 and either sequester it permanently in geologic formations or convert it for use in products. There are many potential methods, including pairing carbon-beneficial forms of bioenergy plus carbon capture and storage (BECCS), direct air capture, and accelerated rock weathering (Clarke et al. 2014). There is currently no large-scale deployment of these net carbon-negative technologies, and many questions remain regarding their potential costs, adverse side effects, and co-benefits. However, most IPCC scenarios rely on CO_2 removal technologies to stay below 2 °C of warming (IPCC 2014).

BECCS is the most mature and well-understood CO_2 removal technology to date, making it a useful representation of CO_2 removal technologies in the MCS analysis; other options may ultimately prove to be less expensive or more scalable. Many CO_2 removal technologies are still nascent and may require substantial RD&D before they would be ready for mass deployment. Investments in RD&D today can help to identify key negative emissions opportunities and provide an “insurance policy” in the event that emissions reductions are needed more rapidly than envisioned or if alternative mitigation strategies are difficult to achieve.

The development of CO_2 removal technologies is not a justification to continue emitting freely. They represent a suite of strategies that complement rather than substitute for emissions reductions. Even with extensive RD&D, we expect to have many years of cheaper emissions reduction opportunities to exploit in the energy and land sectors before needing to mobilize these technologies at scale.

FIGURE E5:
POTENTIAL 2050 LAND USE CHANGES CONSISTENT WITH THE MCS



The results presented here exemplify a potential future U.S. land use scenario that could be consistent with the U.S. MCS vision, reflecting 50 million acres of forest expansion, 40 million acres of biomass production, 17 million acres of developed land expansion, and constant cropland levels compared to 2015 areas. Such a future would need to go hand in hand with strategies to minimize impacts to natural grasslands, natural forests, wetlands, and other high-value conservation areas.

can ensure carbon beneficial forms of biomass, or only those sources that result in net reductions of CO_2 to the atmosphere, are utilized to support U.S. decarbonization.

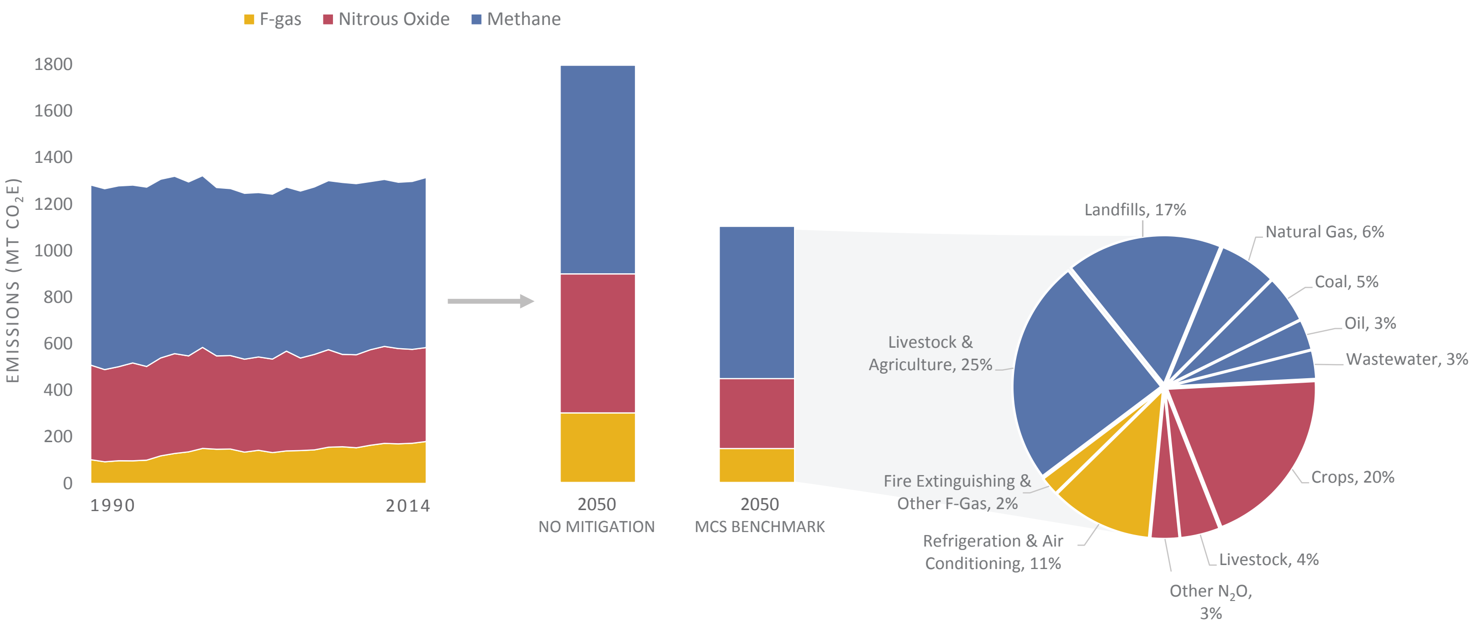
An illustrative 2050 land use scenario consistent with MCS goals, which could entail 50 million acres of forest expansion and 40 million acres of biomass production from 2015 areas, would need to be managed carefully (Figure E5). However, these changes can be made ecologically and economically feasible by focusing on opportunities to deliver multiple products and services on the same acre, including agroforestry, precision agriculture, and bioenergy crop-pasture rotational strategies. For example, in Iowa alone, an estimated 27 percent of cropland, or 7 million acres, may not be profitable in commodity crop production but could be well-suited to perennial grasses or agroforestry (Brandes et al. 2016). Focusing nationally on such areas could minimize land use competition and help increase rural landowner incomes while delivering environmental benefits like improved soil health and reduced nutrient runoff.

Taking greater climate action in the land sector requires incentive structures to encourage farmers, ranchers, and forest owners to sequester more carbon, along with appropriate policy and carbon accounting frameworks to ensure these incentives are consistent with our long-term climate goals. This can create new revenue streams for rural communities, bolstering economic vitality in U.S. farming, ranching, and forestry sectors and creating new job opportunities for young farmers, ranchers, and foresters. The ability to support land carbon outcomes at the scale required for our 2050 goals will depend on both budgetary resources for incentives and innovative, science-based policy frameworks. An important step in this direction, consistent with previous Administration proposals, is to continue improving crop insurance and related programs in order to further incentivize producers to choose production practices that minimize climate change impacts and that achieve multiple strategic carbon, conservation, and water goals for every dollar of federal investment. Looking ahead, comprehensive climate policy could provide additional resources for land carbon and related conservation incentives.

REDUCING NON-CO_2 EMISSIONS

Methane, nitrous oxide, and fluorinated gases are powerful heat-trapping gases, currently responsible for 20 percent of total U.S. GHG emissions on a CO_2 equivalent (CO_2e) basis. Absent ambitious climate action, they are projected to increase rapidly through 2050. The Obama Administration has already taken action to reduce non-CO_2 emissions, providing an important foundation for future reductions. For example, the United States has promulgated policies to reduce methane leaks that can be costly to industry, and has collaborated with stakeholders on opportunities to reduce coalbed and agricultural emissions.

FIGURE E6: U.S. NON-CO_2 MITIGATION BY 2050, COMPARED TO "NO MITIGATION" SCENARIO



Note: "MCS Benchmark" emissions are scaled to be consistent with EPA projections data used in the Global Mitigation of Non-CO_2 Greenhouse Gases report (EPA Report 2014) in order to reflect residual non-CO_2 emissions consistent with U.S. GHG Inventory data. These projections include distinct activity assumptions from those used in GCAM model results displayed in other figures. "No Mitigation" scenarios estimates are per Deep Decarbonization Pathways Project (Williams et al. 2014).

However, there is much more to be done. The MCS envisions enhanced actions to further drive down non-CO_2 emissions. This includes new and more stringent standards and incentives to reduce methane from oil and gas production and from landfills. In 2016 EPA took the first steps in the process of developing emissions standards for existing sources in the oil and gas sector. New technology and improved agricultural practices will support farmers and ranchers in reducing methane and N_2O from livestock operations and crop production. In addition to current domestic and international programs to phase down HFCs, there are additional opportunities to address existing stock through new disposal and recycling programs and by bringing cost-effective alternative products to market.

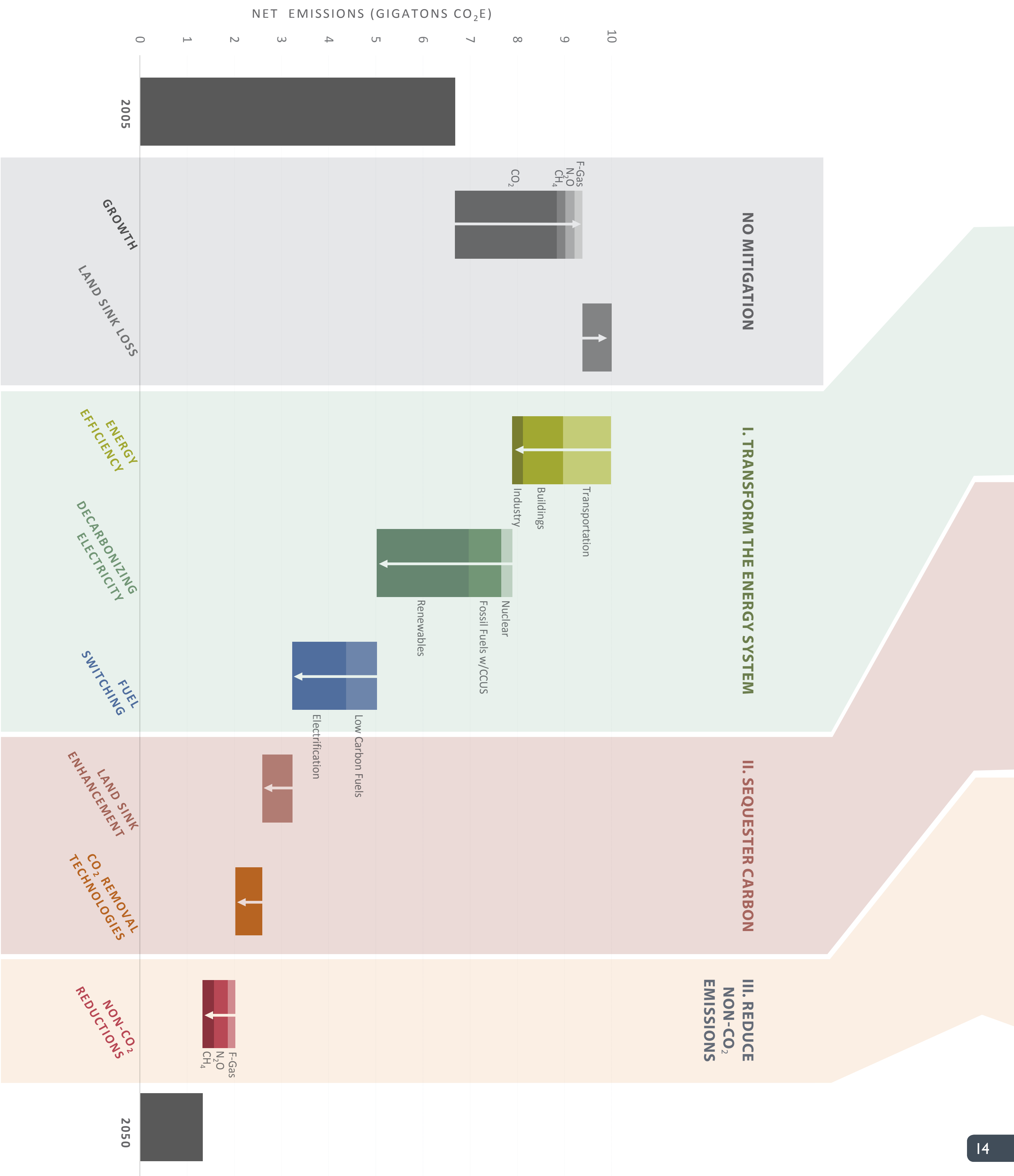
Even with ambitious action, non-CO_2 emitting sectors remain a major source of emissions in 2050, due to challenges in monitoring emissions, lack of cost-effective substitutes, and increases in food production and other drivers of emissions (Figure E6). The MCS analysis does not account for any major technological advances that may be achievable with continued innovation and policy over the next few decades. The MCS envisions increased support for RD&D to identify and pursue these opportunities at scale.

ACHIEVING DEEP DECARBONIZATION IN 2050

Figure E7 shows how the three major categories of actions described above—transitioning to a low-carbon energy system, sequestering carbon through forests, soils, and CO_2 removal technologies, and reducing non-CO_2 emissions—can all contribute to delivering reductions in net GHG emissions of at least 80 percent below 2005 levels by 2050. Figure E7 portrays the results of the MCS Benchmark scenario, just one of many different pathways to 80 percent reductions.

The MCS envisions achieving the decarbonization displayed in Figure E7 through a broad suite of cost-effective public policies and investments, discussed in detail throughout the report and summarized in Box E2. The Obama Administration has taken action across all three categories of emissions, but achieving deep decarbonization will require longer-term and increasingly ambitious policy action.

FIGURE E7: COMPONENTS OF 80 PERCENT GHG REDUCTIONS IN MCS BENCHMARK SCENARIO



BOX E2: LONG-TERM U.S. MID-CENTURY STRATEGY POLICY PRIORITIES

I. TRANSFORM TO A LOW-CARBON ENERGY SYSTEM

- Double clean energy innovation investment to yield new scaled-up solutions before mid-century for even the most challenging energy uses.
- Extend state/local policies and sectoral emissions regulations to continue driving deployment of clean technologies, shifting to economy-wide carbon pricing over time.
- Implement complementary policies to overcome barriers to the deployment of cost-effective energy efficiency and clean energy technologies.
- Modernize electricity regulatory structures and markets to encourage flexible, reliable, cost-effective, and clean electricity generation.
- Scale up targeted support, including economic and workforce development, to ensure all Americans benefit from the low-carbon energy transition.

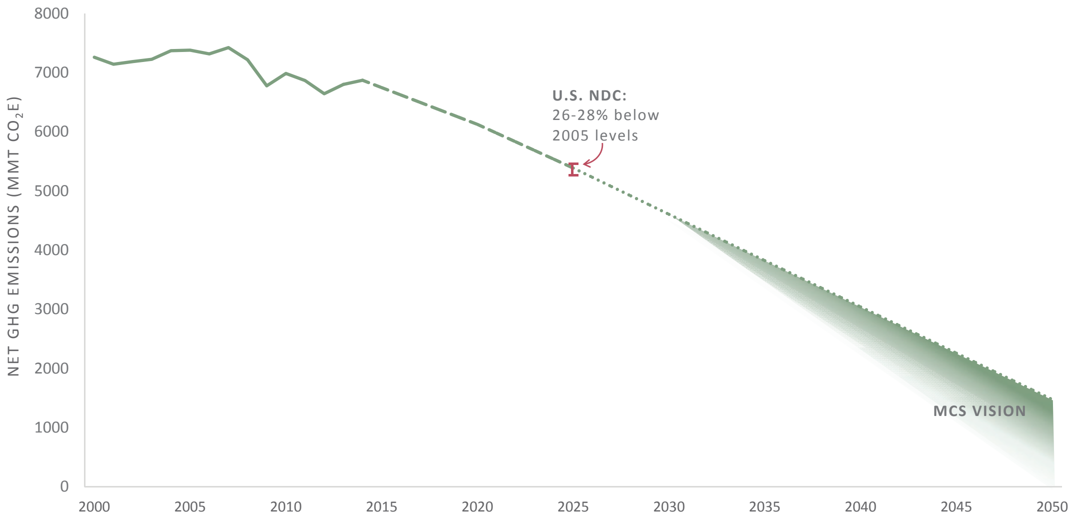
II. SEQUESTER CARBON THROUGH FORESTS, SOILS, AND CO_2 REMOVAL TECHNOLOGIES

- Ramp up durable private land carbon incentives to support forest carbon-enhancing activities and soil carbon sequestration, underpinned by science-based carbon accounting protocols and policy frameworks.
- Quickly scale up forest restoration and expansion on federal lands.
- Reduce land use competition and land use change through research and policies to increase working land productivity and promote smart urban development.
- Support data collection and research to inform future policy, including mitigation "hot spot" mapping, quantification and breakthroughs for soil carbon potential, and improved U.S. GHG Inventory capabilities.
- Support development and deployment of CO_2 removal technologies, including demonstrations and early-stage commercial deployment of carbon-beneficial BECCS.

III. REDUCE NON-CO_2 EMISSIONS

- Support RD&D to measure and monitor diffuse methane sources.
- Enhance regulations to drive down methane emissions from waste and oil and gas.
- Scale up RD&D, technical assistance, and incentives for reducing nitrogen fertilizer application through precision agriculture, slow-release fertilizer, and other alternatives.
- Scale up RD&D, technical assistance, and incentives to reduce livestock-related methane and methane capture strategies like anaerobic digesters and innovations like diet additives.
- Implement policies to phase down HFC use and properly dispose of HFC-using appliances and support RD&D for HFC alternatives.

FIGURE E8:
"BEYOND 80" MCS PATHWAY



BEYOND 80 PERCENT: OPPORTUNITY TO ACHIEVE HIGHER AMBITION

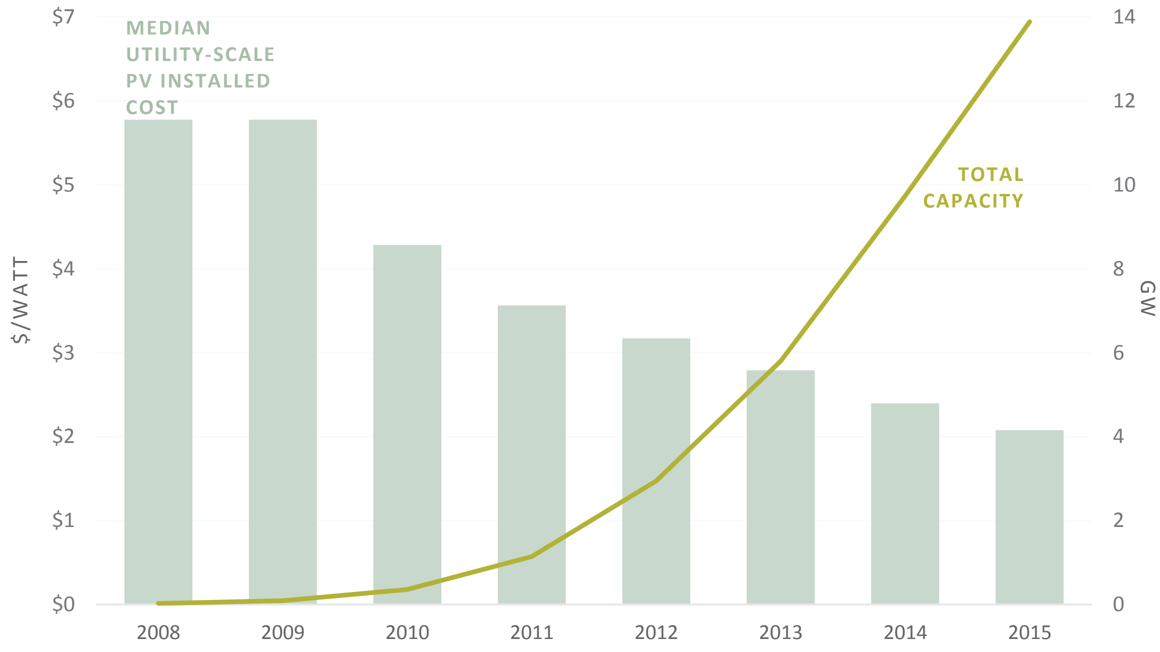
Reducing net U.S. GHG emissions to 80 percent below 2005 levels will require a concerted and comprehensive effort to transform the energy system, bolster the land carbon sink, and reduce non-CO_2 emissions in an economy experiencing strong and consistent growth. While these goals are ambitious, continued rapid clean energy technology development and deployment around the world will create a virtuous cycle in which ambition drives down costs, in turn eliciting greater ambition (Trancik 2015).

A prime example of this global virtuous cycle is the recent rapid growth of the international solar energy market. Policies in Germany and RD&D investments in the United States prompted manufacturing advances in China and elsewhere that significantly reduced solar panel costs, stimulating further increases in global demand (Graichen et al. 2016, Cox et al. 2015, CPI 2011). Now, solar energy is increasingly cost-competitive and is being deployed at a pace (over 10 GW per year in the United States) that would have been unthinkable a decade ago (Figure E9). A recent MIT study showed how the costs of solar and wind energy are likely to fall precipitously through 2030 due to the increased deployments that come out of the Paris Agreement pledges (Trancik 2015). Compared to the MIT study, the MCS Benchmark scenario conservatively assumes a slower pace of cost reductions in solar energy through 2030, despite larger global deployments. Moreover, global capacity of solar energy triples between 2030 and 2050 in the MCS Benchmark scenario, underscoring the potential for deeper cost reductions by mid-century.

Replicating this cycle across a broad portfolio of clean energy technologies could accelerate the pace of a cost-effective low carbon energy transition. To plan for this outcome, we developed an illustrative “Beyond 80” scenario (Figure E8), in which emissions reductions greater than 80 percent by 2050 are made possible by the accelerated global diffusion of low carbon solutions. Such technological progress would significantly reduce the costs of decarbonization and enable all countries, including the United States, to ratchet up policy ambition and achieve deeper emissions reductions by 2050.

The Beyond 80 pathway would entail even deeper and more rapid GHG reductions across all sectors and increase the importance of negative emissions. For example, an additional 5 GW per year of clean electricity generation capacity is needed in the Beyond 80 scenario compared to the MCS Benchmark scenario, or a 9 percent increase in annual capacity additions. However, due to greater technological progress, the total costs of building and operating power plants are roughly the same in both scenarios.

FIGURE E9: SOLAR ENERGY COSTS AND DEPLOYMENT IN THE UNITED STATES



Clean energy innovation and global ambition create a virtuous cycle of technology cost reductions, enabling emissions reductions greater than 80 percent by 2050. Source: U.S. Department of Energy (2016b). Note: Costs in real 2015 dollars.

THE MID-CENTURY STRATEGY AND THE U.S. ECONOMY

The United States can achieve rapid emissions reductions while maintaining robust economic growth. The link between economic growth and CO_2 emissions in the United States has weakened significantly over recent decades (Figure E10). During the Obama Administration, the United States has experienced a sustained period of decreasing emissions and strong economic growth for the first time in history. From 2008 to 2015, energy CO_2 emissions fell nine percent while the U.S. economy grew by 10 percent. Globally, there is evidence that this trend could be taking root as well. Over the last two years, the global economy grew by over six percent while energy emissions stayed flat.

Ambitious and sustained global action on climate change is not just an environmental priority, it is also a pro-growth economic strategy. Pursuing high-carbon strategies (or business as usual) will lead to large and possibly catastrophic damages to the future U.S. and global economies. Economic damages from climate change will arise from a range of impacts, including effects on human health, agriculture, sea level rise, and increasingly severe storms, droughts, and wildfires, among many others. Economists' estimates of the magnitude of damages (in terms of reduced consumption) of a do-nothing strategy (resulting in about 4°C warming by 2100) range from about 1 to 5 percent of global gross domestic product, incurred every year (Nordhaus 2013). Other recent studies have projected significantly larger economic consequences of unmitigated climate change (Burke et al. 2015). Such a do-nothing approach will disproportionately harm the most vulnerable Americans, including children, the sick, the poor, and the elderly (USGCRP 2014, 2016).

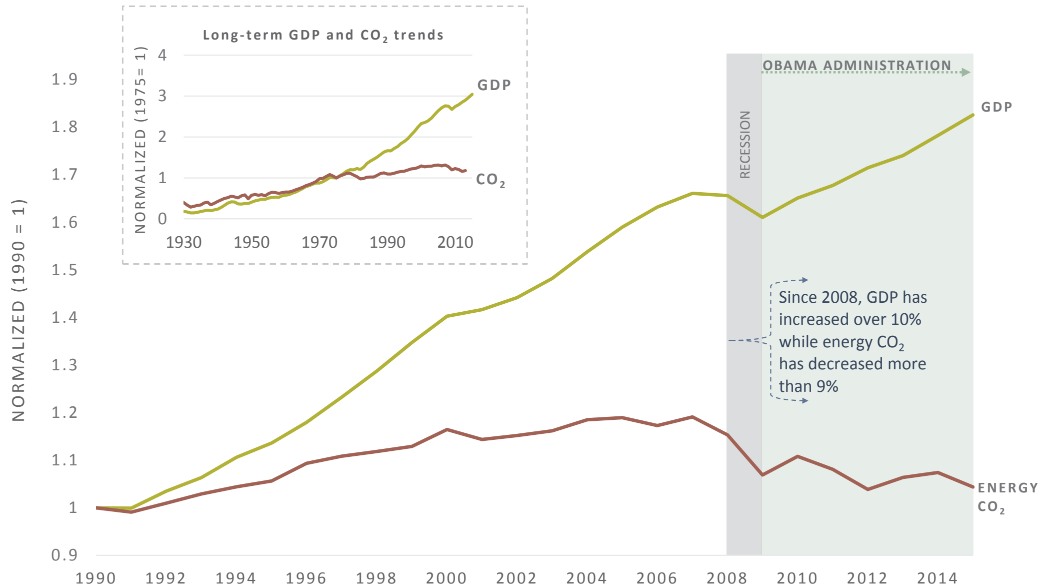
Of course, the transition to a low-GHG economy will require substantial shifts in resources. The electric power sector is a prime example, where we need to invest in decarbonizing the electricity system and increasingly shift to using electricity in the buildings, transportation, and industrial sectors over time. The MCS analysis finds annual average investments in electricity generating capacity of 0.4 to 0.6 percent of GDP from 2016 to 2050, which compares to 0.2 percent of GDP from 2000 to 2013 (IEA 2014). At the same time, expenditures on fossil fuels will decline considerably.

The following principles can help to ensure that decarbonization policies create and preserve economic opportunities for all Americans:

- **Implement market-based policies that reward outcomes.** Market-based policies encourage emissions reductions where and when they are most cost-effective, and they provide opportunities for all industries to contribute to a low-GHG economy. This leverages the ingenuity of U.S. businesses, which have repeatedly met stringent environment and safety standards with cost-saving innovations that often improved businesses' bottom lines.
- **Act as quickly as possible.** Increasing policy ambition sooner rather than later will benefit the U.S. economy. The MCS envisions an energy system transition over many decades, sending early signals to investors and workers and thus avoiding abrupt shifts in employment. Investing quickly in a lower-carbon infrastructure will ease the long-term transition and avoid the early retirement of productive assets later on. Similarly, in the land sector, taking swift action to increase carbon sequestration now will deliver much larger dividends by mid-century than if we delay. According to a recent Council of Economic Advisers (CEA) report, every decade of delayed climate policy increases the costs of meeting a given emissions target by about 40 percent.
- **Support Americans vulnerable to a low-GHG transition.** By implementing the MCS over many decades, most American workers and businesses will have ample time to adjust to a changing economy, as they would need to do over any 34-year period. However, additional support may be needed for low-income households and for Americans who are particularly reliant on a high carbon economy. A prime example is President Obama's proposed Power Plus Plan, a package of investments in economic and workforce development targeted to coal communities and workers, abandoned coal mine reclamation, and health and retirement security for coal miners and their families.

FIGURE E10:

U.S. ENERGY CO_2 EMISSIONS AND GROSS DOMESTIC PRODUCT

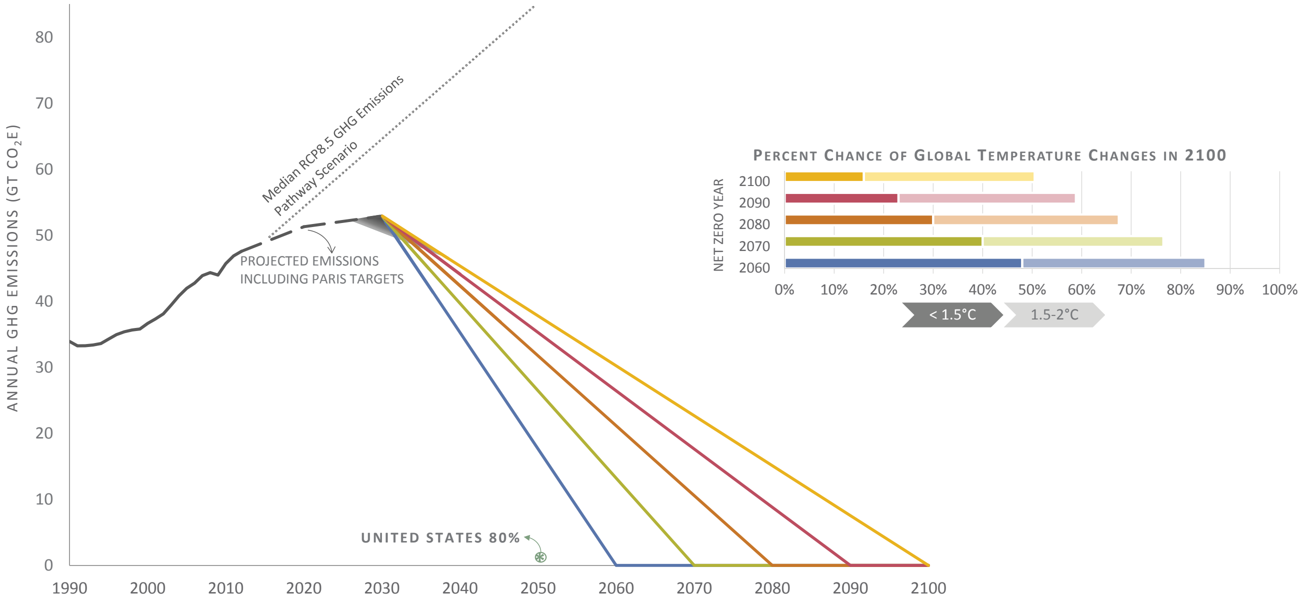


Sources: GDP data per U.S. Bureau of Economic Analysis; emissions data per Carbon Dioxide Information Analysis Center and U.S. Energy Information Administration.

INTERNATIONAL COOPERATION ON CLIMATE

Keeping global temperature increases well below 2°C in accord with the Paris Agreement is likely to require global peaking of greenhouse gas emissions no later than 2030, with rapid reductions thereafter to achieve net-zero GHG emissions as soon as possible. Figure E11 shows that if all countries follow emissions pathways implied by their NDCs under the Paris Agreement and then implement rapid reductions starting in 2030, reaching net-zero global GHG emissions in 2080 would mean a roughly two-thirds chance of limiting warming to below 2°C in 2100. This MCS puts the United States on a trajectory to achieve net-zero

FIGURE E11: GLOBAL TRAJECTORIES TO NET-ZERO GHG EMISSIONS AND PROBABILITY OF GLOBAL TEMPERATURE CHANGES



The United States MCS puts the nation on a path consistent with a successful global outcome. Achieving the Paris Agreement temperature goals will require increasing global ambition leading to 2030 and steep reductions to net-zero global GHG emissions following 2030. We show the probability of staying below 2°C and 1.5°C across global scenarios by 2100. While there could be an overshoot of the Paris Agreement temperature objectives before 2100, achieving net-zero GHG emissions globally could bring temperatures below peak levels in 2100 and beyond.

emissions decades before that. If all other countries adopted the 2020-2050 rate of U.S. decarbonization starting in 2030, global net-zero GHG emissions could be achieved by 2070.

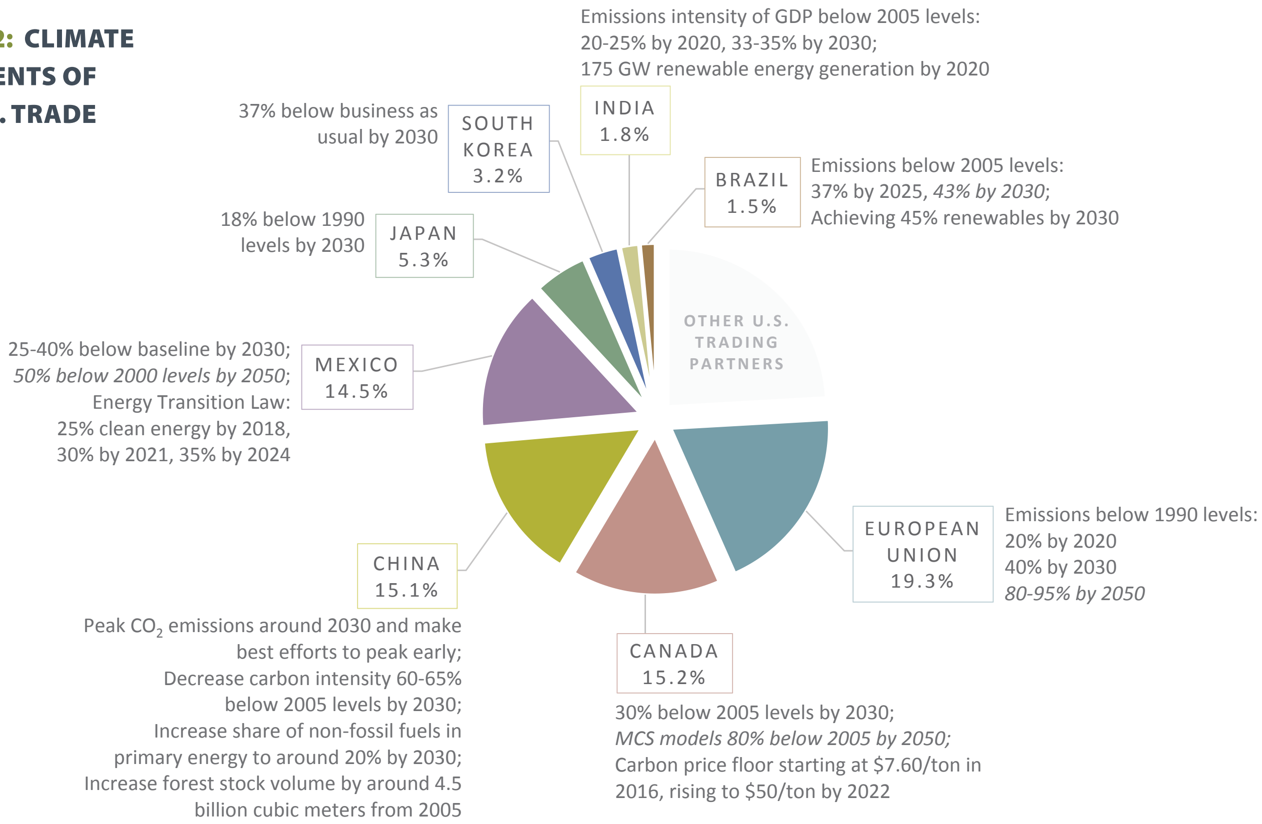
Figure E11 also shows that if all countries follow their current NDCs, global emissions must sharply decline after 2030 to put the Paris Agreement temperature goals within reach. This underscores the importance of increasing global action between now and 2030, as reflected by the shaded triangle on the figure.

The United States is releasing its MCS now in concert with two of its largest trading partners and economically integrated neighbors, Canada and Mexico. Both countries are implementing ambitious domestic actions, including a new Canadian carbon price rising to $50 per metric ton of CO_2 by 2022 and Mexico's Energy Transition Law, which will increase the share of clean electricity from 20 percent to 35 percent by 2024. The other major trading partners of the United States have set ambitious targets as well (Figure E12), underscoring the economic opportunities of a low carbon economy.

Germany is also releasing its MCS this week and many other countries, including China, India, the United Kingdom, and Norway, have either announced intentions to develop mid-century strategies or are already developing them, with plans to release in the coming months and years. We urge all nations to join in developing ambitious and transparent mid-century low-GHG emissions strategies and releasing them by 2018.

Long-term planning is an iterative process; this report should not be viewed as a final, fixed product, but rather the beginning of an ongoing effort. We encourage all countries to undertake similar ongoing efforts and to revisit their mid-century strategies at least every five years to assess progress and increase ambition wherever possible. We hope the U.S. MCS serves as a useful template for other countries undertaking long-term climate strategies and look forward to continued engagement on the development of our visions for a low-carbon future.

FIGURE E12: CLIMATE COMMITMENTS OF MAJOR U.S. TRADE PARTNERS



Note: Segment size represents country's contribution to U.S. total trade volume (U.S. Census Bureau 2016). Total trade equals the value of imports from country plus U.S. exports to country. Remainder of circle is comprised of other trading partners, the large majority of which have also developed NDCs. Aspirational goals are indicated in italics.

1

Introduction

In the 1800s, scientists discovered that carbon dioxide (CO_2) and other heat-trapping gases in the atmosphere affect Earth's temperature through "the greenhouse effect." By 1957, careful measurements confirmed that CO_2 concentrations in the atmosphere and global temperatures were gradually increasing in tandem. By the turn of the 21st century, overwhelming scientific evidence had documented the existence and cause of global warming—the climate is changing at a rate not seen before by human civilization, caused by releases of CO_2 and other greenhouse gases (GHGs) from human activities such as the burning of fossil fuels and clearing of forests and grasslands.

Recognizing the need for global action, countries around the world came together at the First World Climate Conference in 1979, calling on all governments "to foresee and prevent potential man-made changes in climate that might be adverse to the well-being of humanity." In 1992, countries adopted an international treaty, the United Nations Framework Convention on Climate Change (UNFCCC), with the objective of "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system."

Despite these efforts, GHG emissions have continued to climb, and temperatures have increased along with them. Fifteen of the sixteen warmest years on record occurred between 2000 and 2015, and periods of extreme heat occur more regularly. The warming of the oceans and melting of glaciers is causing sea levels to rise, making flooding more common when storms hit (U.S. Global Change Research Program 2014).

Galvanized by over a century of science and growing international concern, in December 2015 more than 190 countries came together in Paris to adopt the most ambitious climate change agreement in history. To avoid the worst effects of climate change, Parties to the Paris Agreement aim to undertake the rapid reductions in GHG emissions needed to achieve a balance between anthropogenic emissions and removals by sinks by the second half of this century, or "net-zero" GHG emissions before 2100. The Paris Agreement aims to limit the increase in the global average temperature to well below 2°C and to pursue efforts to limit the increase to 1.5°C. At the core of the Paris Agreement are country-specific targets or "nationally determined contributions" (NDCs) for 2025 or 2030, and intentions to update these targets in five-year cycles.

In addition to these near-term contributions, countries are also asked to engage in long-term planning. To this end, the Paris Agreement invites Parties to develop mid-century, long term low greenhouse gas emission development strategies. These mid-century strategies will help to ensure that short-term targets are not designed as ends in themselves, but rather as means to more ambitious long-term actions to limit net GHG emissions in order to meet the Paris Agreement temperature objectives.

This report presents the United States' mid-century low-GHG emissions strategy (MCS), providing an ambitious vision to reduce net GHG emissions by 80 percent or more below 2005 levels by 2050.

BENEFITS OF LIMITING CLIMATE CHANGE

Left unchecked, from 2000 to 2100, global average temperature increases of 2 to 5°C (3.6 to 9°F) and sea level rise of two to four feet are likely, and much larger increases are possible (USGCRP 2014, IPCC 2013). Climate change will reduce long-run economic growth and jeopardize national security. Effects will include more frequent and severe heat waves, droughts, floods and extreme weather events, degraded air quality, changing rainfall patterns, and disrupted ecosystems, all of which pose risks to human health and welfare. Changes to the climate will disproportionately harm the most vulnerable Americans, including children, the sick, the poor, and the elderly (USGCRP 2014, 2016). According to the Pentagon, conflicts over natural resources and refugee flows are likely to increase around the world, and impediments to political stability such as poverty, environmental degradation, and weak political institutions will be heightened, making climate change an urgent and growing national security risk (DOD 2015a, 2015b).

If the international community fails to take additional strong action to combat climate change, the damages from climate change will increase as temperatures rise, and scientists warn of critical thresholds (or "tipping points") beyond which abrupt and/or irreversible changes to the climate or the biosphere could occur with catastrophic consequences for human civilization (Kopp et al. 2014). Such risks include mass extinctions (Kopp et al. 2014), dramatic changes in ocean currents, and the rapid melting of the Antarctic ice sheet (DeConto and Pollard 2016). The exact conditions that would lead to such global catastrophic consequences are poorly understood because they are so far outside the range of conditions of the readily observable past.

But uncertainty is no reason for inaction. Just as we take precautions to avoid major risks in our own lives, and just as we expect governments to take precautions to avoid major risks to their citizens, deep decarbonization will protect Americans against the extreme risks of climate change.

The benefits of decarbonizing the U.S. economy are not limited to avoided climate change. In addition to CO_2, the combustion of fossil fuels emits harmful air pollutants such as sulfur dioxide, nitrogen oxide, and particulate matter. Air pollution is linked to premature mortality and a range of harmful health effects, including respiratory and cardiovascular problems. In the United States, the number of particulate matter and ozone-related deaths attributed to emissions from power plants and mobile sources alone is 36,000 per year (Fann, Fulcher, and Baker 2013).[4] With a decarbonized energy system would come cleaner air, and thus a healthier and more productive workforce (EPA 2011).

The continued development of cost-effective clean transportation fuels can help shield the U.S. economy from the economic harm caused by oil market volatility (Hamilton 1983, 2009; Kilian and Vigfusson 2014) and reduce our reliance on oil from foreign governments. Any serious strategy to achieve long-term decarbonization necessarily involves sustained reductions in oil consumption and thus the transition to sources of energy with less volatile prices (DOE 2016).

The world's largest economies recognize that scaling up low-carbon technologies is not only essential to meeting the Paris Agreement, but also an economic opportunity. We are already seeing accelerated investment in low-carbon technologies—for example, global 2015 investment in renewable energy reached a record $286 billion (BNEF 2016). The International Energy Agency estimates that the Paris pledges could lead to $7.4 trillion in cumulative global investment in renewable energy through 2040 (IEA 2015). By investing in low-carbon solutions, American companies and workers can lead the clean energy and low carbon global economy of the 21st century.

The Paris Agreement signals a new era of prominence for climate change on the international stage, including the expectation of ambitious U.S. actions. Going forward, ambitious domestic action on climate change will be a prerequisite for credible leadership on the international stage, influencing multilateral and bilateral relationships with our most important political and economic allies.

DEVELOPING A MID-CENTURY STRATEGY

President Obama announced in March 2016 that the United States would complete a mid-century low greenhouse gas emissions strategy and submit it to the UNFCCC secretariat before the end of the year. Following that announcement, the President directed an interagency group led by the White House to assist with the development of the U.S. MCS.

The MCS stands on the shoulders of decades of work across government agencies. It is based on robust literature related to U.S. decarbonization from peer-reviewed journal articles and studies conducted by private, public, and non-profit organizations. The MCS was further informed by the input received at a series of stakeholder listening sessions with non-governmental and private sector organizations, and by ongoing collaboration with other nations that are developing mid-century strategies, including Canada and Mexico.

Finally, the MCS is supported by original analysis and modeling that portrays pathways to a low-GHG economy by 2050. The MCS analysis combines economy-wide modeling that encapsulates all sources and sinks of GHG emissions with more granular sector-specific models. We reference the results of this analysis throughout the remainder of this report, as we describe our vision for a mid-century low-GHG pathway.

[4] The estimate is for premature deaths in 2016, but it does not include regulations promulgated since the study was conducted in 2013, and therefore does not account for the Mercury and Air Toxics Standards or the Clean Power Plan, which will result in reduced reliance on fossil fuels and will therefore support MCS objectives of reducing GHG emissions as well as lowering premature mortality.

2

U.S. GHG EMISSIONS AND TRENDS

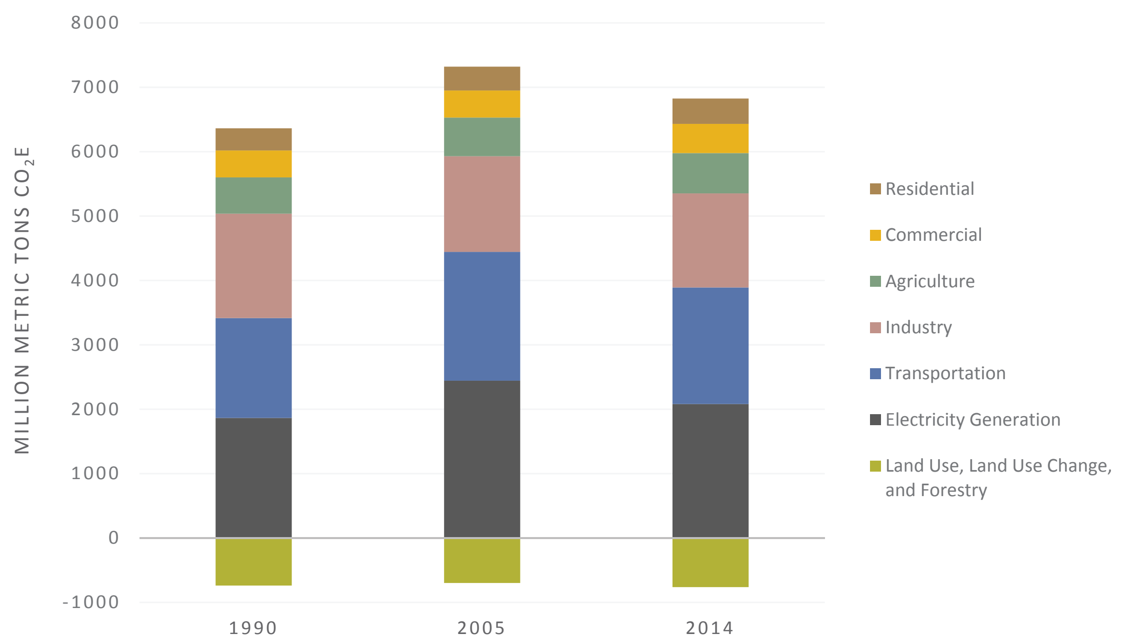
Annual emissions of greenhouse gases in the United States increased throughout the 20th century, primarily due to the combustion of coal, natural gas, and petroleum to meet growing demand for energy services, but also due to agricultural activities, industrial processes, and changes in land use. U.S. greenhouse gas (GHG) emissions peaked in 2007 and have steadily declined since then. This trend is expected to continue over the next decade, in large part due to the policies finalized under the Obama Administration. However, additional ambitious policies are necessary to put the United States on a pathway to achieving the MCS. In this chapter, we describe current U.S. GHG emissions and near-term projections.

PROGRESS TO DATE

Since peaking in 2007, U.S. GHG emissions have declined. In 2014, net GHG emissions were 9 percent below 2005 levels (Figure 2.1). The United States has achieved even deeper reductions in energy-related CO_2 emissions since 2014 (EIA 2016d).

Analysis by the Council of Economic Advisers (CEA) shows that while some of the decline in emissions since 2008 is due to lower-than-expected economic growth caused by the Great Recession of 2008-2009, major drivers include improvements in energy efficiency and the deployment of lower emissions technologies, including renewables and natural gas (EOP/CEA 2016). Much of this deployment occurred as a result of market trends toward lower cost clean energy.

FIGURE 2.1: U.S. NET GHG EMISSIONS BY SECTOR



Note: End-use sector totals exclude emissions from electricity. Source: U.S. Greenhouse Gas Inventory 2016.

Under President Obama's leadership, the United States has implemented an ambitious suite of policies and measures intended to cut GHG emissions, including:

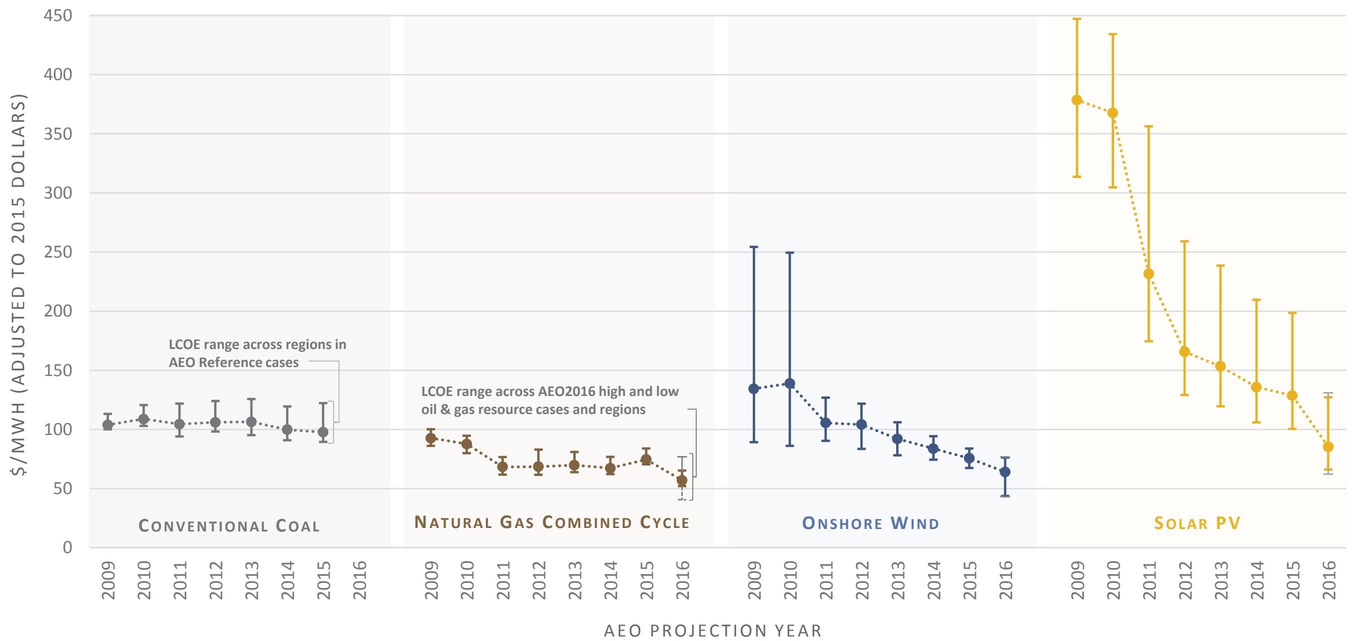
- Tax incentives, RD&D, and loan guarantee programs to spur investments in clean energy;
- First-ever federal carbon pollution standards for power plants;
- Greenhouse gas and fuel economy standards for cars and trucks;
- Energy efficiency standards in buildings and appliances;
- Standards to reduce methane emissions from landfills and new and modified sources in the oil and gas sector;
- Domestic and international actions to phase down hydrofluorocarbon production and use; and
- Programs to promote federal government sustainability

These federal actions are complemented by policies and measures at the state and local levels. California, home to over 12 percent of Americans, passed ambitious climate legislation requiring emissions reductions to 1990 emissions levels by 2020, and 40 percent below 1990 levels by 2030 (SB 32 2016). The nine states participating in the Regional Greenhouse Gas Initiative established a cap on power sector CO_2 emissions, and have invested billions in complementary programs that accelerate the deployment of energy efficiency and renewable energy technologies.

In addition, 29 states and the District of Columbia require a minimum level of electricity to be generated from renewable or alternative energy sources. Some states, such as New York, have or are considering expanding these mandates to include all non-emitting sources, including nuclear power plants. Twenty states require a minimum level of energy savings from energy efficiency measures. Driven in part by these energy efficiency requirements, utility investment in energy efficiency programs has increased more than 60 percent in the last 6 years, from $3.9 billion to $6.3 billion (ACEEE 2016).

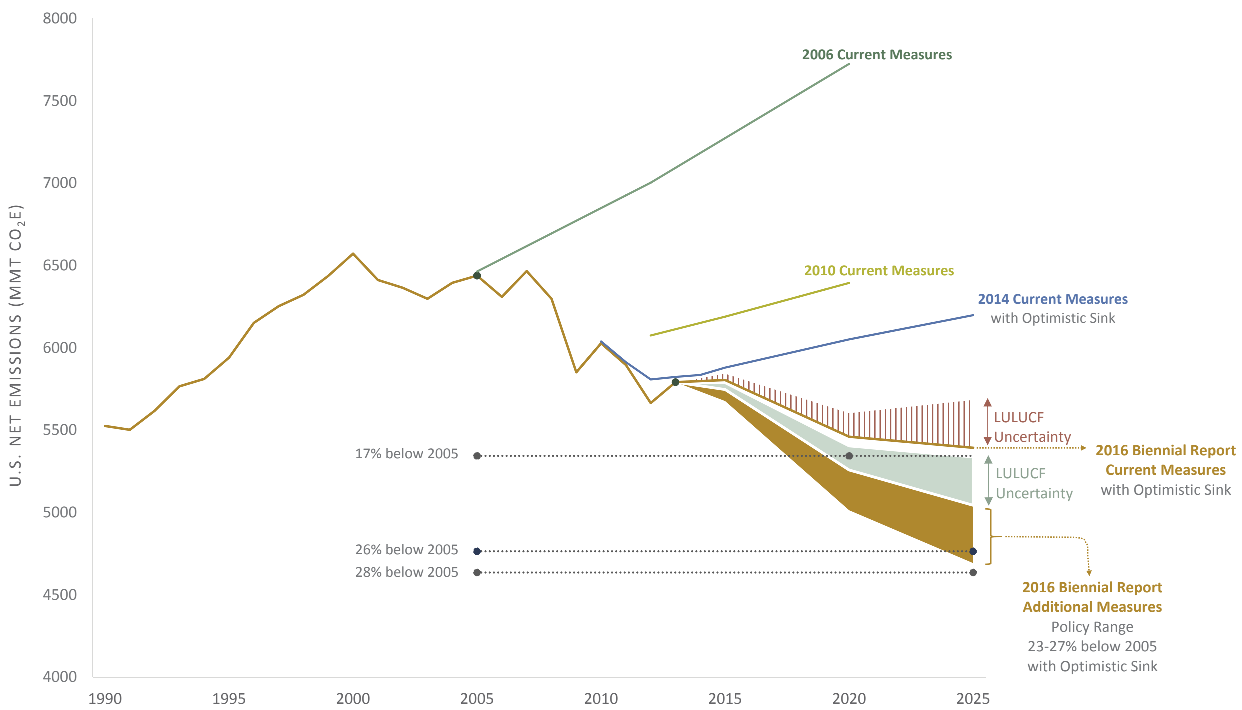
Also contributing to the trend of declining emissions are technological advancements in renewable energy (Figure 2.2), assisted in part by federal research, development, and deployment through the American Recovery and Reinvestment Act, as well as ongoing sustained investments and programs at DOE, EPA, USDA, and other agencies. Private sector investments played a critical role as well. Since 2008, the installed costs of solar photovoltaic (PV) cells have declined by about 60 percent, the levelized cost of wind power by 40 percent, and the cost of LED bulbs by over 90 percent. At the same time, electric generation from wind has tripled and solar generation increased more than thirtyfold. Advances in horizontal drilling and hydraulic fracturing have led to a major increase in natural gas generation, primarily replacing higher carbon coal generation (EIA 2016c). Federal R&D and tax credits for unconventional gas production laid the foundation for this recent success.

FIGURE 2.2: U.S. EIA LEVELIZED COST OF ELECTRICITY (LCOE) PROJECTIONS FOR SELECTED TECHNOLOGIES, AVERAGE, AND RANGE



Note: Each LCOE projection is for plants having start dates five years after the projection year (e.g., 2013 for AEO2008, 2021 for AEO2016). Ranges represent the minimum and maximum LCOE across regions in EIA's AEO Reference cases; the extended ranges shown for AEO2016 represent the range of LCOE's across regions from the AEO2016 High Oil and Gas Resource and Technology and Low Oil and Gas Resource and Technology cases. "Conventional coal" values are for EIA's pulverized coal (without CCS) model technology type; AEO2016 does not contain LCOE estimates for coal plants without CCS. "Natural gas combined cycle" values are for EIA's "advanced combined cycle" model technology type. In addition, the LCOE values shown reflect EIA's assumptions for new plant costs at the time of each projection; do not reflect the impact of production tax credits or investment tax credits; and are adjusted to 2015 dollars using a GDP price deflator index reflecting AEO2016 macroeconomic indicators and historical inflation. Sources: U.S. Energy Information Administration, National Energy Modeling System.

FIGURE 2.3: U.S. EMISSIONS PROJECTIONS WITH CURRENT MEASURES AND ADDITIONAL MEASURES CONSISTENT WITH OBAMA ADMINISTRATION'S CLIMATE ACTION PLAN (U.S. DEPARTMENT OF STATE 2016)



MEETING 2020 AND 2025 TARGETS

Before President Obama took office, U.S. GHG emissions were projected to increase indefinitely. Now, emissions are projected to decline for the foreseeable future. As demonstrated in the Second Biennial Report of the United States of America, projected emissions are considerably lower than the projections from comparable analyses completed in previous years (Figure 2.3).

The Second Biennial Report further demonstrates that the United States is on track to meet its 2020 target (net GHG emissions in the range of 17 percent below 2005 levels by 2020) and is laying the foundation to reach its 2025 target (26-28 percent reductions by 2025). As shown in Figure 2.3, and in keeping with UNFCCC guidelines, the report projects emissions both under Current Measures and Additional Measures. The Current Measures scenario incorporates policies and measures that were finalized by mid-2015, including the Clean Power Plan,[5] light-duty vehicle fuel efficiency standards, and consumer appliance efficiency standards. The Additional Measures scenario assumes the implementation of all policy actions from the Current Measures scenario and additional policies consistent with the President's Climate Action Plan. Notably, the Additional Measures scenario is based on a range of actions including, but not limited to, policies that were proposed but not finalized by the date of publication. The United States has subsequently finalized heavy-duty vehicle fuel economy standards, standards to reduce methane emissions from landfills and new and modified sources in the oil and gas sector, and additional appliance and equipment efficiency standards.[6]

The impact of policies finalized under President Obama will grow in magnitude over time as they take full effect. For instance, before the Clean Power Plan takes full effect, the United States is projected to deploy 100 GW of additional wind and solar generation over the next six years, in part due to bipartisan tax incentives renewed in 2015 (Mai et al. 2016).

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[5] Implementation of the Clean Power Plan has been stayed by the U.S. Supreme Court during the pendency of a set of legal challenges. The Obama Administration is confident that the Plan will be upheld by the courts as it is based on a strong legal and technical foundation.

[6] For more information on the Additional Measures scenario, see Appendix 2: Methodologies for Current Measures and Additional Measures of BR2.

3 A VISION FOR 2050

Achieving greenhouse gas emissions reductions of at least 80 percent below 2005 levels by 2050 will entail balancing many challenges. How will we continue to satisfy the demands of a growing economy for energy and lands? What is the scale and pace of investments required? What are the most important sectors and emissions sources to focus on, and what are the key opportunities and challenges going forward? By answering these and other questions, the MCS provides a strategic framework to guide policies and investments that will put the United States on a low-GHG pathway.

This chapter provides a high-level overview of the vision for the U.S. MCS, describing the characteristics of low-GHG energy and land systems in 2050, important interactions among sectors, and robust actions needed to get from here to there. In the chapters that follow, we provide additional detail on the strategies for decarbonizing the U.S. energy system, sequestering carbon in U.S. lands, and reducing non-CO_2 emissions.

THE MCS ANALYSIS

Quantitative projections are one important ingredient of a long-term strategy, allowing for internally consistent accounting across energy sub-sectors and land use options as well as interactions across the energy and land use sectors. The MCS analysis brings together state-of-the-art modeling tools and the best available data on the evolution of the energy and land sectors (see Box 3.1).

The Global Change Assessment Model (GCAM), an economy-wide model that captures important interactions across energy and land sectors and additional sources of non-CO_2 emissions, is central to our MCS development. Additional analysis by DOE, EPA, and USDA complemented the GCAM analysis by providing many of the input assumptions and enabling a more granular understanding of dynamics within the energy and land sectors. For example, DOE performed detailed energy sector modeling to support the energy inputs and analysis in GCAM.

While the MCS analysis outlines possible pathways to a lower-GHG future, our scenarios also draw and build on a robust existing literature on U.S. and global decarbonization pathways (Box 3.2).

BOX 3.1: U.S. MCS MODELING TOOLS AND DATA SOURCES

- **Global Change Assessment Model (GCAM)** – Dynamic recursive model representing energy and land sectors linked with a climate model; used to explore the interactions of emissions-reducing investments and activities across the U.S. and global economy. The MCS scenarios were produced in GCAM by the Pacific Northwest National Laboratory (PNNL).
- **Global Timber Model (GTM)** – Intertemporal optimization economic model that can reflect afforestation and land use change, forest management, and forest products activity in response to policies and markets; models all regions of the world, including global market interactions; used to assess forest dynamics under various demand and land carbon sink scenarios.
- **U.S. Forest Assessment System Service Model (USFAS, USFS Model)** – A forest-inventory model embedded within partial equilibrium assessments of timber, agriculture, and land markets; used to assess forest dynamics under various land carbon sink scenarios.
- **U.S. Forest Service Forest Inventory and Analysis Database** – provided historic input data for forestry models (GTM, USFAS Model).
- **National Energy Modeling System (NEMS)** – A granular model of the U.S. energy markets created by the U.S. Department of Energy (DOE). NEMS is used to generate projections of energy production, demand, imports, and prices through the year 2040.
- **Advanced Technology Case**[7] – Energy sector inputs to the MCS analysis, developed by U.S. DOE with the use of NEMS and refined by PNNL for use in GCAM; assumes all current DOE program goals are achieved, including cost, performance, and deployment goals.
- **Stretch Technology Case** – Energy sector inputs to the MCS analysis, developed by U.S. DOE with the use of NEMS and refined by PNNL for use in GCAM. Assumes additional funding for RD&D (such as through Mission Innovation) and enables a greater level of technological progress, including reduced costs and increased performance.
- **U.S. Greenhouse Gas Inventory** – An annual report developed by the U.S. EPA that tracks total annual U.S. emissions and removals by source, economic sector, and greenhouse gas going back to 1990.
- **U.S. EPA Non-CO2 Marginal Abatement Cost (MAC) Model and Report** – A bottom-up engineering cost model that evaluates the cost and abatement potential of non-CO_2 mitigation technologies. The associated non-CO_2 mitigation report provides a comprehensive economic analysis on the costs of technologies to reduce non-CO_2 gases and the potential to reduce them by sector.

[7] While the DOE inputs for its "Advanced Technology Case" attempt to represent DOE program goals, not all goals are of equal ambition, probability, or timescale, and these results therefore should not be taken as DOE's prediction of what will happen, but are simply one illustrative scenario.

Like all long-term projections, the MCS analysis is limited in its ability to depict the complexity of real-world markets and uncertainties, and the intention is not to predict with precision the long-term evolution of the energy and land sectors, but instead to provide a basis for understanding the key opportunities and challenges related to achieving the MCS vision.

BOX 3.2: U.S. LITERATURE ON DEEP DECARBONIZATION IN THE UNITED STATES

A number of studies have explored pathways to "deep decarbonization" of the U.S. energy sector. Two studies are particularly helpful for our purposes: (1) the Energy Modeling Forum 24 model intercomparison study (EMF 24) (Fawcett et al. 2014) and (2) the Pathways to Deep Decarbonization in the United States report (DD Pathways) (Williams et al. 2014). The following broad insights emerge from the literature:

1. **There are many pathways to deep decarbonization, and they do not require major technological breakthroughs.** Both the EMF 24 and DD Pathways studies portray multiple pathways for the United States to achieve domestic emission reductions of 80 percent or more by mid-century, while continuing to meet American demand for electricity, transportation, manufacturing, and other energy services. Both studies rely solely on technologies that either are in commercial use today or can reasonably be expected to be commercialized by the time of their deployment in the model. That said, technological breakthroughs can significantly increase the pace and reduce the costs of decarbonization.
2. **Nearly all deep decarbonization scenarios show large increases in the deployment of certain technologies and strategies, including energy efficiency, electrification, wind, solar, and biomass.** All scenarios in the EMF 24 and DD Pathways studies show large increases in: (1) energy efficiency, causing energy use to decline by at least 30 percent in all DD Pathways scenarios and roughly 20 percent in EMF 24, compared to respective business-as-usual scenarios in 2050; (2) electrification, with electricity generation increasing by 60 to 113 percent between 2005 and 2050 across the DD Pathways scenarios due to increased electricity usage in transportation, buildings, and industry; (3) wind and solar energy, with solar generation increasing by 21 to 83 times and wind generation increasing 4 to 25 times over 2014 levels by 2050 in the DD Pathways scenarios; and (4) bioenergy, with biomass use increasing by over four times today's levels in both the DD Pathways and EMF 24 scenarios.
3. **Deep decarbonization will not be achieved without ambitious climate policies.** A transformation to a low-carbon energy system is unlikely to occur absent a strong policy commitment. Even with optimistic assumptions across low-carbon technology costs, the EMF 24 results show emissions increasing above 2005 levels by 2050 absent climate policies.
4. **Costs of deep decarbonization depend on technological progress and policy structures.** Estimates of the costs of deep decarbonization vary widely, but certain insights are robust across studies. First, greater technological progress lowers the costs of decarbonization. The EMF 24 results indicate that the costs of achieving 50 percent emission reductions are about twice as high with pessimistic technology cost assumptions than with optimistic assumptions. Second, the use of flexible, comprehensive, market-based policies lowers the costs of decarbonization. EMF 24 explored a pathway that involved only increasingly stringent electricity and transportation regulations, and found costs that were two to five times higher than an economy-wide carbon price that achieved the same emissions reductions. Finally, the sooner policy action is implemented, the cheaper it is to achieve a given emissions target.
5. **The land sector can play an important role in offsetting emissions sources difficult to address by mid-century.** To date, deep decarbonization studies have devoted significantly more attention to the energy sector than to land. However, there is a growing body of literature that looks at the scale of potential for increasing carbon sequestration on U.S. landscapes, indicating that significant carbon sequestration is possible through expanding and enhancing U.S. forests and modifying agricultural practices to sequester carbon in cropland and grassland soils.

OVERVIEW OF THE MCS SCENARIOS

It is important for the United States to have a clear vision for how to decarbonize our economy. The MCS analysis uses a scenario approach to explore multiple low-GHG pathways consistent with the MCS vision. We model numerous pathways due to the uncertainties surrounding the evolution of technologies, economic conditions, and social dynamics over the coming decades.

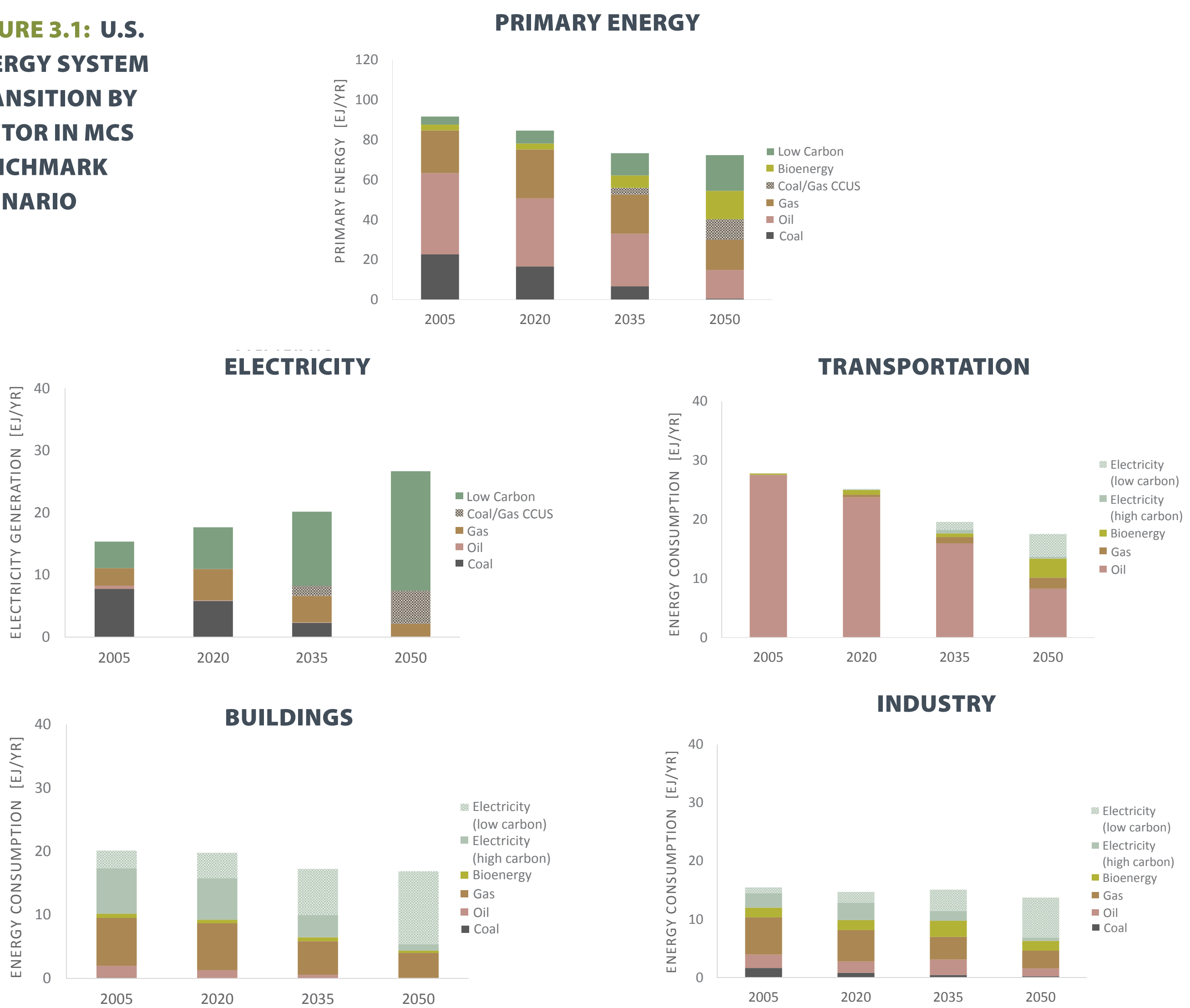
The MCS analysis highlights findings that are robust across scenarios, which provide a strong basis for immediate action. All low-GHG pathways require ambitious actions across the economy. We envision flexible policies and institutions that promote a broad portfolio of existing and emerging low-GHG technologies. Flexibility promotes cost-effectiveness, and it enables shifts in course as technologies evolve over time.

The MCS scenarios differ in regard to their reliance on key low carbon technologies and decarbonization strategies. Each will have different implications for societal priorities, including limiting climate change, the costs of decarbonization, environmental impacts, energy security, and safety. They are not intended to span the full range of possible low-GHG pathways consistent with the MCS vision.

MCS BENCHMARK SCENARIO

The MCS scenarios are organized around a **MCS Benchmark** scenario, which should be interpreted as a starting point for the analysis and a basis for comparison, and not as a "most likely" pathway. Underpinning this scenario are energy technology assumptions developed by DOE (its Advanced Technology Case), which assumes continued innovation spurred by decarbonization policies and current levels of RD&D funding (i.e., not including the Mission Innovation commitment to double such funding). The scenario also assumes a maintained land carbon sink and the availability of a broad range of low-GHG technologies, including CO_2 removal technologies that contribute negative emissions by 2050.

FIGURE 3.1: U.S. ENERGY SYSTEM TRANSITION BY SECTOR IN MCS BENCHMARK SCENARIO



Primary Energy declines over time with a growing economy as a result of improved energy efficiency across sectors. The electricity system is nearly decarbonized by 2050, and electricity production increases to support electrification across transportation, buildings, and industry. Efficiency increases markedly in the transportation sector, largely through the deployment of electric vehicles, which consume 1.6 to 3.7 times less energy per mile than conventional vehicles.

The MCS Benchmark scenario portrays a pathway to net GHG emissions of 80 percent below 2005 levels in 2050. Figure 3.1 shows the associated transition of the U.S. energy system.

While the MCS Benchmark scenario portrays one plausible pathway to 80 percent reductions, additional scenarios explore important uncertainties associated with that pathway. Two are focused on success in generating negative emissions, three show different pathways to a low-carbon energy system, and one explores the potential for greater emissions reductions by 2050.

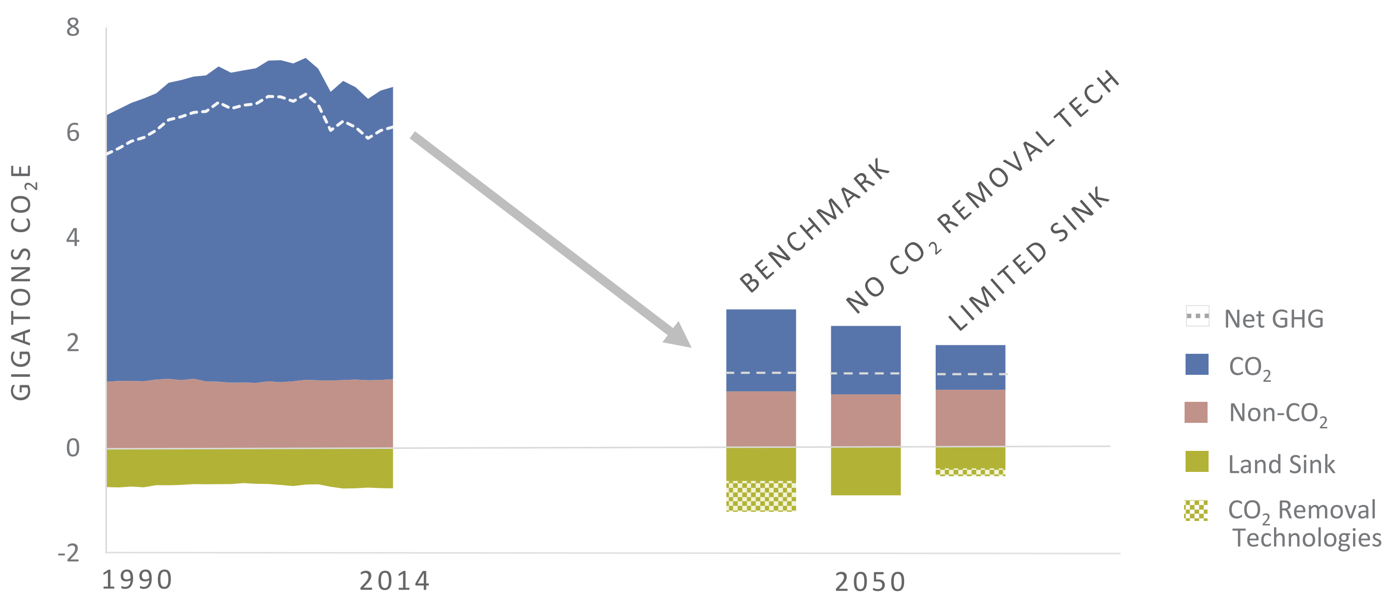
NEGATIVE EMISSIONS SCENARIOS

Two alternative scenarios illustrate the implications of achieving different levels of negative emissions in 2050. Given uncertainty around land sector dynamics and the ability to economically scale negative emissions technologies, anticipating scenarios in which negative emissions are limited is important.

- In the **No CO_2 Removal Technology** scenario, we assume that engineered CO_2 removal technologies like BECCS are unavailable. Instead, a larger emphasis is placed on enhancing the land sink and achieving a low carbon energy transition more rapidly than in the MCS Benchmark scenario.
- The **Limited Sink** scenario assumes not only limited availability of CO_2 removal technologies but also limited success in maintaining and enhancing the land sink. With far fewer negative emissions in 2050, this scenario requires an even greater emphasis on rapidly reducing energy CO_2 emissions.

Figure 3.2 shows how greater success in delivering negative emissions through the land sector and CO_2 removal technologies results in less pressure to mitigate the most challenging energy sector and non-CO_2 emissions in achieving 80 percent reductions. CO_2 emissions from fossil fuel combustion and industrial processes decrease by 74, 79 and 86 percent in the MCS Benchmark, No CO_2 Removal Technology and Limited Sink scenarios, respectively

FIGURE 3.2: U.S. NET GHG EMISSIONS UNDER THREE MCS BENCHMARK SCENARIO



Multiple pathways to 80 percent GHG reductions by 2050 are achievable through large reductions in CO_2 emissions, smaller reductions in non-CO_2 emissions, and delivering negative emissions from land and CO_2 removal technologies. Note: "No CO_2 Removal Tech" assumes no availability of negative emissions technologies like BECCS but does include CCUS for fossil fuels.

ENERGY TECHNOLOGY SCENARIOS

Three additional scenarios explore challenges and opportunities associated with the low carbon energy transition (the implications of these three scenarios are explored in greater detail in Chapter 4):

- The **No CCUS** scenario achieves 80 percent reductions by 2050 without the use of carbon capture, utilization and storage (CCUS) technologies[8] for both fossil energy and bioenergy. Similar to the No CO_2 Removal Technology scenario, a greater emphasis is placed on enhancing the land carbon sink to produce negative emissions. Without fossil CCUS, a more rapid phase-out of coal and natural gas is required, and thus a greater reliance on alternative low carbon energy sources. Compared to the MCS Benchmark scenario, coal and natural gas use in the No CCUS scenario are 97 and 28 percent lower, respectively, in 2050.
- The **Smart Growth** scenario portrays a different pathway to decarbonization in the transportation and buildings sectors. In transportation, vehicle travel increases only moderately over the next few decades, despite a growing economy, as a result of smart growth strategies like improved urban planning and well-developed mass transit systems. To reflect the uncertainty surrounding the growth of clean vehicles, this scenario also assumes less adoption of electric vehicles compared to the MCS Benchmark scenario.[9] This scenario places greater emphasis on increasing the energy efficiency of appliances and building materials, along with retrofits to consume less electricity. Overall primary energy consumption in the Smart Growth scenario is 9 percent lower than in the MCS Benchmark scenario in 2050.
- The **Limited Biomass** scenario explores an alternative to the MCS Benchmark scenario with lower bioenergy consumption and no deployment of BECCS. Our ability to produce carbon-beneficial forms of biomass has broad implications for the U.S. MCS due to the versatility of bioenergy. Biomass can serve as an alternative to fossil fuels in transport, industry, and building applications, as well as support negative emissions through BECCS. The degree to which the U.S. strategy relies on biomass will therefore have key implications on the transition in the transportation sector, on the manner in which the U.S. produces electricity and liquid fuels, and on the potential size of the CO_2 sink. In 2050, the U.S. consumes about half as much bioenergy in the Limited Biomass scenario compared to the MCS Benchmark scenario, but still more than double today's consumption of bioenergy.

Each of the six scenarios described above display a pathway to 80 percent reductions below 2005 levels in 2050. In the **Beyond 80** scenario (described in detail later in this chapter), a virtuous cycle between stronger global action to reduce emissions and more rapid advances in low-carbon technologies leads to deeper reductions by 2050.

CENTRAL ELEMENTS OF THE U.S. MCS VISION

The MCS analysis points to a set of robust elements for the transition to a low-GHG pathway that can guide our national strategy for achieving deep decarbonization. Additional detail on how these elements could be implemented in practice is provided in the chapters that follow.

Element 1: Increasing efficiency across the energy system. By continuing to take advantage of widespread opportunities to cost-effectively improve the efficiency of energy consumption and production, we can achieve economic growth without increasing energy use, thus easing the challenges of a low-carbon energy transition. Key opportunities include "smart-grid" technologies that reduce electricity use, greater fuel economy in vehicles, and more efficient industrial processes, among many others. Technological advancements will enable even greater levels of cost-effective efficiency improvements. In addition, pursuing "smart growth" strategies such as better urban and transportation planning can drive structural reductions in the country's energy needs. In the MCS Benchmark scenario, primary energy use declines by over 20 percent between 2005 and 2050.

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[8] Note that in this report we refer to "carbon capture, utilization and storage," or "CCUS," to reflect the fact that captured carbon dioxide can be recycled and utilized. The technology is also commonly referred to as "carbon capture and storage," or "CCS."

[9] In reality, smart growth strategies and electric vehicle penetration may be positively correlated. We are not suggesting a negative correlation with this scenario formulation, but rather using these assumptions to portray a markedly different pathway to decarbonization in the transportation sector.

Element 2: Electricity produced almost entirely from clean generation sources by 2050. Nuclear and renewable energy generation sources are widely used today, and with continued innovation, these and other low carbon technologies will play a greater role in the electricity system going forward. The MCS Benchmark scenario shows 92 percent of generation in 2050 coming from a diverse portfolio of clean sources, including significant contributions from solar, wind, nuclear, hydro, and CCUS. Nearly all fossil fuel power plants without CCUS are phased out by 2050. A wide range of potential electricity system configurations are possible in 2050, depending on advancements in technologies, public acceptance, and regulatory support for the emergence of key low carbon resources. Regardless of its configuration, the new electricity system will look very different from that of today, requiring new grid infrastructure and operational approaches.

Element 3: Broad utilization of clean electricity and low-carbon fuels across the buildings, industry, and transportation sectors. A low carbon electricity system can provide energy to an increasing number of uses, including in vehicles, for heating and cooling, and for steam and heat production in certain industries. For example, in the MCS Benchmark scenario, nearly 60 percent of light-duty vehicle miles traveled are supported by electric vehicles by 2050. Other low carbon fuels (e.g., carbon beneficial forms of biomass) will play an important role as well, particularly for energy needs that are difficult to electrify, such as aviation, heavy-duty vehicles, and many industrial processes. In the MCS Benchmark scenario, direct fossil fuel use (i.e., not including electricity generated using fossil fuels) decreases by 58 percent, 55 percent, and 63 percent in buildings, industry, and transportation, respectively, from 2005 to 2050.

Element 4: Maintain and potentially enhance the land carbon sink, ensuring that U.S. landscapes continue to sequester substantial amounts of carbon. A robust land carbon sink in 2050 can help reduce the costs of decarbonization and create flexibility for meeting our GHG reduction goals. The MCS analysis shows that the land sector could sequester 23 to 45 percent of economy-wide emissions in 2050. We can continue to sequester carbon across U.S. landscapes through forest expansion, improved forest management, and other forestry opportunities in addition to increasing carbon stored in croplands and grasslands through enhanced agricultural practices and agroforestry.

Element 5: Develop CO_2 removal technologies that sequester and store carbon. While not currently deployed at scale, CO_2 removal technologies like BECCS have the potential to bolster negative emissions. Developing these technologies may be necessary in the long run to constrain global average temperature increases to well below 2°C. If they become cost-effective, deploying CO_2 removal technologies can significantly reduce the costs of decarbonization. However, the United States can achieve the MCS vision with or without these technologies. While some of the illustrative scenarios explored here rely on significant BECCS deployment, we also explore futures in which CO_2 removal technologies are unavailable.

Element 6: Reduce non-CO_2 GHG emissions, despite growth in the activity levels of major sources. Sustained action to mitigate emissions of methane, nitrous oxide, and fluorinated gases are needed to avoid a significant increase in these emissions by 2050. The MCS analysis shows reductions in non-CO_2 emissions of approximately 10 to 30 percent below 2005 levels by 2050. Deeper reductions are difficult to achieve without considerable innovation and creative policies, particularly in the agricultural sector, where increased food production is likely to drive emissions upward. However, the MCS envisions RD&D investments to identify and pursue additional opportunities to drive down non-CO_2 emissions beyond those reductions portrayed in the MCS analysis.

THE ROLE OF PUBLIC POLICY

The MCS envisions a suite of ambitious and cost-effective decarbonization policies. Many different policies can serve this purpose, including market-based incentives and regulations at all levels of government. Major policy priorities across the energy system, lands, and sources of non-CO_2 emissions include the following:

- **Expanding local/state policies and sectoral regulations and shifting to economy-wide GHG emissions pricing over time.** Putting a price on GHG emissions serves the dual purposes of promoting cost-effective emissions reductions and encouraging private sector investments in low carbon energy supply technologies. A GHG price also encourages a level playing field for all low carbon technologies and produces a stream of revenue that can be used in productive ways. Some of these same benefits can be achieved by expanding and harmonizing local/state policies and sectoral regulations emissions regulations.

- **Increased support for public and private RDD&D.** Increased support for innovation in low-GHG technologies will reduce the costs of emissions reductions. With different sectors and technologies come different priorities and needs with respect to research, development, demonstration, and deployment (RDD&D), as well as different approaches for government support. For certain technologies at early stages of commercial deployment like carbon capture and storage, second generation biofuels, and emerging advanced nuclear energy, support programs can bring the first set of commercial-scale facilities to market, driving cost reductions through learning and economies-of-scale. Supporting a broad range of technologies is likely to lower the costs of decarbonization because we do not know today how technologies will progress over many decades.
- **Support for energy efficiency.** Various market barriers may inhibit consumers from fully taking advantage of cost-effective opportunities to improve end-use energy efficiency, even in the presence of market-based approaches for pricing carbon. Efficiency standards for appliances, vehicle fuel economy standards, building codes, and programs that encourage consumers to use more energy efficient technologies can provide cost-effective emissions reductions.
- **Infrastructure and regulatory support for low-GHG technologies.** Investments in infrastructure and regulatory systems enable the widespread deployment of many low-GHG technologies. For example, high penetration of wind and solar power generation in some regions may require investments in transmission, storage, and grid management technologies, and refueling stations are needed for widespread penetration of electric- or hydrogen-powered vehicles. Power sector regulations and market designs should appropriately compensate both generation and distributed energy resources (including energy efficiency, distributed generation, and demand response) for their full contribution to reliable and affordable electricity.
- **Incentives for negative emission technologies or strategies.** The effective and economically efficient use of land carbon sinks and CO_2 removal technologies requires incentives, preferably equivalent to the economy-wide carbon price. Additionally, negative emissions technologies need enabling policies and safeguards to ensure carbon reductions, such as appropriate carbon accounting frameworks for land carbon sinks (discussed further in Chapter 5) and a long-term liability and stewardship regime for geologic storage.

Innovation and policies that reduce net GHG emissions are mutually reinforcing, because policies spur investments in low-GHG technologies, and innovation improves the cost-effectiveness of policies. Where possible, policy makers should also capitalize on correlations between GHG emissions reductions and other societal objectives, like increased standards of living and reduced air and water pollution.

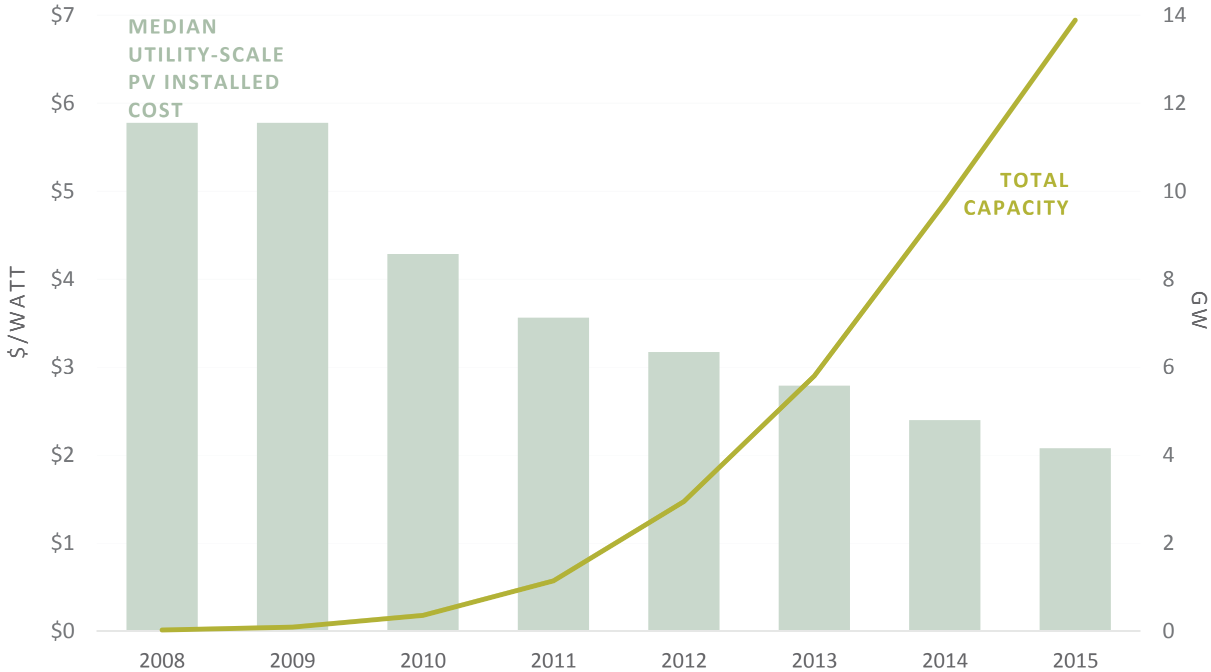
INCREASING 2050 AMBITION

Reducing net U.S. GHG emissions to 80 percent below 2005 levels will require a concerted and comprehensive effort to transform the energy system with an economy experiencing strong and consistent growth. While these goals are ambitious, even greater emissions reductions can be achieved if continued rapid progress in clean energy technologies around the world creates a virtuous cycle in which ambition drives down costs, in turn allowing more ambition (Trancik 2015).

A prime example of this global virtuous cycle is the recent rapid growth of the international solar energy market. Policies in Germany and R&D investments in the United States prompted manufacturing advances in China (and elsewhere) that significantly reduced solar panel costs, stimulating further increases in global demand (Graichen et al. 2016, Cox et al. 2015, CPI 2011). Now, solar energy is increasingly cost-competitive and is being deployed at a pace (over 10 GW per year in the United States) that would have been unthinkable a decade ago. Replicating this cycle across a broad portfolio of clean energy technologies could accelerate the pace of a cost-effective low carbon energy transformation.

To develop a deeper understanding of this outcome as part of the vision for this MCS, we developed a Beyond 80 scenario (Figure 3.4) in which emissions reductions exceed 80 percent below 2005 levels by 2050.

FIGURE 3.3: SOLAR ENERGY COSTS AND DEPLOYMENT IN THE UNITED STATES



Clean energy innovation and global ambition create a virtuous cycle of technology cost reductions, enabling emissions reductions greater than 80 percent by 2050. Source: U.S. Department of Energy (2016b). Note: Costs in real 2015 dollars.

Several factors are important in making the Beyond 80 scenario realistic. The first is clean energy innovation. While the technology assumptions in the MCS Benchmark scenario assume current policies and RD&D funding levels going forward, the Beyond 80 scenario envisions increased ambition of decarbonization policies and funding for RD&D, not only in the United States but also in countries around the world, consistent with the goals of the Paris Agreement and the Mission Innovation commitment to double government RD&D investments in low-carbon energy technologies. To enable planning for this future, DOE has developed a set of technological assumptions that reflect significant additional progress across all energy sectors, referred to as the "Stretch Technology" assumptions. With the Stretch Technology assumptions, achieving any emissions target is more feasible and less expensive.[10]

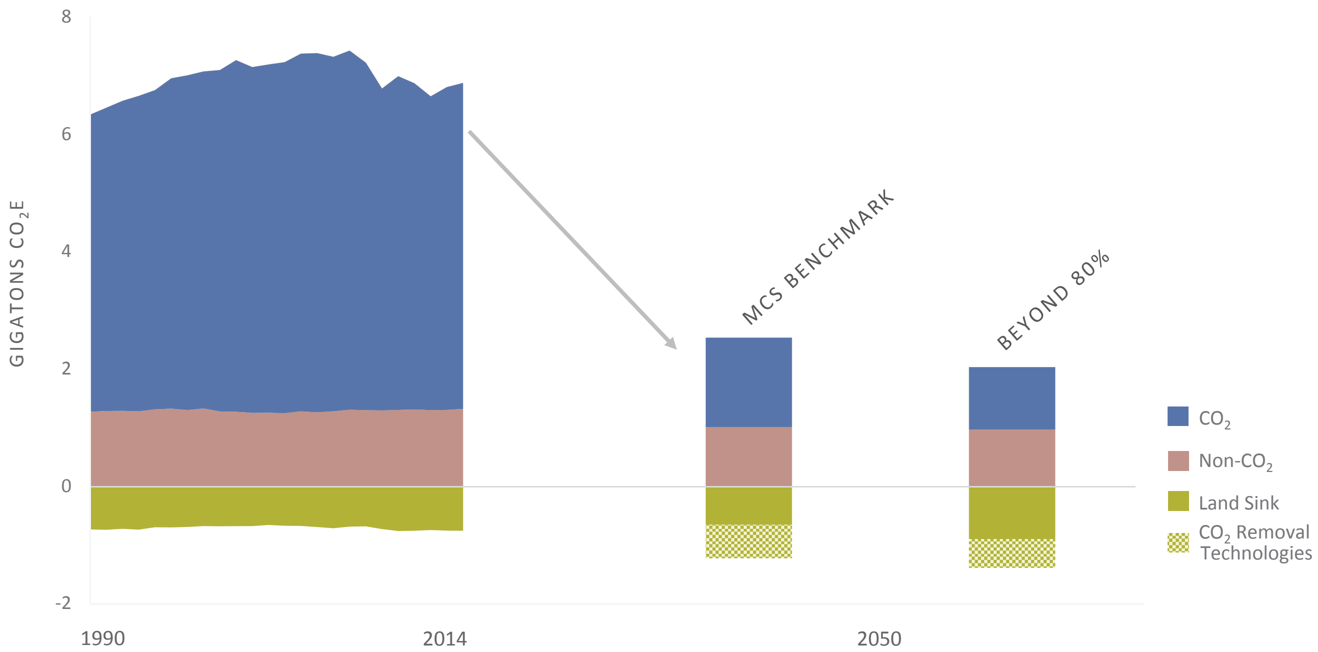
Second, the Beyond 80 pathway requires faster and more widespread clean energy deployments across all sectors. In this pathway, clean technologies provide 98 percent of electricity generation in 2050, which will require the deployment of an additional 5 GW of capacity per year compared to the MCS Benchmark scenario. However, due to the greater technological progress in the Beyond 80 scenario, the total costs of building and operating power plants are roughly the same in both scenarios.

Third, the Beyond 80 scenario depends more heavily on negative emissions compared to the MCS Benchmark scenario. This increases the importance of cost-effective strategies to bolster the land sink and develop CO_2 removal technologies, for example, through innovations like larger, deeper crop roots and increasing forest carbon sequestration and storage.

Finally, the Beyond 80 scenario requires more ambitious global adoption of clean technologies. In addition to globally coordinated investments in RD&D, the increased ambition in this scenario is propelled by more rapid deployment of clean energy and negative emissions technologies. Such deployment has feedback effects on costs and policy ambition, as described in a recent MIT study that showed how the costs of solar and wind energy are likely to fall through 2030 due to the increased deployments that come out of the Paris Agreement pledges (Trancik 2015). Compared to the MIT study, the MCS Benchmark scenario conservatively assumes a slower pace of cost reductions in solar energy through 2030, despite larger

[10] The Beyond 80 scenario portrays the technological progress associated with Stretch Technology enabling deeper emissions reductions compared to the other MCS scenarios. Of course, the same technological progress would also increase the feasibility and reduce the costs of any emissions objective, including 80 percent.

FIGURE 3.4: COMPONENTS OF ILLUSTRATIVE "BEYOND 80" SCENARIO



global deployments. Moreover, global capacity of solar energy triples between 2030 and 2050 in the MCS Benchmark scenario, underscoring the potential for deeper cost reductions after 2030.

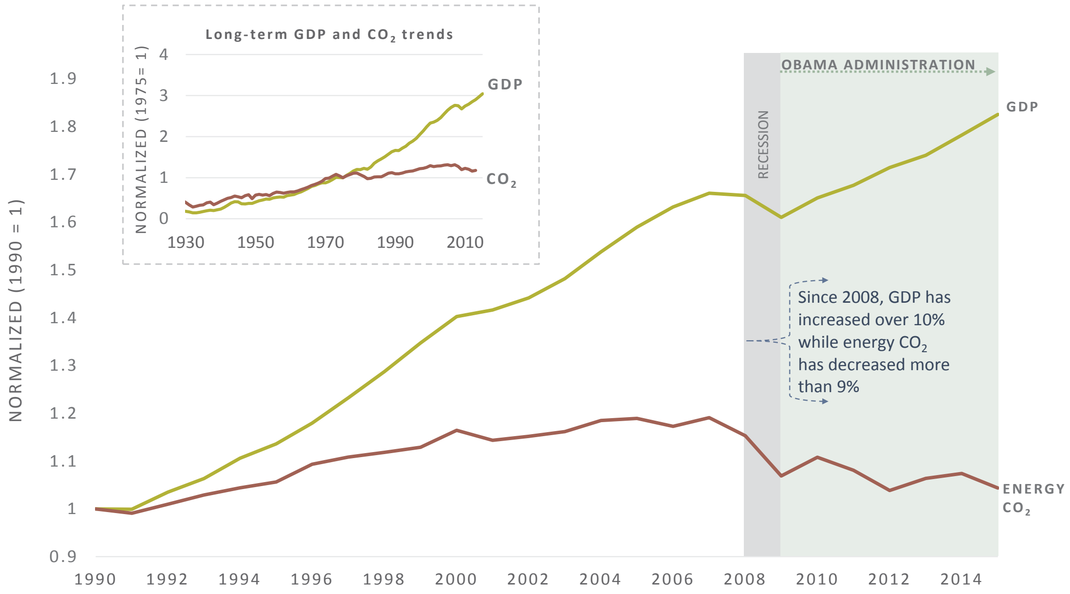
This virtuous cycle of technology development and deployment can allow for the more rapid global GHG reductions required in the second half of the century, particularly in order to meet the more ambitious end of the Paris Agreement temperature goals. These topics are discussed in further detail in Chapter 7.

THE MID-CENTURY STRATEGY AND THE U.S. ECONOMY

The United States can achieve rapid emissions reductions while maintaining robust economic growth. The link between economic growth and CO_2 emissions in the United States has significantly weakened in recent decades. During the Obama Administration, the United States has experienced a sustained period of strong economic growth and decreasing emissions for the first time in history (Figure 3.5). From 2008 to 2015, energy CO_2 emissions fell 9 percent while the U.S. economy grew by 10 percent. Globally, there is evidence that this trend could be taking root as well. Over the last two years, the global economy grew by over 6 percent while energy emissions stayed flat.

Ambitious and sustained global action on climate change is not just an environmental priority, it is also a pro-growth strategy. Pursuing high-carbon strategies (or business as usual) will lead to large and possibly catastrophic damages across the future U.S. and global economies. Economic damages from climate change will arise from a range of sources, including effects on human health, agriculture, sea level rise, and increasingly severe storms, droughts, and wildfires, among many others. According to the President's Council of Economic Advisers (CEA), warming of an additional 1°C above the 2°C target called for in the Paris Agreement could increase economic damages by approximately 0.9 percent of global output. This is the equivalent of reducing U.S. GDP by about $150 billion each year (2014). Economists' estimates of the magnitude of the damages (in terms of reduced consumption) from a do-nothing strategy (resulting in about 4°C warming by 2100) range from about 1 to 5 percent of global GDP (Nordhaus 2013), incurred every year; other recent studies have projected significantly larger economic consequences of unmitigated climate change (Burke et al. 2015).

FIGURE 3.5:
U.S. ENERGY CO_2 EMISSIONS AND GROSS DOMESTIC PRODUCT



Sources: GDP data per U.S. Bureau of Economic Analysis; emissions data per Carbon Dioxide Information Analysis Center and U.S. Energy Information Administration.

Such a do-nothing approach will disproportionately harm the most vulnerable Americans, including children, the sick, the poor, and the elderly (U.S. Global Change Research Program 2014, 2016). Existing health disparities and other inequities increase vulnerability to climate health impacts like heat waves, degraded air quality, and extreme weather. Low-income families are the most vulnerable to disruptive events that cause the household breadwinners to miss work.

Of course, decarbonization will require substantial resources to shift away from GHG-intensive activities. The electric power sector is an important example, where we need to decarbonize the electricity system and increasingly electrify the buildings, transportation, and industrial sectors. The MCS analysis finds annual average investments in electricity generating capacity of 0.4 to 0.6 percent of GDP from 2016 to 2050, which compares to 0.2 percent of GDP from 2000 to 2013. At the same time, expenditures on fossil fuels will decline considerably.

The transition will benefit the U.S. economy in multiple ways as well, as described in Chapter 1. Improved air quality will mean a healthier and more productive workforce. Developing alternative transportation fuels will diversify our energy portfolio, helping to shield the U.S. economy from adverse economic consequences of oil market volatility. Finally, the Paris Agreement signals a sustained shift in the global economy towards low carbon investment, which creates economic opportunity for American businesses.

The MCS envisions a suite of public policies that maximize the economic benefits and minimize the economic costs of the low-GHG transition. The following principles can help to ensure that decarbonization policies create and preserve economic opportunities for all Americans:

- **Implement market-based policies that reward outcomes.** Market-based policies encourage emissions reductions where and when they are most cost-effective, and they provide opportunities for all industries to contribute to a low-GHG economy. This leverages the ingenuity of U.S. businesses, which have repeatedly proven their ability to meet stringent environment and safety standards, often with innovations that would not have been predicted by regulators.
- **Act as quickly as possible.** Increasing policy ambition sooner rather than later will benefit the U.S. economy. The MCS envisions an energy system transition over many decades; sending early signals to investors will avoid abrupt shifts in employment, capital, and other materials. Every year, the United States builds and deploys new power plants, vehicles, and buildings that will produce and consume energy for decades into the future. Investing soon in a lower-carbon

infrastructure will ease the long-term transition. In contrast, investing in high-carbon infrastructure today would lock in a higher emissions pathway and thus increase the costs of achieving our targets later on. Similarly, in the land sector, taking swift action to increase carbon sequestration now will deliver much larger dividends by mid-century than if we delay. According to a recent CEA report, every decade of delayed climate policy increases the costs of meeting a given emissions target by about 40 percent.

- **Support Americans vulnerable to a low-GHG transition.** By implementing the MCS over many decades, most American workers and businesses will have ample time to adjust to a changing economy, as they would need to do over any 34-year period. However, additional support may be needed for low-income households and Americans who are particularly reliant on a high carbon economy—a prime example is President Obama's proposed Power Plus Plan, a package of investments in economic and workforce development targeted to coal communities and workers, abandoned coal mine reclamation, and health and retirement security for coal miners and their families.

BOX 3.3: THE ROLE OF CO_2 REMOVAL TECHNOLOGIES

Along with land carbon sequestration, engineered CO_2 removal technologies offer another opportunity for "negative emissions." While typically more expensive than land carbon sequestration, CO_2 removal technologies offer various advantages compared to land carbon sequestration, including the capability to store CO_2 on geological time scales and fewer limits to scaling the technologies once they are available and economic, due to massive amounts of technical geologic storage potential (NETL 2015).

There are several recognized CO_2 removal technologies, including (Clarke et al. 2014):

Carbon beneficial forms of bioenergy plus carbon capture and storage (BECCS): Any facility that combusts biomass for electricity or converts biomass to fuel and captures resulting CO_2 for utilization (e.g., enhanced oil recovery) or storage in underground reservoirs.

Direct Air Capture (DAC): The capturing of CO_2 from ambient air and either utilizing it or storing it underground. The energy intensity of DAC is much greater than that required for CCUS because CO_2 is more dispersed in ambient air. DAC is therefore unlikely to be economically competitive before all major CO_2 point sources utilize CCUS.

Accelerated rock weathering: An approach that speeds up natural reactions of magnesium or calcium silicates with atmospheric or dissolved CO_2 to create carbonate solids. Suggestions for scaling this option include finely crushing highly reactive minerals like olivine and distributing them in the open ocean, allowing for carbon storage in the deep sea (Hartmann et al. 2013).

No CO_2 removal technology has been deployed at scale to date, and many important questions remain regarding potential costs, unintended consequences, and co-benefits. Currently, BECCS is the most mature and well-understood, making it a useful representation of a CO_2 removal technology for the MCS analysis. BECCS can be utilized across power generation, industrial applications, and biofuel production. Early BECCS projects, like the Decatur Project in Illinois, have captured the pure CO_2 stream from ethanol production and stored it at pilot scale in a saline aquifer; there are other examples of ethanol production plus CCUS for enhanced oil recovery (Finley 2014, Sanchez and Kammen 2016). BECCS for power production has not yet been tested at scale, and its full negative emissions potential depends on the upstream land carbon effects of biomass production, an issue discussed further in Chapter 5.

In the future, other CO_2 removal technologies may prove cost-competitive, but significant RD&D and incentives for negative emissions may be required before they are ready for mass deployment. Pilot, demonstration, and first-of-kind commercial projects are needed to demonstrate viability and to identify challenges as well as opportunities for cost reductions (Lomax et al. 2015).

In its Fifth Assessment Report, the Intergovernmental Panel on Climate Change (IPCC) finds that "BECCS forms an essential component of the response strategy for climate change in the majority of scenarios in the literature" for achieving long-term global outcomes that are likely to constrain warming below 2°C (IPCC 2014). Indeed, the vast majority of the projections used by IPCC with CO_2e concentration targets of 450ppm (roughly a 2°C scenario) or less by 2100 overshoot this target at some point, and then rely on negative emissions from BECCS to return to it.

Even if developed and deployed successfully, CO_2 removal technologies should not be seen as justification to continue emitting freely—they represent a suite of strategies that complement rather than substitute for emissions reductions.

4

DECARBONIZING THE U.S. ENERGY SYSTEM

The U.S. energy system is essential to our economic growth and prosperity. We use energy to power our homes and businesses, to transport people and goods, and to build our infrastructure.

Our energy system is also highly carbon-intensive and is the primary source of U.S. GHG emissions. Today, fossil fuels supply about 80 percent of the nation's energy consumption (EIA 2016d). Petroleum products are the largest contributor to emissions, supplying the vast majority of energy for transportation. Coal is the most carbon-intensive fossil fuel, supplying energy for electricity and industrial uses. Natural gas is less carbon-intensive than coal or petroleum, but is still a major contributor to energy GHG emissions due to its widespread use in the electricity, buildings and industrial sectors.

Recent policies and market forces have stimulated a shift towards a cleaner and more efficient energy sector. The MCS envisions an accelerated transition to a low-carbon U.S. energy system that maintains reliability and affordability while improving human health and satisfying the demands for transportation, industrial output, and building services (Figure 4.2) that come with a growing economy. This chapter focuses on the key opportunities and challenges associated with decarbonizing the U.S. energy system. We begin with a high-level overview of cross-cutting priorities, and then examine the four major energy sectors in turn: (1) electric power, (2) transportation, (3) buildings, and (4) industry.

FIGURE 4.1: U.S. CO_2 EMISSIONS FROM ENERGY CONSUMPTION BY FUEL, 2015 (EIA 2016D)

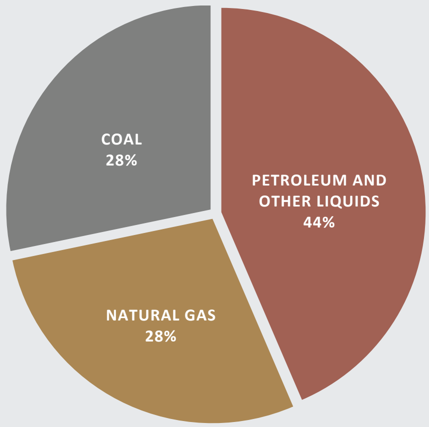
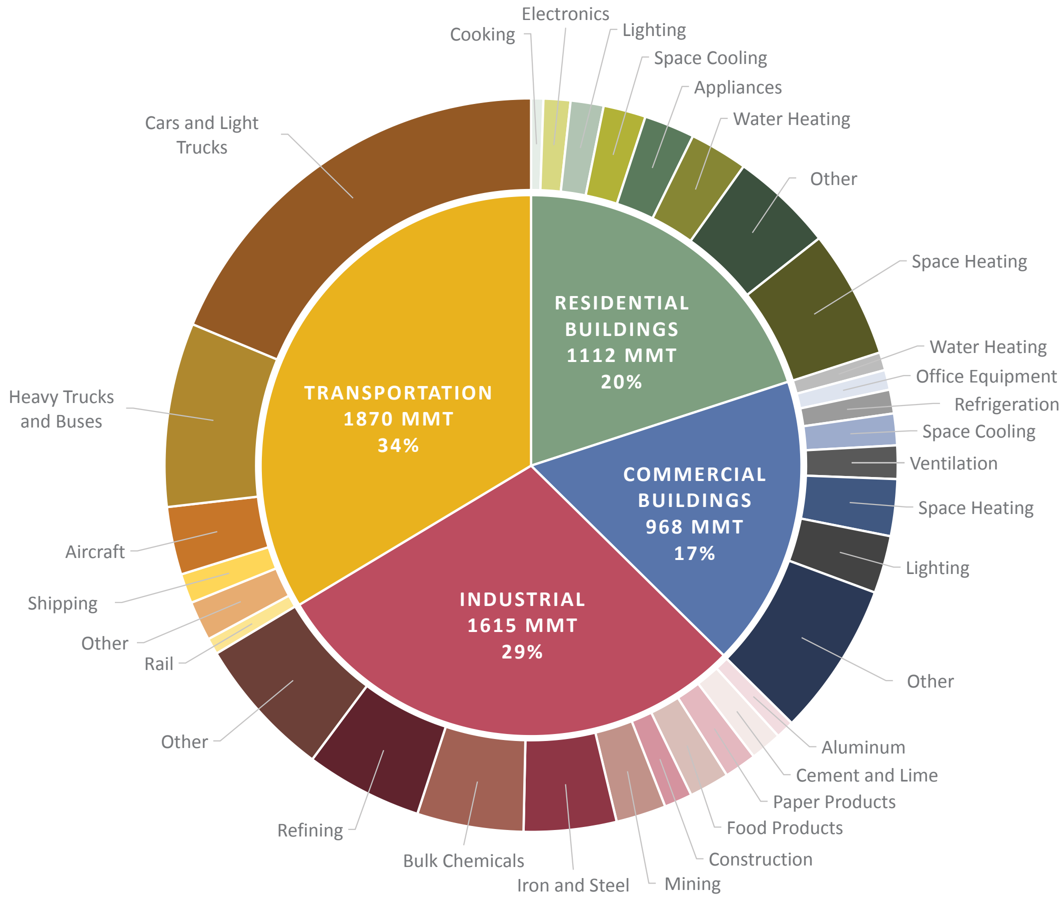


FIGURE 4.2: CO_2 EMISSIONS BY SECTOR AND END USE WITH ELECTRICITY EMISSIONS DISTRIBUTED ACROSS END-USE SECTORS, 2014



Note: Includes all CO_2 emissions from these sectors, including end-use energy use (EIA 2016a) and process emissions for the industrial sector (EPA 2016) attributed to EIA sub-sectors. The "discrepancy" categories from the EIA data have been omitted.

BOX 4.1: THE MCS VISION FOR A LOW-CARBON U.S. ENERGY SYSTEM IN 2050

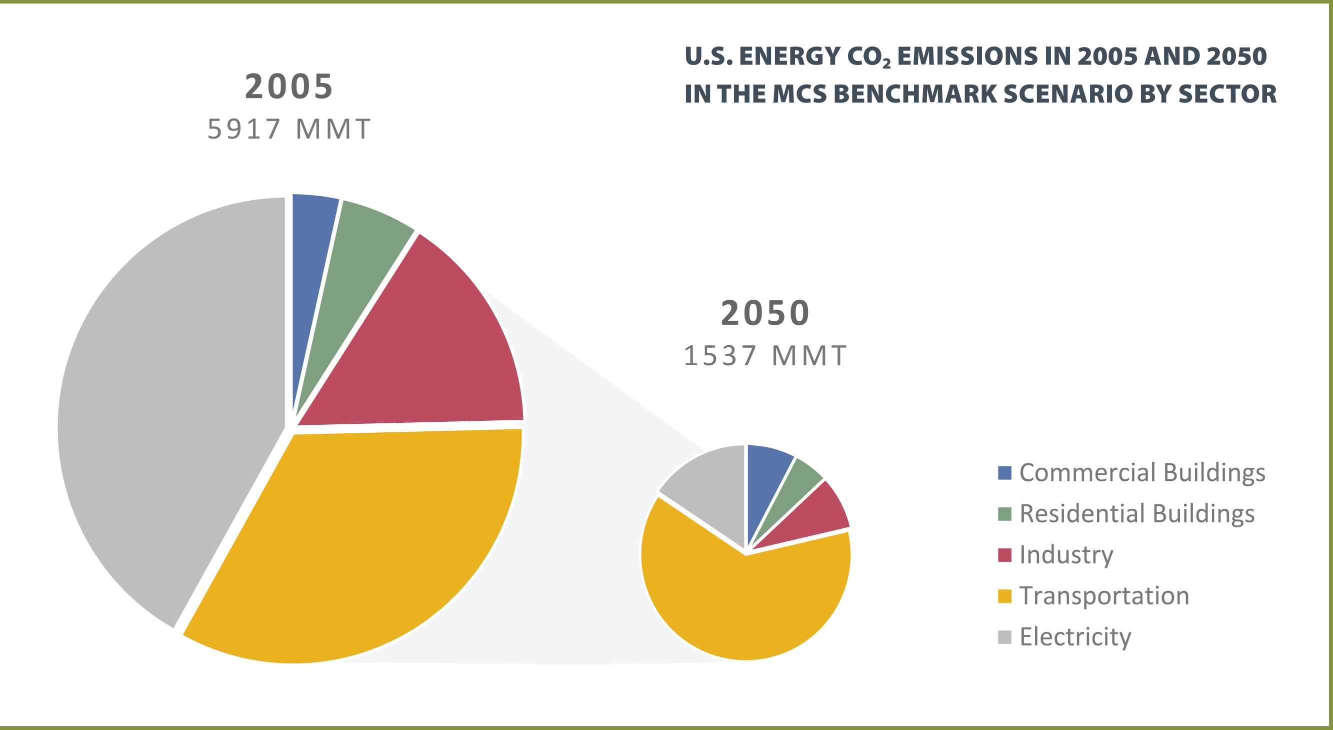
The MCS envisions a low-carbon energy system achieved through significant reductions in both the energy required to power the economy and the carbon-intensity of energy production. This involves three fundamental changes to the U.S. energy system:

1. **Improving energy efficiency, including smart growth.** Cost-effective energy efficiency opportunities that lower both pollution and energy bills are widely available, and further innovation and policy will expand these opportunities. Improved urban and transportation planning and low energy use buildings can drive structural reductions in the country's energy needs. Improving energy efficiency will limit growth in the need for electricity generation and fuels, making the energy transition easier and less costly to achieve.

2. **Near-complete decarbonization of electricity.** Nearly all fossil fuel electricity generation is replaced with low-carbon generation by 2050. The MCS envisions large and sustained investments in low-carbon generation, and the type of generation deployed (e.g., renewables, nuclear, fossil fuels, or bioenergy with CCUS) will have important ramifications for infrastructure, regulatory structures, and the need for enabling technologies such as energy storage and enhanced demand response markets to better match supply and demand over different time scales.

3. **Switching to electricity and other low-carbon fuels in transportation, buildings, and industry.** A clean electricity system creates opportunities to reduce emissions by powering an increasing number of energy end-uses with electricity instead of direct fossil fuel use (vehicles, heating, etc.). Carbon beneficial forms of biomass and other energy carriers such as hydrogen could also play an important role, particularly for energy end-uses that are difficult to electrify.

The figure below shows the direct emissions (i.e., electricity from end-uses is presented as a separate category) from the U.S. energy system in 2005 and in the MCS Benchmark scenario in 2050, omitting the negative emissions from BECCS. While the majority of residual 2050 emissions are from the transportation sector in this scenario, other plausible decarbonization pathways could show deeper reductions in transportation emissions.



The 2050 chart does not account for the negative emissions generated by CO_2 removal technologies, resulting in 963 MMT CO_2 of net emissions in the energy sector.

CROSS-CUTTING PRIORITIES

We do not know precisely what the energy sector will look like in 2050, but we do know how to spur a cost-effective low-carbon energy transformation. The MCS analysis points to two cross-cutting priorities: (1) support for clean energy innovation and (2) strong decarbonization policies.

Support for clean energy innovation. Clean energy innovation, including incremental advancements in existing technologies and fundamental breakthroughs that introduce entirely new options, can reduce the costs and increase the pace of the low-carbon energy transition. Innovation will also propel deeper emissions reductions outside of the United States, which is critical for limiting global climate change.

According to the National Research Council's *Rising to the Challenge*, "The capacity to innovate is fast becoming the most important determinant of economic growth and a nation's ability to compete and prosper in the 21st century global economy" (2015). Numerous studies have found large public returns on research, development, demonstration, and deployment (RDD&D) in energy. For example, a retrospective analysis by the National Academies of Sciences, Engineering, and Medicine found a 20 to 1 return (in direct economic benefits) on public investment in energy efficiency RDD&D from 1978 to 2000 (National Research Council 2001). Clean energy innovation is likely to pay large dividends as well, since U.S. consumers spend $1 trillion per year on energy, and the external (non-market) costs of pollution add hundreds of billions more (National Research Council 2010; Muller, Mendelsohn, and Nordhaus 2016; Shindell 2015; DOE 2016a; DOE 2016b).

BOX 4.2: HOW TO ACHIEVE A LOW-CARBON ENERGY TRANSITION:

- Double clean energy innovation investment to yield new scaled-up solutions before mid-century for even the most challenging energy uses.
- Extend state, local and sectoral emissions policies to continue driving deployment of clean technologies, shifting towards economy-wide carbon pricing over time.
- Implement complementary policies to overcome barriers to the deployment of cost-effective energy efficiency and clean energy technologies.
- Modernize electricity regulatory structures and markets to encourage flexible, reliable, cost-effective, and clean electricity generation.
- Scale up targeted support, including economic and workforce development, to ensure all Americans benefit from the low-carbon energy transition.

Still corporate investments in RDD&D in the energy sector are low (Nemet and Kammen 2007), and although venture capital firms invested substantially in clean energy technologies from roughly 2007 to 2012, those investments have subsequently declined (American Energy Innovation Council 2015; Gaddy, Sivaram, and O'Sullivan 2016). Contributing factors include high-investment requirements and risks, long timeframes for returns on investment, low margins (for example, electricity and fuels are low-cost commodities), market structures, and the lack of a price on CO_2 emissions. Adding to the challenge, despite large national expenditures for energy, federal spending on R&D for energy is small compared to the amounts devoted to R&D in other areas, such as health and defense (WRI 2014).

The MCS envisions sustained investment in clean energy technologies, from both the public and private sectors, including:

- Research conducted by the government, as well as support and incentives for R&D from nongovernment organizations.
- Support for the demonstration and deployment of clean energy technologies in situations where the private sector is likely to underinvest.
- Strong and stable market incentives that encourage private sector investors to make long-term investments in clean energy.

An important step is to follow through on the Mission Innovation commitment by the United States and 19 other governments in 2015 to double their respective public sector clean energy RD&D investments over five years. In the MCS analysis, the Beyond 80 scenario explores the potential effects of an expanded level of funding consistent with Mission Innovation, whereas the other scenarios contemplate only current levels of funding (a conservative assumption).

Strong decarbonization policies. Well-designed policies shift the costs of carbon pollution into the activity of creating it. Such policies send market signals that motivate early and sustained investment in innovation and the deployment of clean energy technologies. The MCS envisions an ambitious and sustained suite of policies to decarbonize the energy system.

Under President Obama's Climate Action Plan, the United States has acted under existing laws to cut emissions with sector-specific policies, including: emissions regulations; tax incentives for clean energy technologies; standards for energy-efficient appliances, buildings, and vehicles; and voluntary partnership programs to address market barriers to low-carbon strategies. Future administrations can use similar authorities to continue on the pathway forged by the Obama Administration. Along with expanded state and local climate policies, these actions can put the country on a pathway to emissions reductions of 80 percent or more.

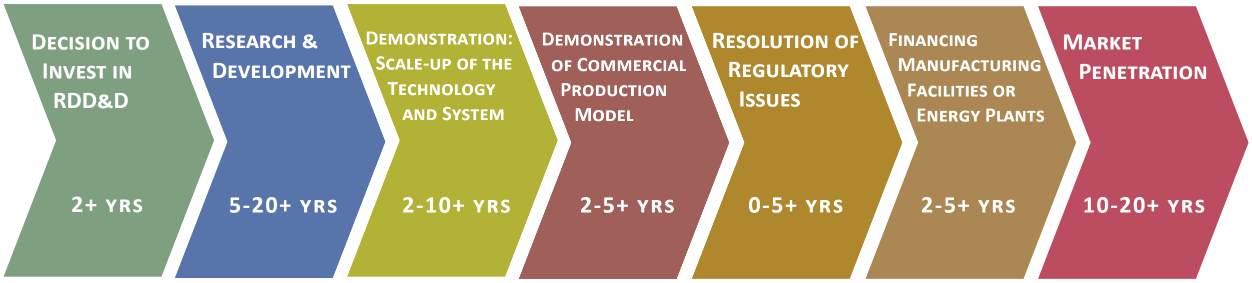
A key priority for future policymakers over time should be aligning the U.S. approach with efficient carbon pricing—either through further optimizing an increasingly ambitious state/sectoral approach or by moving to an economy-wide policy mechanism. A carbon price encourages emissions reductions however they can be achieved most cost-effectively, putting the market to work to identify the cheapest emission reduction opportunities and most effective technologies. A strong, comprehensive, predictable, and equitable carbon price can be achieved through direct carbon taxes or emissions limits with tradable permits (i.e., cap-and-trade).

By itself, a price signal is insufficient to cost-effectively achieve emissions reductions in all markets. A comprehensive suite of energy decarbonization policies should include complementary non-price policies to overcome the multiple barriers to the deployment of cost-effective energy efficiency and clean energy technologies, discussed in further detail below.

Finally, across all sectors, support for innovation and policy actions to transform the energy sector should be undertaken as soon as possible. While 2050 may seem far in the future, a cost-effective energy transition requires nearer-term actions to overcome technical and structural barriers. The innovation process can be iterative, requiring early deployment and technology learning over time. New clean energy technologies may require long gestation periods before achieving significant deployment (Figure 4.3). By ramping up clean energy innovation now, consistent with Mission Innovation, and focusing on solutions for the energy uses that we are least likely to decarbonize in the near term (e.g., certain industrial emissions), the United States can transition to a low-carbon energy system more rapidly and cost-effectively.

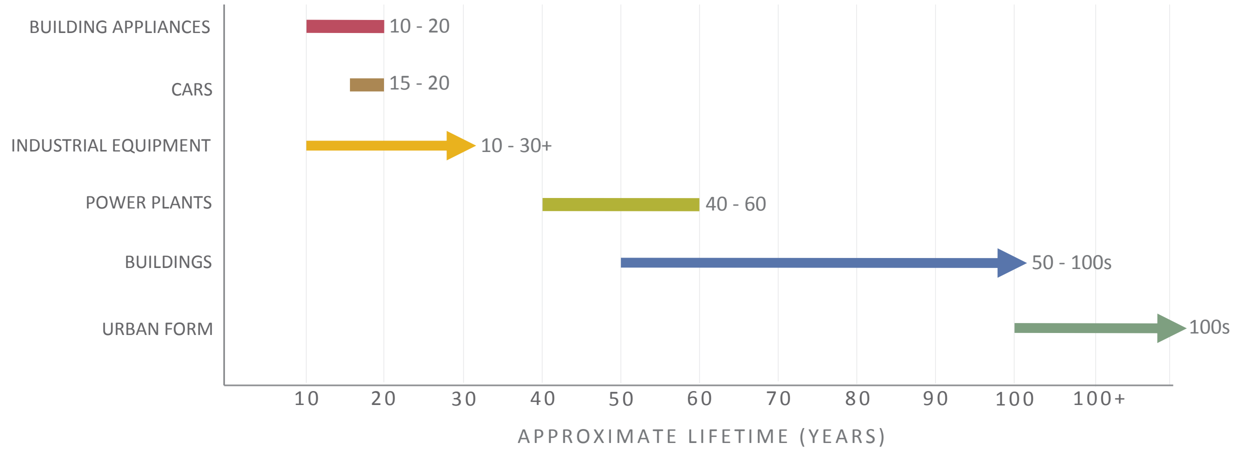
Energy infrastructure also have long lifetimes (Figure 4.4). Large infrastructure investments will be needed in the next few decades to replace aging infrastructure, which presents a vital opportunity to increase the pace and lower the costs of the energy transition with early low-carbon investments. Moreover, the deployment of innovative low-carbon technologies today drives down costs through economies-of-scale and learning-by-doing, building momentum towards a low-carbon future.

FIGURE 4.3: APPROXIMATE GESTATION TIME RANGES FOR RDD&D



Note that RDD&D is not a linear process; there can be substantial interaction and iteration across these various activities.

FIGURE 4.4: APPROXIMATE LIFETIME RANGES FOR VARIOUS CAPITAL STOCKS



Source: Lutz et al. 2011; Davis, Diegel, & Boundy 2015; EIA 2011; O'Connor 2004.

ELECTRIC POWER SECTOR

Generating the electricity we use in our homes and businesses without producing GHG emissions is perhaps the most pivotal element to achieving the MCS vision. The electric power sector has historically been the largest source of GHG emissions in the United States (EPA 2016). Coal and natural gas provide about two-thirds of U.S. electricity generation (see Figure 4.5). Due mainly to its high carbon content, coal is responsible for over three-quarters of electric power sector CO_2 emissions (EPA 2016).

In recent years, the United States has made considerable progress in producing electricity with fewer GHG emissions. Reduced electricity demand growth and increased deployment of natural gas and renewable generation have contributed to a 21 percent decline in electricity sector CO_2 emissions between 2005 and 2015 (EIA 2016d).

Even as technology cost trends and policies continue to drive emissions reductions in the coming decades, additional actions are needed over time. Analysis by DOE for the MCS indicates that without further innovation and additional policies that drive down emissions, over half of U.S. electricity generation in 2040 will come from fossil fuels without CCUS.

THE MCS VISION FOR THE ELECTRIC POWER SECTOR

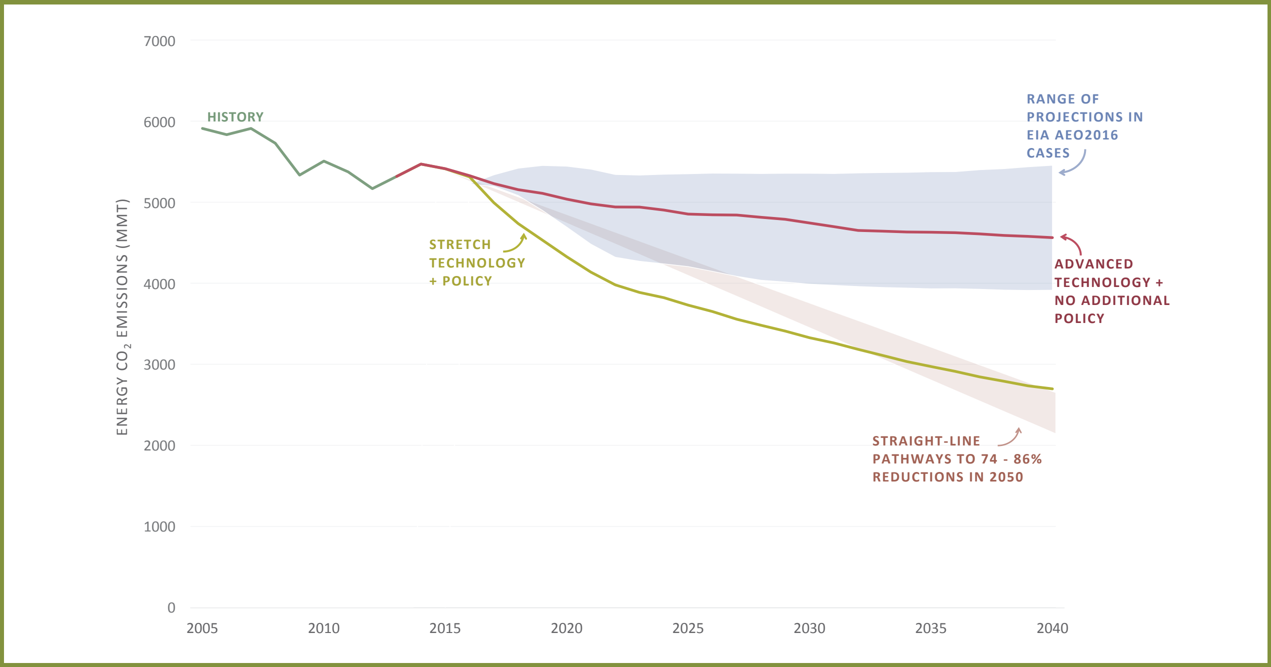
Along with a modernized electricity grid and an expanded role for energy storage and flexibility, numerous low-carbon technologies can contribute to decarbonizing the sector. The MCS analysis shows large increases in total electricity generation provided by the following low carbon generation sources (Figure 4.6):

BOX 4.3: U.S. DEPARTMENT OF ENERGY ANALYSIS IN NEMS

The U.S. Department of Energy (DOE) performed its own original analysis in support of the MCS using a version of the National Energy Modeling System (NEMS), a detailed model of the U.S. energy system with projections through 2040. Unlike the GCAM analysis discussed elsewhere in this report, the DOE analysis was not designed to achieve any specific emissions objective (such as 80 percent reductions by 2050 in the MCS Benchmark scenario). The analysis looked at two GHG pathways:

1. An "Advanced Technology + No Additional Policy" scenario, a proxy for achieving current DOE program energy goals (including technology cost and performance goals), and no additional policies are used to drive down emissions.

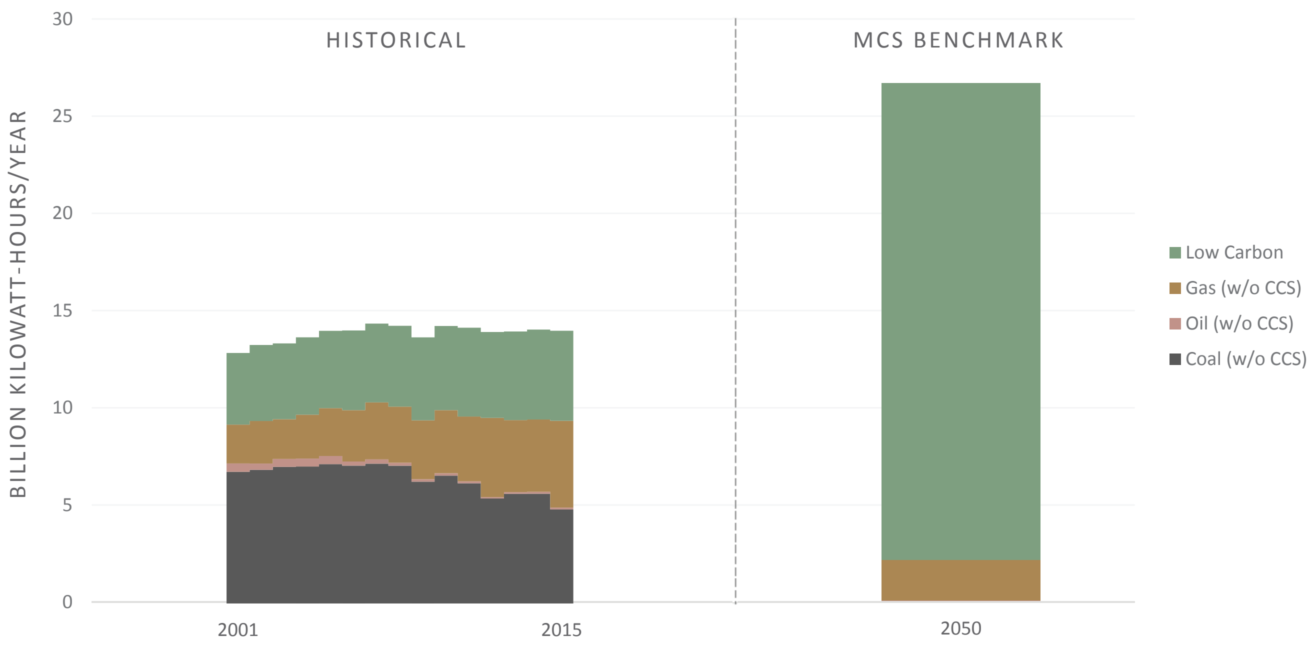
2. A "Stretch Technology + Policy" scenario with an economy-wide carbon price used as a proxy for comprehensive policy action to drive down energy CO_2 emissions. The carbon price starts at $20 per metric ton in 2017 and increases by 5 percent per year (in real terms). In this scenario, the combination of additional support for technological progress (such as through Mission Innovation) and the carbon price leads to further emissions reductions compared to the "Advanced Technology + No Additional Policy" scenario.



MCS scenarios in GCAM that achieve 80 percent reductions in economy-wide net GHG emissions show energy CO_2 reductions of 74 to 86 percent.

The DOE analysis shows that combined with successful innovation, the carbon price puts energy CO_2 emissions on a pathway consistent with the MCS vision. A key finding of the DOE analysis is that the combination of technology advances and additional policies can drive greater emission reductions than the sum of each approach on its own.

FIGURE 4.5: NET GENERATION IN THE ELECTRIC POWER SECTOR, HISTORICAL AND MCS



Source: EIA 2016d, MCS analysis.

- **Renewable energy, primarily solar and wind energy.** Although currently only 6 percent of the electric generation mix (EIA 2016d), wind and solar are the fastest-growing generation sources due to technology improvements, federal tax credits, net metering policies, and state-level policies (e.g., renewable portfolio standards). In 2015, wind and solar accounted for 68 percent of all new electricity generating capacity additions in the United States (EIA 2016e). Technological advances and an increasingly flexible electricity grid will support a continued rapid pace of deployment for solar and wind energy, and the share for these technologies is expected to double to 12 percent by 2021 even in the absence of additional policies and before the Clean Power Plan is fully in effect. (EIA 2016a).
- **Nuclear energy.** While nuclear energy provides about 60 percent of U.S. carbon-free electricity today, since 2013 five nuclear reactors have shut down and closure announcements have been made for another nine reactors. While five new nuclear reactors are scheduled to come online by 2019, building new nuclear plants in the United States remains a challenge due to high investment costs and risks, lengthy licensing and construction periods, and a decline in market competitiveness in certain regions of the country. Continued investments are necessary to extend the lifetimes of the current fleet while also investing in advanced Light Water Reactors and next-generation nuclear plants.
- **Fossil fuels and carbon-beneficial forms of bioenergy with CCUS.** Coal and natural gas power plants can continue to play a major role in the U.S. electricity system if their associated CO_2 emissions are captured and prevented from being released into the atmosphere. CCUS technology can significantly reduce or eliminate emissions from coal or natural gas plants, but it is not widely used in the United States today due to high costs and the lack of sufficient market incentives to invest in and deploy CCUS. That said, the first two power plants with CCUS in the United States are scheduled to begin commercial operation by early 2017. In addition, combining carbon beneficial forms of bioenergy with CCUS offers an important opportunity for negative emissions, by capturing CO_2 as the biomass is grown and storing CO_2 underground after combustion.

Other decarbonization scenarios could show greater contributions from additional sources like hydro, geothermal, and wave energy.

FIGURE 4.6: ELECTRICITY GENERATION ACROSS MCS SCENARIOS

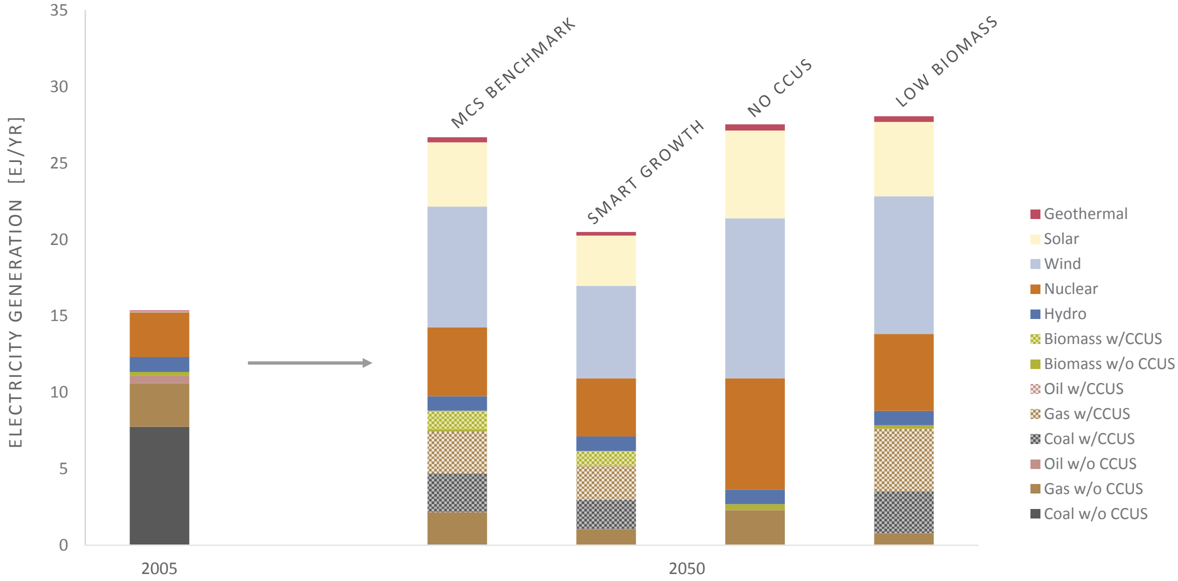


Figure 4.6 shows 2050 electricity generation mixes for four of the MCS scenarios, and it portrays two major challenges facing the sector:

1. **Near-complete decarbonization.** Electricity is generated almost entirely from low-carbon sources by 2050. The decarbonization of the electric power sector is likely to proceed more rapidly than in end-use sectors due to the cost-effectiveness and widespread potential of many low-carbon electricity sources already available in the marketplace, centralized decision-making by regulators and utilities about large central-station generation assets, and the increasing ability of consumers to switch to low-carbon distributed options such as solar photovoltaic (PV) electricity. By combining coal and natural gas with CCUS technology, the electricity system continues to use considerable amounts of fossil fuels in some MCS scenarios, but the vast majority of fossil fuel electricity generation without CCUS is phased out by mid-century.

2. **A major expansion of generation resources.** Generation from electricity expands considerably to satisfy both a growing economy and the increasing electrification of the transportation, buildings, and industrial sectors. Larger efficiency improvements in the production and consumption of electricity or a greater reliance on other low carbon fuels in end-use sectors could ease the pace of the expansion of the electricity system.

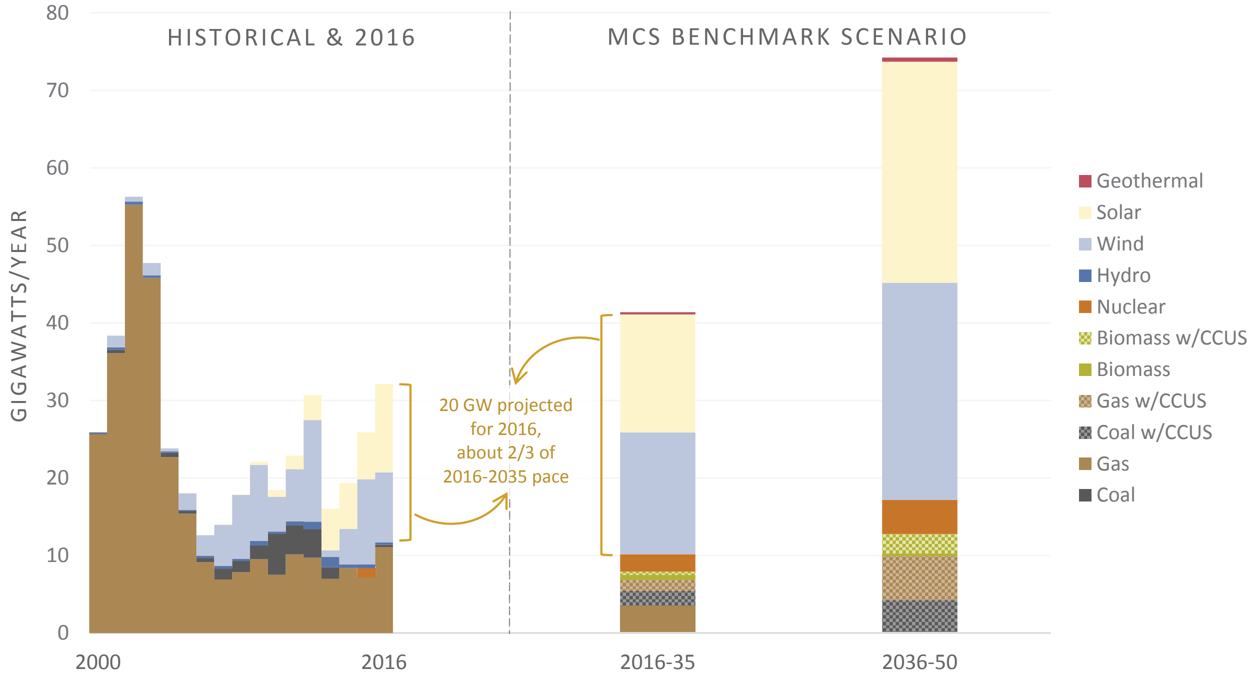
There are major benefits to supporting a wide range of electricity generation technologies. First, decarbonizing the electricity system does not depend on the success of any single technology, and the capacity additions required from any single technology are lessened due to what other technologies can contribute. Second, supporting a wide range of technologies today through a portfolio approach is likely to lower the costs of decarbonization in the long run, because we do not know today how technologies will progress over many decades; policies should be designed to enable the lowest cost technologies to emerge (while ensuring reliability).

Figure 4.7 shows average annual capacity additions for the MCS Benchmark scenario, with historical capacity additions (and 2016 projections) provided for comparison. Solar and wind energy account for the majority of capacity additions, with deployments of roughly 30 GW per year between 2016 and 2035 and over 50 GW per year between 2035 and 2050. This will require an increase in annual gigawatts of capacity additions of about 6 percent per year from 2020-2050 from the current expected pace of roughly 20 GW per year between 2016 and 2020.

The other three scenarios displayed in Figure 4.6 show different pathways to a decarbonized electricity sector, and many more are possible. The “No CCUS” scenario shows how the sector might be decarbonized without the usage of CCUS, an important contingency given that this technology is not yet widely used today. In this scenario, 2050 generation from solar and wind increase by over 30 percent compared to the MCS Benchmark scenario, and generation from nuclear energy increases by over 60 percent—nuclear capacity additions are roughly 6 GW per year between 2016 and 2050, similar to the deployment pace of nuclear energy in the 1970s. Similarly, the "Low Biomass" scenario portrays the 2050 electricity sector with a reduced reliance on electricity generated from biomass (including BECCS). Finally, the "Smart Growth" scenario portrays a pathway to decarbonization with a lower burden on the electricity system, due to strategies like improved urban planning and more efficient buildings that reduce electricity demand.

The evolution of technology costs, technology performance, and system reliability needs will influence the ultimate configuration of the electricity system. The result will have important ramifications for necessary infrastructure and regulations, and will depend on the co-development of key enabling technologies such as energy storage and grid management technologies, as well as the design of electricity markets that reward innovative low-cost grid services. For example, as the demand for electricity from electric vehicles grows, ensuring that customers can choose to charge their vehicles when rates are low (i.e., the wind is blowing and/or the sun is shining) will make a renewables-intensive power grid cheaper for all customers.

FIGURE 4.7: AVERAGE ANNUAL CAPACITY ADDITIONS BY FUEL, HISTORICAL AND MCS BENCHMARK SCENARIO



Note: 2016 data are AEO 2016 reference case projections. Source: EIA 2016a; MCS analysis.

A MODERNIZED ELECTRICITY GRID

The MCS envisions a U.S. electricity system that is reliable, resilient, secure, and affordable.

Historically, the grid was designed for large-scale generation located remotely from consumers and centrally controlled to serve passive loads. However, the grid is experiencing a period of transformation due to a variety of factors, including increasing penetration of variable generation resources, distributed generation (e.g., solar PV systems on residential rooftops, energy storage), advanced communications and control systems, and increasingly dynamic and interactive demand-side resources.

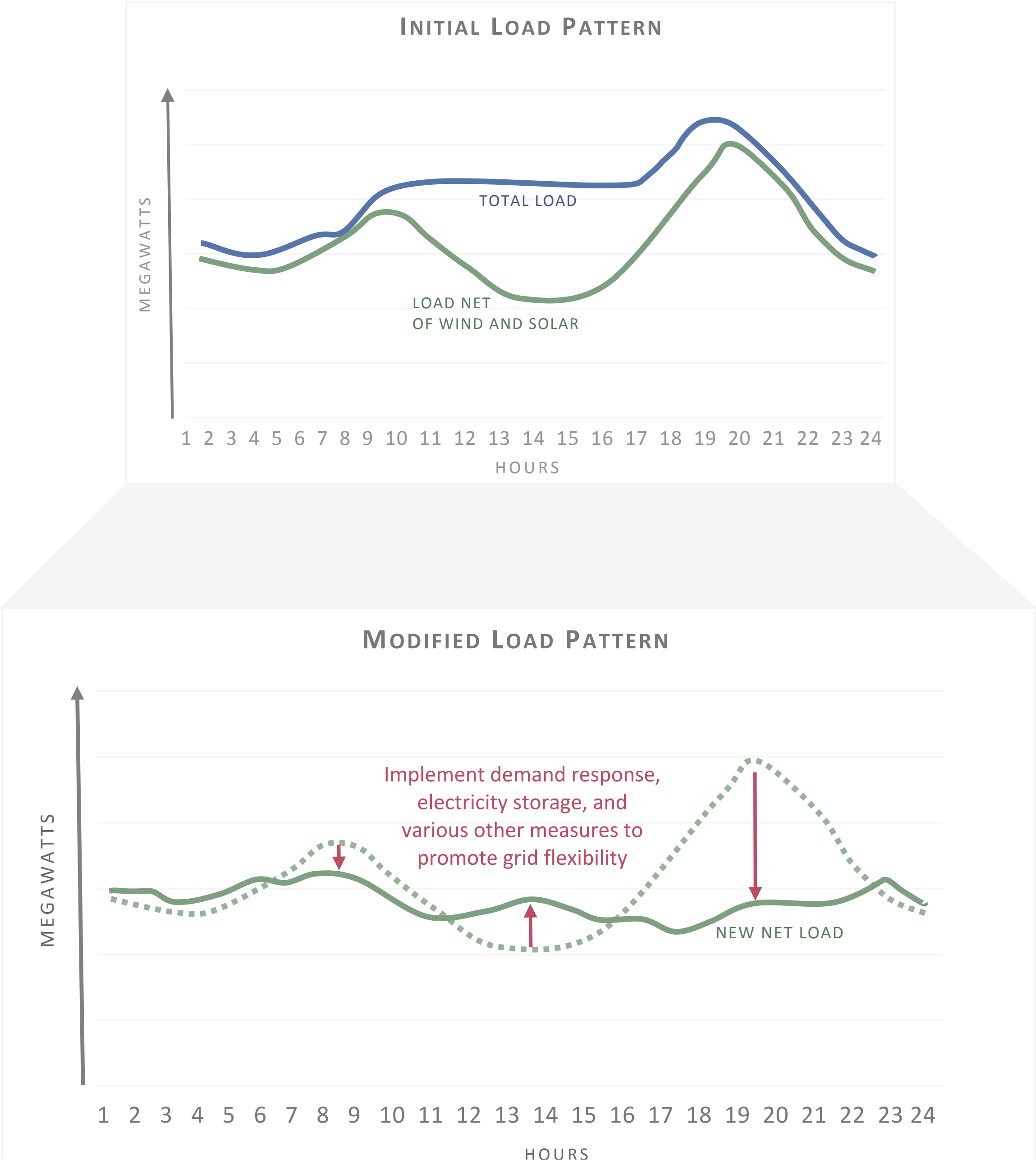
The power system has many thousands of generation facilities and millions of miles of power lines serving consumers. It is owned and operated by more than 3,000 utilities—private as well as public—and is overseen by municipal, state, and federal officials, each with different authorities. The modern grid must continue to balance supply and demand for electricity while enabling the large-scale integration of renewable generation, dynamically optimizing operations and resource use, rapidly detecting and mitigating disturbances, enabling consumers to manage their electricity use and participate in markets, and providing strong protection against physical and cyber risks.

Grid operators must continuously and nearly instantaneously match electricity supply with demand. This is primarily accomplished today by ramping up and down the output of dispatchable generation sources like natural gas. As the share of variable resources such as wind and solar increase, a more flexible power system becomes increasingly important to enable electricity supply to match demand (Figure 4.8). On the supply side, energy storage technologies (e.g., batteries, pumped hydropower, compressed air energy) enable electricity to be generated now and used later, and upgrades in our transmission networks enable larger amounts of electricity to be moved over longer distances. Demand-side management (including demand response, storage, and energy efficiency) can enable flexible demand, and time-varying electricity pricing can encourage consumers to use electricity at times when it can be supplied most affordably. Improved forecasting for wind and solar generation and better communications between grid operators can also help facilitate the integration of more solar and wind energy.

With a more flexible electricity system, variable renewable generation could supply over 50 percent of our electricity generation (Hand et al. 2012, Mai et al. 2014). With technological advancements and the increased usage of electricity storage, solar and wind could account for an ever larger share of total generation—whether this outcome is cost-effective depends on how other generation technologies progress as well. Electricity markets on the modernized grid should provide accurate price signals and recognize the full value of flexible resources, thereby encouraging efficient investment in and deployment of these resources. In addition, expanding the size of regions over which the grid is managed can assist with the management of variable renewable resources in a modernized grid. For instance, wide-area energy imbalance markets can help to efficiently address variability by leveraging geographic diversity and dispatching across a broad set of resources (Milligan et al. 2013). Finally, during times of high renewables generation and low demand, wind and solar energy could also be used to produce low-carbon fuels (e.g., hydrogen or synthetic natural gas) (Melania and Eichman 2015).

To ensure continued reliability, a modern grid will benefit from innovations in a host of technical and institutional areas to manage diverse and dynamic electricity supplies and loads, and to protect against outages. Current costs of power system disruptions have been estimated at roughly $20 billion to $50 billion per year, not including damage due to extreme weather (Campbell 2012). Without investments in resilience, costs will increase as climate change increasingly impacts the power sector. Higher temperatures can reduce the efficiency of thermal electricity production, reduce transmission capacity, and increase demand for electricity to cool buildings (DOE 2013, DOE 2016d, EPA 2015).

FIGURE 4.8: GRID FLEXIBILITY MEASURES TO ENABLE INCREASED VARIABLE WIND AND SOLAR PENETRATION



Note: Flexibility measures can reduce the need to rapidly ramp dispatchable generation to meet load net of variable wind and solar generation. Flexibility measures include demand response, targeted energy efficiency, peak-oriented renewables, storage, better forecasting and planning especially for variable renewable energy, inter-regional power exchange, and replacement of inflexible generating units with flexible generating units. Source: Adapted from Lazar 2016, Figure 5.

INNOVATION OPPORTUNITIES IN THE ELECTRIC POWER SECTOR

Clean energy technologies are widely commercialized today. Still, further innovation in low-carbon generation sources, electricity storage, and a modernized U.S. electricity grid will reduce the costs and increase the pace of decarbonization. The table below displays numerous innovation opportunities in the electric power sector.

TABLE 1. ELECTRIC POWER SECTOR INNOVATION OPPORTUNITIES

CATEGORY/TECHNOLOGY	REPRESENTATIVE OPPORTUNITIES FOR RDD&D INVESTMENTS
LOW-CARBON GENERATION	
Fossil fuels w/ CCUS	• Improved efficiency of CO_2 capture and transport • Advancement of technologies that improve the cost-effectiveness of safe and permanent storage • Development and large-scale demonstrations • Ensuring flexibility to follow load and support variable generation • Natural gas CCUS (e.g., to manage higher oxygen content, lower CO_2 concentration, higher flue gas temperatures) • CO_2 utilization (e.g., enhanced oil recovery, chemical transformation to carbon-based products such as fuels, structural materials, and high-value chemicals)
Nuclear energy	• Reduced costs and improved performance/safety of advanced nuclear • Demonstration and deployment (e.g., small modular reactors and advanced reactors) • Demonstration and deployment of nuclear-renewable hybrid energy systems with increased flexibility and process heat for industrial applications • Demonstration and deployment of a spent fuel management system
Wind energy	• Taller towers to access higher wind speeds and enable new markets. Focus areas include: longer blades, advanced generator topologies, and hybrid material tower systems • Advanced generator technologies that use affordable and widely available materials (e.g., develop substitutes for neodymium magnets) • Advanced power electronics technologies • High-performance computational modeling for plant optimization and wake dynamics • Offshore floating foundation and installation, operations and maintenance innovation and strategies
Solar PV	• Higher efficiency systems • Reducing the cost of the balance of systems • Development of thin-film solar PVs that use earth-abundant materials • High-durability PV system materials and components with 50+ year lifetimes • Advanced functionality inverters
Concentrated solar power	• Supercritical CO_2 turbine cycles • Production of fuels and other chemicals along with electricity (e.g., thermally-assisted electrolysis, direct thermochemical conversion cycles) • Lower cost materials for solar fields (e.g., heliostat systems), and for high temperature heat transfer systems and optimized storage
Bioenergy	• Reduced costs of biomass production and collection, including higher yield bioenergy crops and advanced biomass like algae • Improved performance and reduce costs of BECCS, especially for cleanup of hot gases in the system and CO_2 separation • Pilot and large-scale demonstration projects
Geothermal (conventional and enhanced geothermal systems)	• Technologies for faster, cheaper drilling and borehole integrity for conventional and enhanced geothermal systems • Improved resource identification for conventional geothermal power production, including remote characterization of potential resources deep underground • Improved ability to develop and maintain effective, large underground thermal reservoirs for significant heat extraction • Characterizing and controlling subsurface stress and induced seismicity

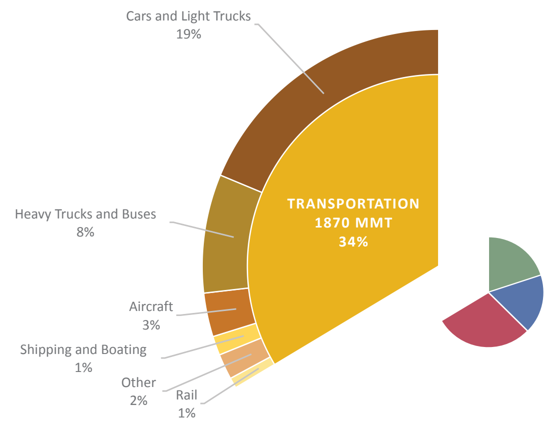
Hydropower	• Improving the performance, efficiency, and flexibility of existing hydropower plants • Development of new generation at non-powered dams using standardized modular technologies • Address concerns regarding environmental impacts of hydropower technologies • New run-of-river system technologies
Marine and hydrokinetic	• Reducing technology costs and risks for wave, tidal, and ocean current • Addressing deployment barriers
Fossil- or bioenergy-fueled combined heat and power (CHP)	• Reduced costs and improved performance of advanced CHP systems • Demonstration and deployment in residential and commercial buildings • Bioenergy-fueled CHP in industrial applications using onsite waste streams • Advanced CHP with CCUS in targeted industrial applications
GRID MODERNIZATION	
	• Improved, lower-cost power flow controllers, transformers, and converters using advanced power electronics • Devices and integrated system testing to enable the use of intelligent devices at the edge of the system to provide grid services • Sensing and measurement to provide complete visibility on the system • System operations, power flow, and controls to enable the control of potentially millions of new devices on the system • Design and planning tools to enable better long-term investment in the grid of the future • Cybersecurity tools
ELECTRICITY STORAGE	
Pumped hydropower storage (PHS)	• Further development of advanced and variable-speed PHS systems • Quantify the value of energy services provided to the grid by PHS
Energy storage (e.g., battery)	• Reduced manufacturing costs • Increased storage capacity (e.g., advanced battery chemistries) • Elongated battery lifetimes through advances in materials and design • New materials (e.g., aluminum ion batteries) that enable electricity to be produced one day and used another • Lower cost energy storage systems located on the transmission and distribution system as well as for the customer

TRANSPORTATION SECTOR

The transportation sector provides mobility for people and goods with on-road vehicles, planes, trains, ships, and other modes. The sector is responsible for about a third of all U.S. CO_2 emissions (EIA 2016a, Table A19), and the decarbonization of transportation is a critical element of the MCS vision.

Oil remains the dominant fuel used in the transportation sector, and about three-fourths of the oil used in the United States is consumed for transportation. Although U.S. oil imports have fallen dramatically with the domestic production of shale oil and increasingly fuel efficient vehicles, U.S. producers remain vulnerable to global oil market crashes and consumers to price spikes.[11] Petroleum-based transportation fuels are also a primary source of air pollution, with serious health impacts.

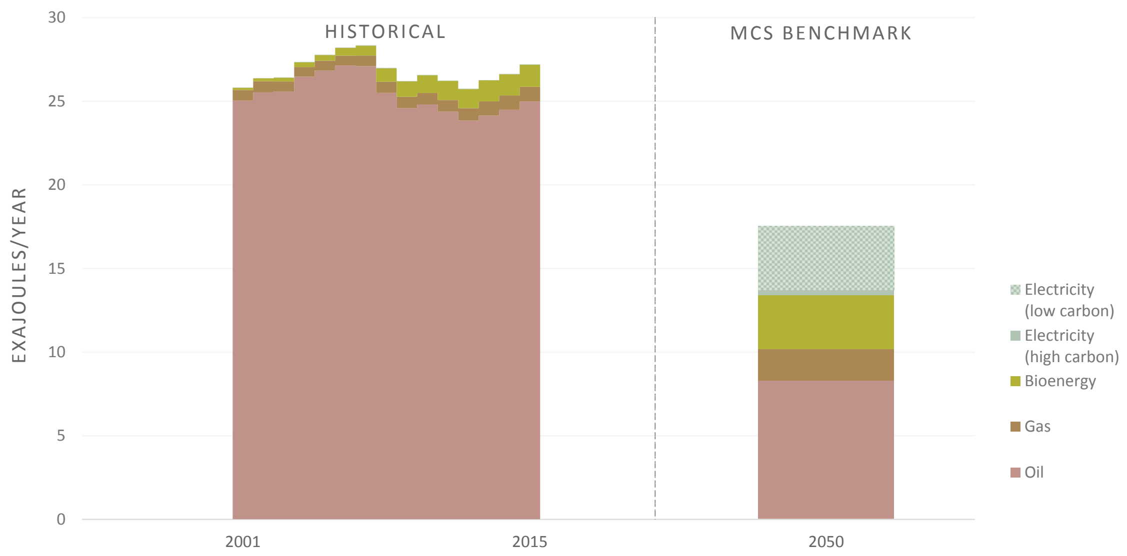
FIGURE 4.9: CO_2 EMISSIONS BY END USE: TRANSPORTATION



[11] A Federal Reserve Bank review found oil price spikes associated with U.S. economic downturns. See Kilian and Vigfusson (2014).

The United States has established fuel economy and GHG emissions standards for both light- and heavy-duty vehicles, which have reduced transportation GHG emissions significantly in recent years. Assuming oil prices are stable or increasing from recent low levels, current policies will reduce emissions for years to come as vehicle fuel economy and GHG emissions standards continue to tighten, older inefficient vehicles are replaced, and technologies improve due to long-term investments in developing lower-emissions vehicles.

FIGURE 4.10: TRANSPORTATION SECTOR ENERGY USE, HISTORICAL AND MCS



Values reported in final energy terms. Conversion losses and transmission losses are not included in this chart.[12] Source: EIA 2016d, MCS analysis.

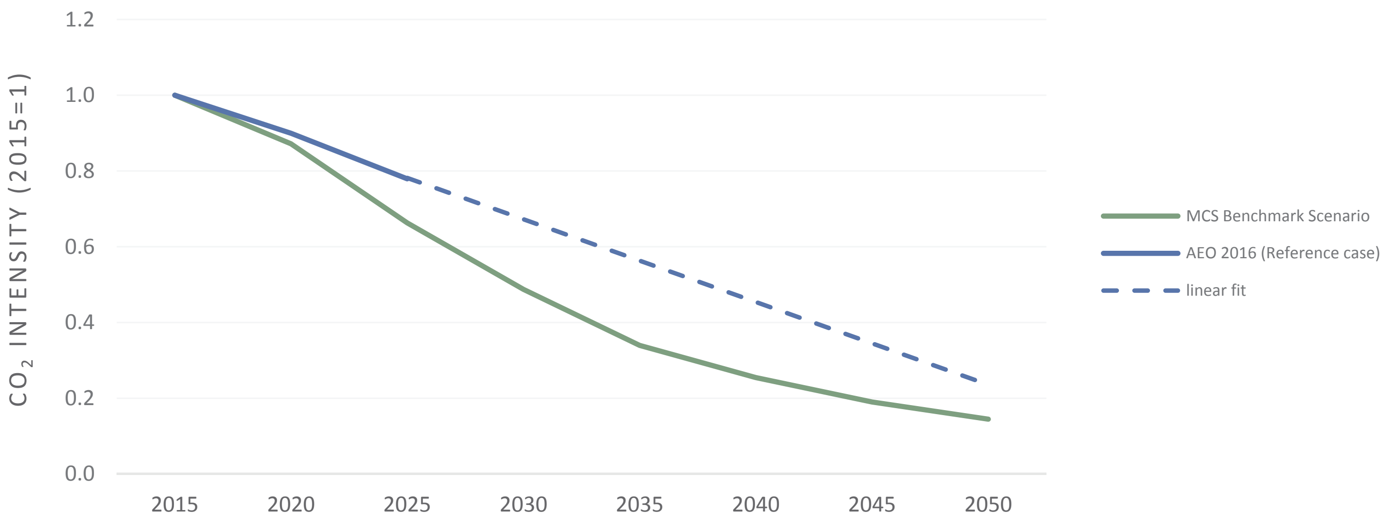
Figure 4.11 shows that if the current expected trajectory of emissions intensity improvements due to fuel economy and GHG emissions standards is sustained through 2050, fleet-wide emissions intensity would decline 76 percent between 2015 and 2050. In the MCS Benchmark scenario, emissions intensity declines 86 percent over the same period. Thus, with only a slight acceleration compared to current trends, fuel economy and GHG emissions standards have the potential to achieve carbon pollution reductions consistent with a deeply decarbonized energy system.

Of course, improvements in emissions intensity of the magnitude displayed in Figure 4.11 will require more than just improvements in the fuel efficiency of conventional internal combustion vehicles. Accordingly, there has been considerable federal and state support for the development of alternative fuels and vehicles and their infrastructure, including programs for EV charging deployment through the American Recovery and Reinvestment Act of 2009, and the Renewable Fuel Standard Program that requires renewable fuels to replace or reduce petroleum. Nine states have followed California's lead in implementing "Zero Emissions Vehicles" standards that require automakers to produce cars and light trucks that release zero emissions during operation.

Remarkable progress has been made in electric vehicles in recent years, including both performance improvements and cost reductions. New passenger battery electric vehicles (BEV) on the market have ranges of over 200 miles on a single charge, far more than nearly all drivers need in their daily lives, and deployment of charging infrastructure on interstates has begun to scale up. Still, alternative fuel vehicles account for only a small portion of U.S. vehicle sales today; widespread market penetration will require additional innovation and policy support.

[12] Energy values for direct fuel consumption are reported in lower heating value. Lower heating value to higher heating value conversion factors used are 1.05 for coal, 1.07 for oil, 1.11 for gas, and 1.05 for bioenergy (PNNL 2016).

FIGURE 4.11: FLEET-WIDE EMISSIONS INTENSITY FOR LIGHT-DUTY VEHICLES UNDER THE MCS BENCHMARK SCENARIO RELATIVE TO A STRAIGHT-LINE EXTENSION OF NEAR-TERM PROJECTIONS TO 2025



Note: Emissions intensities were calculated for each year by dividing fleet-wide LDV emissions by total vehicle miles traveled. Since existing light-duty vehicle fuel economy and GHG emissions standards only extend to 2025, this figure linearly extrapolates Annual Energy Outlook 2016 reference case projections through 2025 out to 2050. The fleet-wide emissions intensity of light-duty vehicles declines 76 percent between 2015 and 2050, relative to 86 percent in the MCS Benchmark scenario.

THE MCS VISION FOR THE TRANSPORTATION SECTOR

With the combination of continued technological advancements and strong policies and standards, significant progress can be achieved in decarbonizing the transportation sector by 2050. The MCS analysis points to the following three strategies:

1. **Increasing fuel efficiency.** Continuing to increase vehicle efficiency and fuel production efficiency will drive down energy use and emissions. Efficiency improvements may be particularly important for transportation modes that are the most difficult to electrify, such as airplanes, ships, and long-haul trucks. In addition to providing emissions reductions, transportation efficiency measures save money for individuals and businesses over the lifetimes of their equipment and reduce our reliance on oil imports.

2. **Developing low-carbon transportation fuels and vehicles.** Decarbonization of the transportation sector requires investments in low-carbon fuels and vehicles, including the following three technologies:

- Electric vehicles (EVs): With a decarbonized electric power sector, EVs are effectively carbon-free vehicles. In addition, the electric drive in an EV is far more efficient than a conventional engine and transmission, meaning EVs consume less energy to drive a given distance than gasoline-powered vehicles. As technologies improve, allowing these vehicles to travel farther on a single charge, the vehicle types and uses will diversify, leading to greater market penetration. Both battery electric vehicles (BEVs) and plug-in electric vehicles provide unique opportunities.

- Fuel cell electric vehicles (FCEVs): Like BEVs, FCEVs are low-carbon alternatives when powered by hydrogen generated from low-carbon sources, and they have much higher efficiencies than gasoline/diesel-powered vehicles, as well as a comparable range of driving distance.

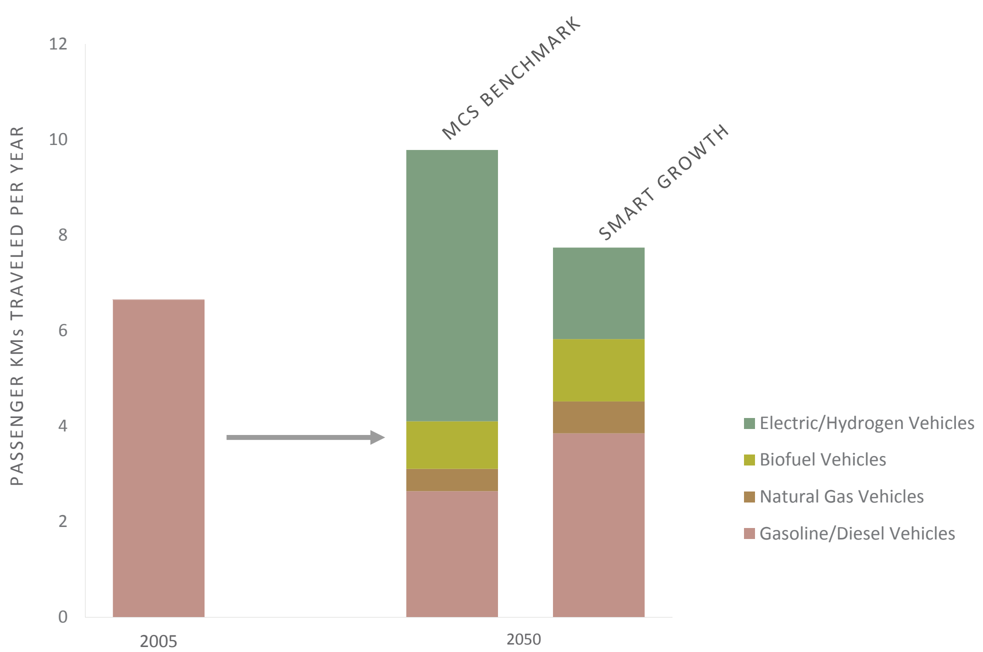
- Biomass-fueled vehicles: When combined with carbon beneficial forms of biomass, "drop-in" biofuels would have a key advantage in that they can be deployed without major changes to existing vehicles or fuel infrastructure (DOE 2015a).

All of these vehicle types are available on the market today. To achieve widespread penetration in upcoming decades, clean vehicles and fuels will require cost reductions, performance improvements, improved consumer acceptance, and development of infrastructure for recharging or fueling.

3. **Reducing vehicle miles traveled.** Transportation energy demand is influenced not only by available technology but also by societal trends. Improved and highly utilized mass transit, higher-density and mixed-use development, increased and efficient ridesharing, and walkable and bikeable neighborhoods can reduce the usage of passenger vehicles. An analysis by DOE finds that these changes to the built environment alone could reduce GHG emissions from urban light-duty vehicles by as much as 16 to 18 percent by 2050, corresponding to a transportation sector emissions reduction of 10 percent (Porter et al. 2013). State transportation departments and metropolitan planning organizations are taking the first steps to include GHG targets and performance measures as they develop their long-term transportation plans and transportation improvement programs. Further, advances in IT and the sharing economy are initiating a shift from a vehicle ownership society to one of shared mobility, where mobility is purchased by the mile rather than by the vehicle. Smart urban planning can capitalize on this shift, freeing up land that is now needed to house vehicles for alternative and more societally beneficial uses, including more compact, walkable cities. Finally, improved freight logistics and modal shifting of freight from long-haul trucks to rail have the potential to drive down the distance traveled and corresponding emissions from heavy-duty vehicles.

The MCS analysis highlights two pathways to a lower-GHG transportation sector. The MCS Benchmark scenario portrays a rapid deployment pathway for clean vehicles, driven by a combination of technology improvements, policy support, and increasing consumer acceptance. By 2035, roughly half of light-duty vehicle sales are clean vehicles. Due to slow stock-turnover (light-duty vehicles can be on the road for 15-20 years), the composition of the vehicle fleet lags behind, but by 2050, clean vehicles account for over 60 percent of light-duty vehicle miles traveled, and significant (though lesser) progress is also made in clean heavy-duty vehicles.

FIGURE 4.12: U.S. LIGHT-DUTY PASSENGER VEHICLES KILOMETERS TRAVELED IN THE MCS



MCS analysis highlights two pathways to a low-GHG transportation sector, with an aggressive deployment pathway for clean vehicles in the MCS Benchmark scenario and the "Smart Growth" scenario focusing on improved mass transit and urban planning.

In the "Smart Growth" scenario, the primary approach for achieving transportation sector emissions reductions is through strategies that limit the increases of vehicle miles traveled as the U.S. population and economy grow. This includes improved mass transit and urban planning. The deployment of clean vehicles is less rapid over the next 34 years, yet deployment of alternative fuel vehicles is still significant, with clean vehicles accounting for roughly one-third of light-duty vehicle sales in 2035 and over 40 percent of VMT in 2050.[13] Compared to the MCS Benchmark scenario, the Smart Growth scenario involves a greater reliance on gasoline and diesel vehicles. Smart growth strategies achieve emissions reductions in other sectors (e.g., buildings) so achieving 80% requires less ambition in clean vehicle penetration. However, deploying smart growth strategies in parallel with electric drive vehicles has the opportunity to contribute to reductions beyond 80 percent.

Additional strategies to reduce transportation sector emissions (not modeled in this MCS) include advances in connected and automated vehicles. With well-crafted policies that direct these emerging trends in a way that accelerates decarbonization, increasing automation and connectivity can reduce GHG emissions through smoother driving, vehicle platooning, right-sizing, lightweighting, accelerated vehicle turnover, reduced congestion, and lower VMT. Earlier this year, the U.S. Department of Transportation took an important first step, issuing a set of guidelines for vehicle developers that will help to ensure the safe testing and deployment of autonomous vehicles.

INNOVATION OPPORTUNITIES IN THE TRANSPORTATION SECTOR

In the MCS analysis, despite major progress in decarbonizing the sector, the majority of total residual emissions in the energy sector in 2050 are from the transportation sector, which points to the importance of continued innovation. This includes cleaner and more efficient vehicles, as well as smart urban design that would reduce vehicle miles traveled. Advances in vehicle automation and connectivity could contribute to both, making efficient vehicles more cost-effective and freeing up urban space used for parking for other uses. For certain transportation modes—particularly those that are difficult to electrify like long-haul trucks and aircrafts—far more RDD&D is needed to uncover the most cost-effective ways to reduce GHG emissions.

BOX 4.3: ELECTRIC VEHICLES IN A MODERNIZED ELECTRICITY SYSTEM

A growing fleet of electric vehicles implies a larger electricity system with an increased need for low-carbon generation. However, EVs may also present an important opportunity to add flexibility to a modern electricity grid. Policies, rate structures, and other regulations should strategically encourage battery charging at certain times, such as when demand for electricity is low or when variable electricity generation from renewable energy is high. Additionally, "Vehicle-to-Grid EVs" could provide a bi-directional flow of power, providing energy storage and supplying electricity to the grid when it is needed most. Similar to other "demand-side management" efforts, EVs would thus reduce the need for relatively expensive power plants to provide generation when demand for electricity is high, and enable increased penetration of variable generation sources like solar and wind.

[13] In reality, smart growth strategies may well lead to the increased penetration of electric vehicles, and we do not mean to imply that there is a negative correlation between smart growth and electric vehicle penetration. Instead, the objective of this scenario is to show a markedly different pathway for achieving emissions reductions in the transportation sector.

TABLE 2. TRANSPORTATION POWER SECTOR INNOVATION OPPORTUNITIES

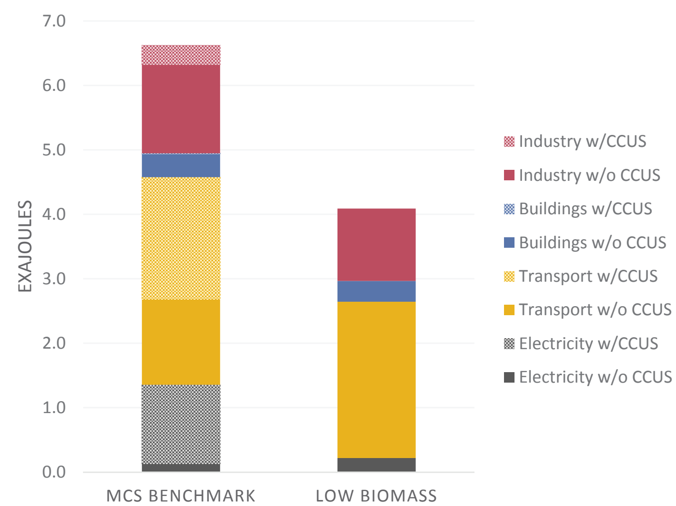
CATEGORY/TECHNOLOGY	REPRESENTATIVE OPPORTUNITIES FOR RDD&D INVESTMENTS
Battery electric vehicles	• Battery chemistries with higher energy densities, lower costs, and longer lifetimes • Hybrid, plug-in hybrid, and battery technology for long-haul heavy-duty vehicles • Faster recharge times • Ability to withstand higher temperatures associated with rapid recharging • New materials and methods for battery terminals (i.e., anodes and cathodes) for longer lifetimes and higher capacities • Optimal integration with the electric power system
Fuel cell electric vehicles	• Improved performance and reduced costs of producing hydrogen with clean energy (e.g., advanced electrolysis, thermally-assisted electrolysis, thermochemical processes, direct solar water splitting from renewable, nuclear, fossil-CCUS sources) • More affordable materials in the fuel cell • Reduced energy needs for hydrogen compression and increased durability of storage • Hydrogen power trucks and buses • Improved performance and reduced costs of producing hydrogen using clean energy (advanced water splitting using renewables/low carbon sources, biomass, waste, thermochemical processes, etc.) • Reduced cost and improved durability of fuel cell materials (catalysts, membrane, etc.) • Improved energy efficiency and reliability of hydrogen compression, storage, and dispensing • Fuel cells in medium- and heavy-duty transportation markets (delivery vans, short-haul freight trucks, etc.)
Biofuels	• Reduced biofuel production costs • Improved production efficiency • Development of "drop in" fuels that can be used in existing transport and require no changes to existing fuel infrastructure • Co-optimization of engines with low-carbon fuel to maximize performance and GHG reductions • Ensure biomass is produced and used in ways that are carbon beneficial (see Chapter 5)
Improved vehicle efficiency	• Reduced costs and improved performance of lightweight materials (e.g., advanced high-strength steels, magnesium alloys, aluminum alloys, and carbon fiber composites) • Vehicle automation and connectivity • Advances in engine efficiency • Advanced transmission systems • Improved waste heat recovery • Improved aerodynamics • Improved heating and cooling systems for passenger space • Reduced tire rolling resistance
Aircraft	• Jet fuels using feedstocks from carbon-beneficial forms of biomass • Airframe technology • Propulsion technology • Systems integration • Fuel cell technology • Hybrid technology
Modal shifting	• Improved deployment and utilization of mass transit • Smarter urban planning • More walkable/bikable cities • Shift long-distance freight transport to rail

BOX 4.4: BIOENERGY USE ACROSS THE ENERGY SECTOR

Carbon-beneficial forms of biomass are a versatile decarbonization tool because they can be processed in multiple forms (liquid, gas, or solid) and utilized to displace fossil fuels in many parts of the economy without large-scale infrastructure changes. The MCS analysis shows bioenergy consumption in 2050 ranging from 4.1 to 6.6 exajoules, and a significant portion of biomass consumption could occur in the transportation sector (see figure below), where it supplies energy for end-uses that are difficult to electrify, including heavy-duty vehicles, aviation, and shipping. Another potentially significant source of biomass demand in 2050 is for industrial use. Finally, bioenergy plus carbon capture and storage (BECCS) provides a unique opportunity for generating negative emissions.

As discussed further in Chapter 5, carbon accounting frameworks must be put in place to ensure biomass use does not come at the expense of the domestic land carbon sink or cause deforestation or other adverse land use changes abroad. The biomass supply estimates used in the MCS are based on assessments and modeling of types and volumes of biomass that could be available by 2050 while meeting many other demands on U.S. landscapes, including growing global food demand, increasing carbon storage in forests and soils, and preserving habitat and high-value conservation areas.

Bioenergy (EJ) in the MCS analysis across electricity, transport, industry, and buildings, 2050. Note that the Low Biomass scenario includes no BECCS by assumption.



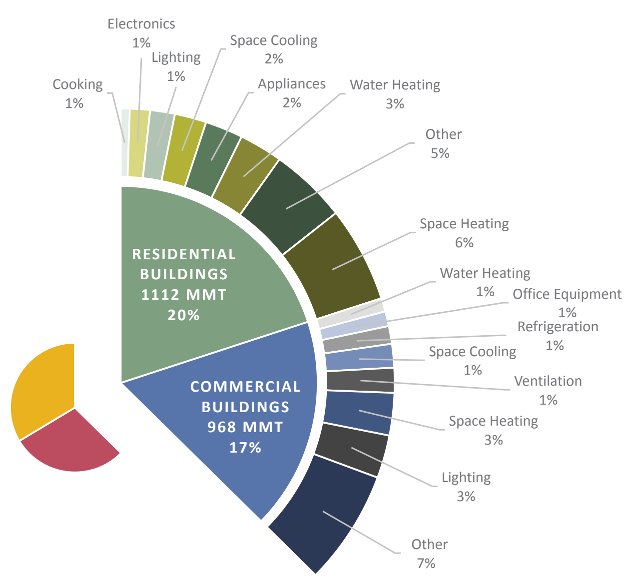
BUILDINGS SECTOR

Residential and commercial buildings are responsible for over one-third of the CO_2 emissions from the U.S. energy system (EIA 2016b). Over 70 percent of building sector emissions come from electricity use, with the remainder from direct fuel use for space heating, water heating, and other services (EIA 2016d, Tables 12.2 and 12.3). Buildings currently consume the majority of electricity in the United States, accounting for about three-quarters of electricity sales in 2015 (EIA 2016c).

Space heating and cooling, lighting, water heating, and refrigeration consume the most energy of U.S. building end-uses, and account for over half of building emissions.

The intensity of energy use in U.S. buildings has declined markedly in recent years due to energy efficiency policies, including federal efficiency standards for most major end-uses, voluntary partnership programs such as ENERGY STAR,

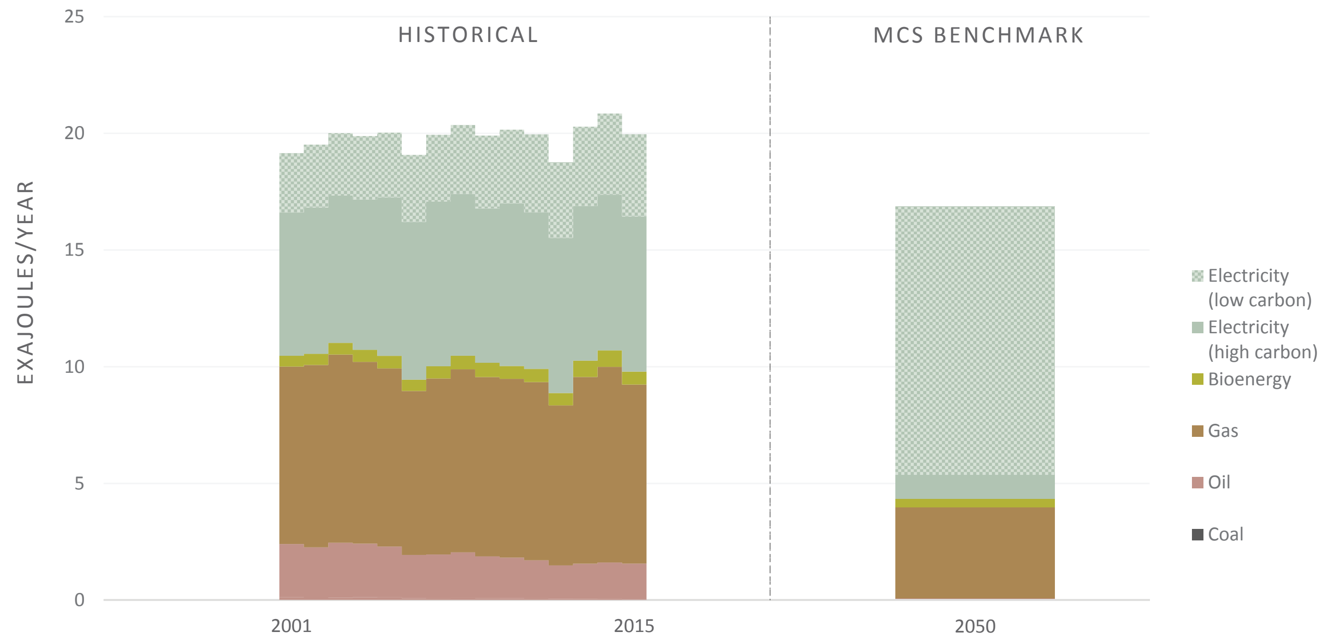
FIGURE 4.13: CO_2 EMISSIONS BY END USE: BUILDINGS



state and local building energy codes, and demand-side energy efficiency programs across all 50 states and including "energy efficiency resource standards" in 20 states that require a minimum level of demonstrated energy savings each year, among many others. Consequently, building CO_2 emissions have decreased 16 percent since 2005 (EIA 2016d) even while building space has increased substantially.

DOE projections indicate these trends are likely to continue and have the potential to save consumers and businesses approximately 1 billion MWh of electricity between 2013 and 2030, and reduce energy costs in the process (DOE 2016h). However, deep reductions in building sector emissions require further investments in energy efficiency technologies and systems, coupled with expanded use of proven policies to support the shift to cleaner fuels.

FIGURE 4.14: BUILDINGS SECTOR ENERGY USE, HISTORICAL AND MCS



Note: Values reported in final energy terms. Conversion losses and transmission losses are not included in this chart.[14] Source: EIA 2016d, MCS analysis.

THE MCS VISION FOR THE BUILDINGS SECTOR

The MCS analysis points to two primary strategies for transitioning to a low-carbon buildings sector:

1. **Energy efficiency.** The continuation of recent trends toward increased energy efficiency in the building sector can reduce costs for consumers, increase system flexibility, and reduce the required buildout of clean power systems (or other low-carbon fuels), making the energy sector transition less costly and easier to achieve. For example, continued efficiency improvements in lighting, building shells, and building energy systems will yield significant benefits. More compact and efficient building designs will lower the energy demands of new buildings.

2. **Electrification of end-uses.** Further electrifying building end-uses—combined with the near-complete decarbonization of the grid—is an important strategy to reduce building emissions. A key opportunity for electrification in buildings lies in space heating and hot water heating appliances. About half of U.S. floor space is currently heated with systems that directly burn fuels. Increased electrification represents an acceleration in current trends for residential and commercial space heating in certain regions of the country (see Box 4.5).

[14] Energy values for direct fuel consumption are reported in lower heating value. Lower heating value to higher heating value conversion factors used are 1.05 for coal, 1.07 for oil, 1.11 for gas, and 1.05 for bioenergy (PNNL 2016).

BOX 4.5: ELECTRIC HEAT PUMPS[15]

Unlike typical gas furnaces, which generate heat by combusting natural gas, heat pumps move heat energy from one place to another to achieve optimal temperature inside a house. In the summer, heat pumps cool houses by removing excess heat energy from air inside the house to outside, while in the winter, heat pumps transfer outside heat energy indoors to warm the home. By transferring rather than generating heat, heat pumps require substantially less energy, run on electricity rather than natural gas, and can provide the same space heating or cooling capacity at as little as one-third the cost of conventional equipment. Additionally, some high-efficiency heat pumps recover heat waste from cooling operations, channeling that heat towards heating water two to three times more efficiently than a conventional water heater.

Recent technological advancements in heat pumps have expanded their use across the United States, including to efficiently meet heating needs in colder regions. Current limitations of heat pumps are very similar to the challenges being faced by air conditioning technology in general: the transition to low-GWP refrigerants, dehumidification performance (latent load performance), heat exchanger performance, and weight and size constraints. Ongoing research is addressing these challenges.

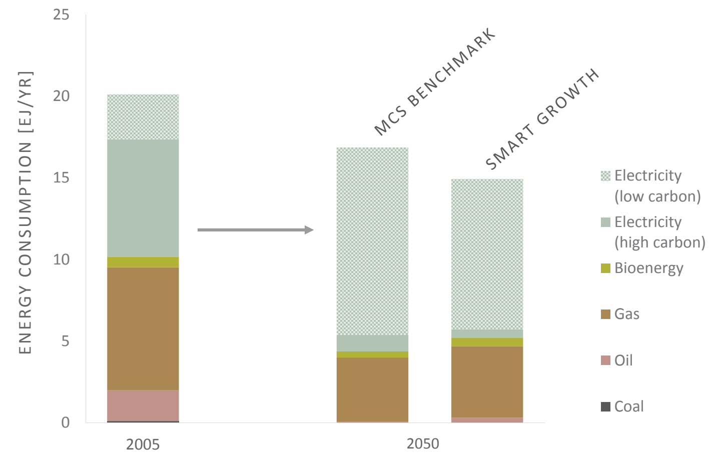
The acceleration of these trends can significantly reduce the costs and increase the pace of decarbonization in the buildings sector. Indeed, a recent study on achieving 80 percent emissions reductions by 2050 in San Francisco finds that "Market adoption of electric heat pumps for 80 percent of citywide heat consumption is the single most impactful lever considered" (SF Environment 2016).

Heat pumps are also used in industry, predominantly for low-temperature applications such as drying lumber and food products, and for distillation of petrochemical products. Industrial heat pumps may be used to increase the temperature of waste heat, capturing an energy resource that was previously unused. In addition to efficiency benefits, heat pumps may offer non-energy benefits of process productivity and product quality improvement. Current limitations of industrial heat pumps include the maximum temperature of heat they can provide. Ongoing research seeks to increase the upper temperature limit to expand use in higher temperature processes.

[15] For more on electric heat pumps, see DOE (2016c).

The MCS envisions reductions in building energy use (even in the context of a growing population and economy) and the near-complete decarbonization of the sector. Two pathways are highlighted in Figure 4.15. Both scenarios rely heavily on electrification and efficiency improvements. The "Smart Growth" scenario relies somewhat less on electrification and more on reduced energy demand. Changes on the scale envisioned in either scenario will require ambitious policies to reduce emissions from the electricity sector, to promote energy efficiency in buildings, and to support the development and deployment of technologies that enable increased electrification.

FIGURE 4.15: ENERGY USE IN U.S. BUILDINGS IN THE MCS ANALYSIS



Decarbonized energy from electricity and, perhaps to a more limited extent, carbon beneficial forms of biomass or hydrogen, are critical to reducing GHG emissions in buildings because CCUS is impractical in the small-scale and widely distributed applications found in the buildings sector. On-site clean electricity generation (e.g., with distributed solar, wind, or geothermal) will contribute to the decarbonization of the buildings sector as well.

The slow stock turnover of buildings is a key consideration in achieving deep emissions reductions in the sector. Building lifetimes are often 50 to 100 years or more, and the existing stock is large and generally less efficient than new buildings. Building features that impact energy use last for decades (e.g., windows, insulation, air-sealing, and large appliances such as air conditioners, refrigerators, and washing machines). This slow stock turnover elevates the importance of ensuring that starting today, new buildings and buildings features are designed for optimal efficiency and low carbon emissions. Retrofitting existing buildings (at a low cost and with minimal disruption) is also critical for capturing near- to mid-term energy savings and emissions benefits (Wilson et al. 2016).

BOX 4.6: ENERGY EFFICIENCY PROGRAMS AND POLICIES

Programs and policies that promote energy efficiency are highly effective at reducing energy usage. Energy efficiency programs are commonly funded by electric and natural gas utilities and their customers, and can avoid the need for these utilities to procure or generate additional, higher-cost electricity. Energy efficiency programs commonly save consumers a significant amount of money over the lifetime of the installed measures. For example, the 44 new or updated appliance standards (in part enabled by RDD&D) put in place since 2009 are projected to cumulatively save by 2030 over $550 billion for consumers and 42 quads of energy (DOE 2016d).

Despite these substantial savings, consumers commonly do not take advantage of economic energy efficiency opportunities in the absence of programs and standards, due to market barriers that include:

- ***Information failures and asymmetries.*** Consumers may have insufficient or inaccurate information regarding their energy use reduction opportunities, the energy efficiency characteristics of goods and services, the comparative cost-effectiveness of product choices, or available incentives for efficient equipment and appliances.
- ***Split incentives.*** Those purchasing major appliances (e.g., landlords) may not be the same people as those who pay the electricity bills (e.g., tenants).
- ***Shortsightedness.*** Consumers may place a high value on near-term financial consequences; public policies should take and incent a longer view.
- ***Lack of investment capital.*** Some consumers cannot afford the upfront costs required to make smart long-term investments in energy efficient equipment.

Policy support for improving the efficiency of buildings and overcoming the barriers mentioned above take many forms, and existing policies and programs include building energy codes, appliance standards, RDD&D, weatherization programs, energy benchmarking programs, energy efficiency tax credits, targeted incentives, market transformation programs, and workforce training programs. Additional and strengthened market-focused programs can help accelerate the adoption of more energy-efficient and cost-effective technologies, and ensure an adequate workforce for designing, building, and operating new energy-efficient systems.

INNOVATION OPPORTUNITIES IN THE BUILDINGS SECTOR

Innovation in the buildings sector will increase the effectiveness and lower the costs of achieving deep emissions reductions. In particular, we need investments in RDD&D for the decarbonization of emissions sources that are difficult to electrify. Key innovation opportunities are described below.[16]

[16] For additional examples and detail, see Chapter 5 of the Quadrennial Technology Review (DOE 2015).

TABLE 3. BUILDINGS SECTOR INNOVATION OPPORTUNITIES

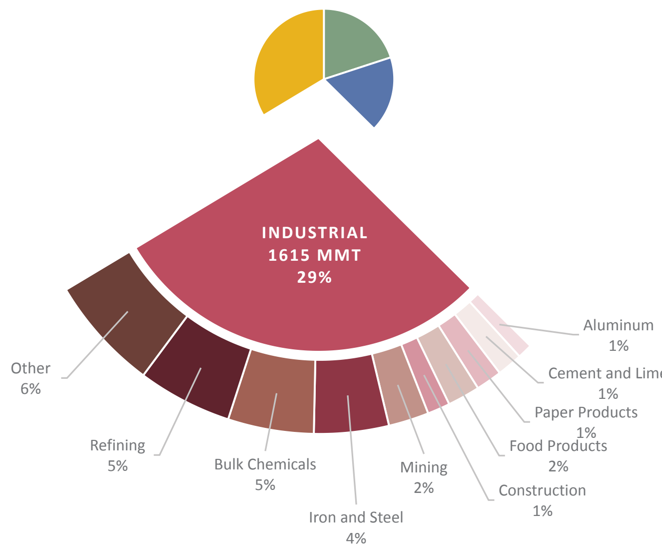
CATEGORY/TECHNOLOGY	REPRESENTATIVE OPPORTUNITIES FOR RDD&D INVESTMENTS
SPACE AND WATER HEATING AND COOLING SYSTEMS	
Electric heat pump for heating and cooling	• Reduce technology costs and improve overall system efficiencies • Enable improved operation at low ambient temperatures • Provide same or better level of space heating and cooling services as alternatives • Develop heat pumps using solid-state materials (e.g., using magnetic, electric, elastic, or other properties) or other advanced cycles
Refrigerants	• End the use of conventional refrigerants that have a high GWP (Global Warming Potential) and improve the performance and reduce the cost of alternative refrigerants that can be used in conventional systems
Renewable alternatives	• Reduce the cost and improve the performance of geothermal heat pump systems • Reduce the cost and improve the performance of solar water heating, particularly for systems in climates with winter freezing
OTHER BUILDING	
Building shell	• Advance building envelope technologies to further reduce thermal loads and control flow of air and moisture • Improve windows for highly insulating properties • Reduce the cost and improve the performance of dynamic solar controls for windows
Lighting and miscellaneous electric loads (MELs)	• Reduce costs and improve performance of LEDs • Advanced lighting system controls and integration • Increased efficiency of MELs (including small devices that are widely used, such as cellphone chargers, large devices that are not widely used, etc.)
Building systems	• Enhanced integration of building energy systems (e.g., lighting control through window controls, occupancy detectors, etc.) • Advanced demand-side management (DSM) technologies and development of DSM aggregation tools and their integration to the grid • Coordination of building energy system performance, on-site generation from renewables or combined heat and power (CHP), and energy storage • Improved collection of building performance data

INDUSTRIAL SECTOR

The industrial sector is responsible for about 30 percent of CO_2 emissions from the U.S. energy system. The sector groups together a diverse set of industries, including chemicals, steel, and cement production. In addition to CO_2 emissions, industrial sector GHG emissions include nitrous oxide, methane, and fluorinated gas emissions, which are discussed in more detail in Chapter 6.

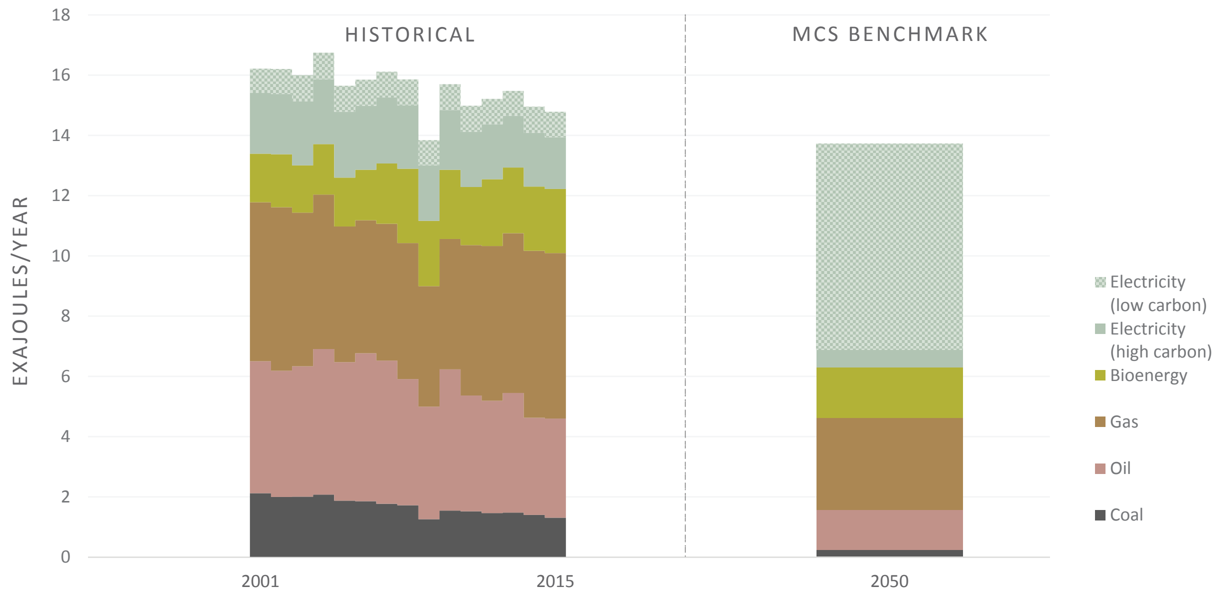
As displayed in Figure 4.17, industrial sector fuel consumption is dominated by onsite-fuel usage, which mainly consists of natural gas and oil. Electricity was responsible for 14 percent of industrial fuel consumption in 2014 (EIA 2016a).

FIGURE 4.16: CO_2 EMISSIONS BY END USE: INDUSTRIAL



Note: Includes energy and process emissions.

FIGURE 4.17: INDUSTRIAL SECTOR ENERGY USE, HISTORICAL AND MCS



Note: Values reported in final energy terms. Conversion losses and transmission losses are not included in this chart. EIA data adjusted to remove non-manufacturing and refining from the industrial sector to align with GCAM definition.[17] Source: EIA 2016a, MCS analysis.

THE MCS VISION FOR THE INDUSTRIAL SECTOR

Due to its heterogeneity, decarbonization of the industrial sector will likely be industry- and process-specific. Cross-cutting themes for reducing industrial sector emissions are likely to include: (1) efficiency improvements and new materials and methods, and (2) fuel switching:

1. **Efficiency improvements and new materials and methods.** Due to the high-energy intensities of many industrial processes, cost-effective improvements in energy efficiency are an important strategy to achieve emission reductions in this sector. Improving the efficiency of heating and motors will be particularly important because they account for approximately 30 percent of total industry energy use. Other strategies include intensification (i.e., multiple processes on the same machine or use of higher process temperatures), the use of improved controls and sensors including using information technology (i.e., "smart manufacturing"), and new, more efficient industrial processes (DOE 2015a).

   Cross-sectoral impacts tied to the manufacturing sector are also important to consider. New materials and production methods (e.g., additive manufacturing and advanced composites) have the potential to reduce energy use within the industrial sector, and can also enable improvements in other economic sectors (DOE 2015a). For example, in vehicle manufacturing, new manufacturing methods can produce components that achieve the same function with less material. These optimized parts can enable lightweight vehicles with improved fuel efficiency, reducing energy consumption in the transportation sector.

2. **Switching to low-carbon fuels and feedstocks, including clean electricity.** With the decarbonization of the electricity system, the increased electrification of industrial energy uses will reduce emissions. With current technologies, a key opportunity is in iron and steel production, where many basic oxygen furnaces can be converted to electric arc furnaces. Where electrification is challenging for physical or economic reasons, certain industrial sub-sectors may be a high-value use for carbon beneficial forms of biomass.

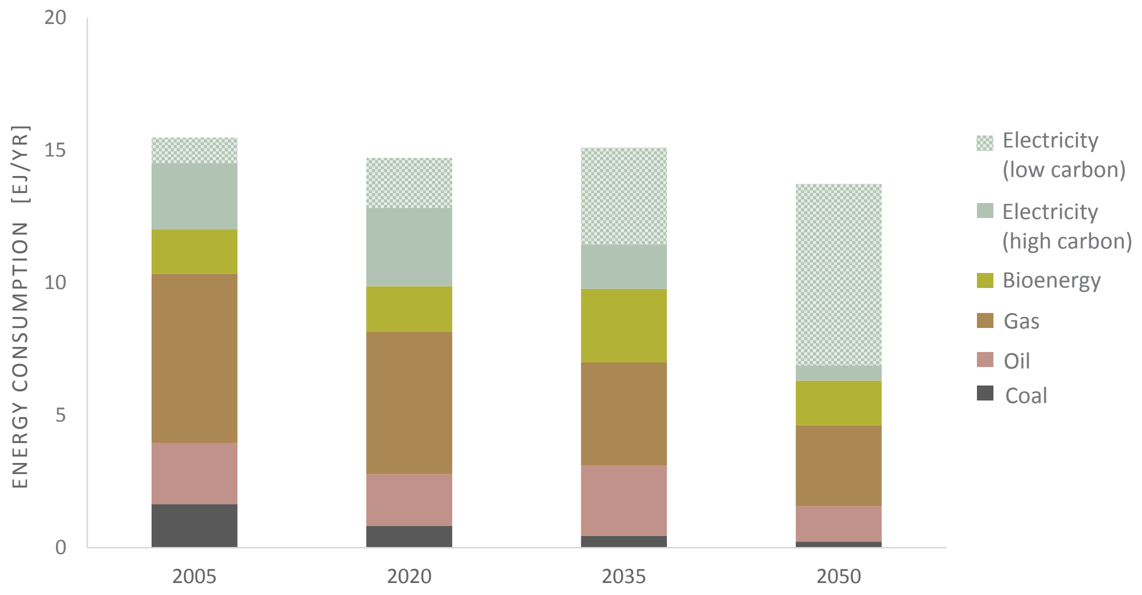
[17] Energy values for direct fuel consumption are reported in lower heating value. Lower heating value to higher heating value conversion factors used are 1.05 for coal, 1.07 for oil, 1.11 for gas, and 1.05 for bioenergy (PNNL 2016).

In addition to the cross-cutting themes described above, industrial CCUS can play an important role in decarbonizing certain sub-sectors. Cost-effective opportunities for CCUS may arise in parts of the chemical industry (e.g., ammonia production), since emissions contain high concentrations of CO_2 (up to 85 percent). In many industrial processes (such as hydrogen production from steam methane reforming, ethanol production, and processing of natural gas, among others), the separation of CO_2 is an inherent part of the fuel production process. Capture from these high-purity sources is less capital intensive in comparison to capture from diffuse sources of CO_2, such as power generation. These industrial CCUS opportunities could provide valuable early experience with permitting, infrastructure deployment, and market opportunities, which in turn could lower the cost of future CCUS projects (IEA 2013).

Combined heat and power (CHP) can also contribute emissions reductions in the industrial sector. With today's electricity generation mix, electricity and process heat generated from CHP use 25 to 35 percent less primary energy than electricity from the grid together with separate production of process heat. However, overall growth in CHP capacity has stalled since the early 2000s due to high equipment costs, technical complexity, and policy changes. Although most industrial CHP today is fueled by natural gas, CHP can contribute to the deep decarbonization of the industrial sector to the extent that waste heat or low carbon fuels are used.

The MCS envisions all of the above-mentioned strategies contributing to a decarbonized industrial sector. As displayed in Figure 4.18 below, even in the context of a growing economy, efficiency increases in the industrial sector cause energy use to decline over time. By 2050, a significantly larger portion of industrial energy demand is met with electricity compared to today. Such changes will require the combination of innovation and ambitious policies that combine to accelerate the adoption of electrification, CCUS, efficiency, and other emissions-reducing alternatives, and make these approaches increasingly cost-effective.

FIGURE 4.18: INDUSTRIAL SECTOR ENERGY CONSUMPTION, MCS BENCHMARK



Despite a growing economy, the MCS envisions declining energy use over time due to increased efficiency and increasing electricity use.

Aside from the need for further innovation, additional barriers to the decarbonization of the industrial sector include low costs of direct fuel use relative to electricity under current policy and market conditions, and the potential exposure of U.S. businesses to competition from foreign companies without comparable regulations. A price on carbon emissions would increase the attractiveness of electrification in the sector, and could include measures that would ensure domestic industries compete fairly with foreign competition. Other important strategies for accelerating industrial decarbonization include workforce and education initiatives, peer-learning networks,[18] and federal assistance programs.[19]

INNOVATION OPPORTUNITIES IN THE INDUSTRIAL SECTOR

Compared to other energy sectors, there has been less attention on low-carbon solutions in the industrial sector. Perhaps for that reason (and due to the need for sub-sector and process-specific solutions), it is less clear how deep reductions in industrial sector emissions will be achieved. Innovation is critical. The table below shows key RDD&D opportunities in fuel-switching, energy efficiency, advanced process technologies, industrial CCUS, and industrial CHP.

TABLE 4. INDUSTRIAL SECTOR INNOVATION OPPORTUNITIES

CATEGORY/TECHNOLOGY	REPRESENTATIVE OPPORTUNITIES FOR RDD&D INVESTMENTS
Fuel-switching and alternative feedstocks	• Increased technical potential and cost-effectiveness of process-heating using clean electricity, carbon beneficial forms of biomass, or advanced nuclear, targeting economic-parity with existing fuels and feedstocks
Energy efficiency	• Improved heat exchange and utilization efficiencies through better insulation, heat capture, novel geometries, and exchange between hot and cold gases and fluids • Use of exhaust heat as an economically-effective input to processes with low-heat requirements • High Performance Computing-based modeling and related information technology to identify and implement energy efficiency in manufacturing
Advanced processes	
Process intensification	• More precise and efficient process approaches and enabling process technologies (e.g., combining separate unit reactions such as reaction and separation into a single piece of equipment) • Improved tools and capabilities enabling scaled implementation of low-carbon intensified processes at economic parity with existing processes
Improved process heating technologies	• Lower-energy processing methods that concentrate, intensify, and deliver heat directly to the material instead of the surrounding environment (e.g., microwave, radio frequency, ultraviolet, other electromagnetic), or alternative non-thermal processes
Improved materials efficiency	• Improved accuracy and performance of additive manufacturing (building objects layer-by-layer from a computer model instead of cutting away material) • Reuse of materials ("circular economy") with improvements in separation and purification of used materials to renewable remanufacture with no performance loss, as well as design and development of alloys for reuse • Advanced materials manufacturing tools and approaches enabling accelerated scale-up from discovery to adoption in energy applications

[18] An example of peer learning is EPA's large industry peer network and partnership under ENERGY STAR for Industry that disseminates extensive energy information to industry.

[19] The Department of Energy funds Industrial Assessment Centers (IACs), where universities are available to perform basic energy efficiency assessments for small- and medium-sized plants. EPA produces industrial sector-specific ENERGY STAR plant energy performance indicators that educate and enable manufacturing plant managers to determine how to invest and improve their plants' energy performance.

CATEGORY/TECHNOLOGY	REPRESENTATIVE OPPORTUNITIES FOR RDD&D INVESTMENTS
Process optimization	• Advanced controls and sensors (e.g., high-performance metrology for real-time in-situ process control) • “Smart manufacturing” driven by information technology, communications, and real-time systems
Advanced materials	
Materials for harsh service conditions	• Heat exchanger alloys and power conversion materials for use in corrosive, high-flow-rate, and/or high-temperature flue gases for waste heat recovery • Higher-temperature and pressure-stable alloys and coatings to enable turbines/turbomachinery to operate more efficiently
Critical materials	• Diversification of supply, development of substitutes, and enhanced reuse and recycling of critical materials
Accelerate materials development	• New computational, experimental, and data tools to reduce the time and cost to develop and deploy new materials
Industrial CCUS	
Existing carbon separation processes	• CCUS on existing industrial processes that involve separation of CO_2 (e.g., hydrogen, ethanol, and natural gas production)
New industrial applications	• Improved ability to handle lower CO_2 concentrations and higher oxygen concentrations in flue gas • Improved ability to manage a wide range of industrial contaminants in the flue gas • Improved ability to operate on diverse systems
Industrial CHP	• Development of low-cost low-carbon fuels • Improve fuel cell system for use in CHP

5 STORING CARBON AND REDUCING EMISSIONS WITH U.S. LANDS

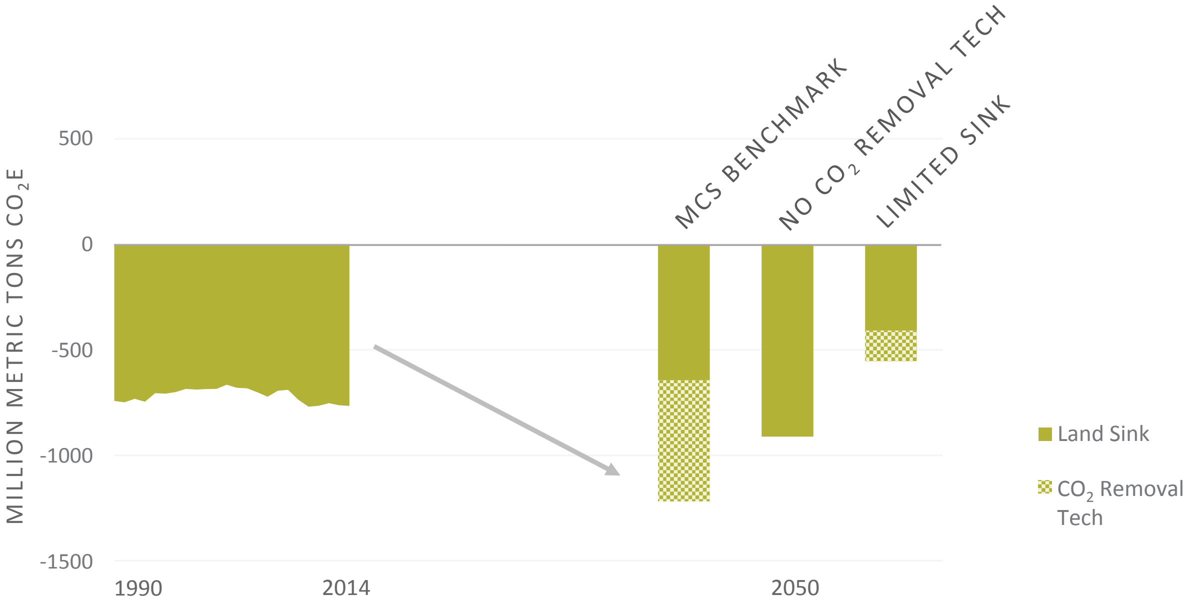
U.S. lands supply a variety of goods and services essential to maintaining our economic prosperity, environmental health, national security, and overall quality of life. Our agricultural lands, including cropland, pasture, and rangeland, provide the food and fiber that feed and clothe hundreds of millions of people in the United States and around the world. Urban and other developed areas provide the space where we live and work. Forests produce the wood products we use to build houses and other structures and the paper products we use in almost every aspect of our lives. Wetlands and other natural areas, including protected landscapes as well as many areas associated with agriculture and forestry uses, provide a host of vital environmental goods such as clean air, clean water, healthy soil, wildlife habitat, and biodiversity protection.

Some land uses and management practices emit CO_2 to the atmosphere and others remove it by sequestering carbon in trees, plants, soils, and products. In aggregate, U.S. lands have been sequestering much more carbon than they emit (a net "carbon sink") for the last three decades, due to millions of acres shifting into forest from other uses—a slow reversal of the extensive agriculture and settlement expansion over the last several centuries—and the continued secondary growth of trees on already forested lands (Oswalt et al. 2014). In 2014, the U.S. land carbon sink sequestered a net 762 million metric tons of CO_2, offsetting 11 percent of economy-wide GHG emissions (EPA 2016b).

How we manage our land resources, both in the near term and over the next several decades, will determine whether U.S. lands can remain a robust carbon sink while delivering across a suite of other objectives, including needs for additional food, fiber, forest products, carbon beneficial forms of bioenergy, living space, recreation, and the suite of environmental goods essential to healthy ecosystems and human well-being.

The MCS analysis estimates 2050 land sector and CO_2 removal technologies could sequester 30 to 50 percent of economy-wide GHG emissions (Figure 5.1). The MCS Benchmark scenario shows a relatively constant annual land carbon sink combined with scaled deployment of negative emissions technologies, like the use of carbon beneficial forms of bioenergy with carbon capture and storage (BECCS). In the No CO_2 Removal Technologies scenario, U.S. landscapes may be managed to deliver more than current annual sink levels, especially if soil carbon sinks can be mobilized. The Limited Sink scenario results in increasing pressure to address challenging parts of the energy system and non-CO_2 emissions. These scenarios suggest that the greater our ability to reduce emissions through lower-cost land sector options compared to CO_2 removal technologies and difficult-to-decarbonize sectors, the more we can reduce overall costs. This finding is reinforced by the literature (Van Winkle et al. in press, Rose et al. 2012, Wise et al. 2009, Murray et al. 2005).

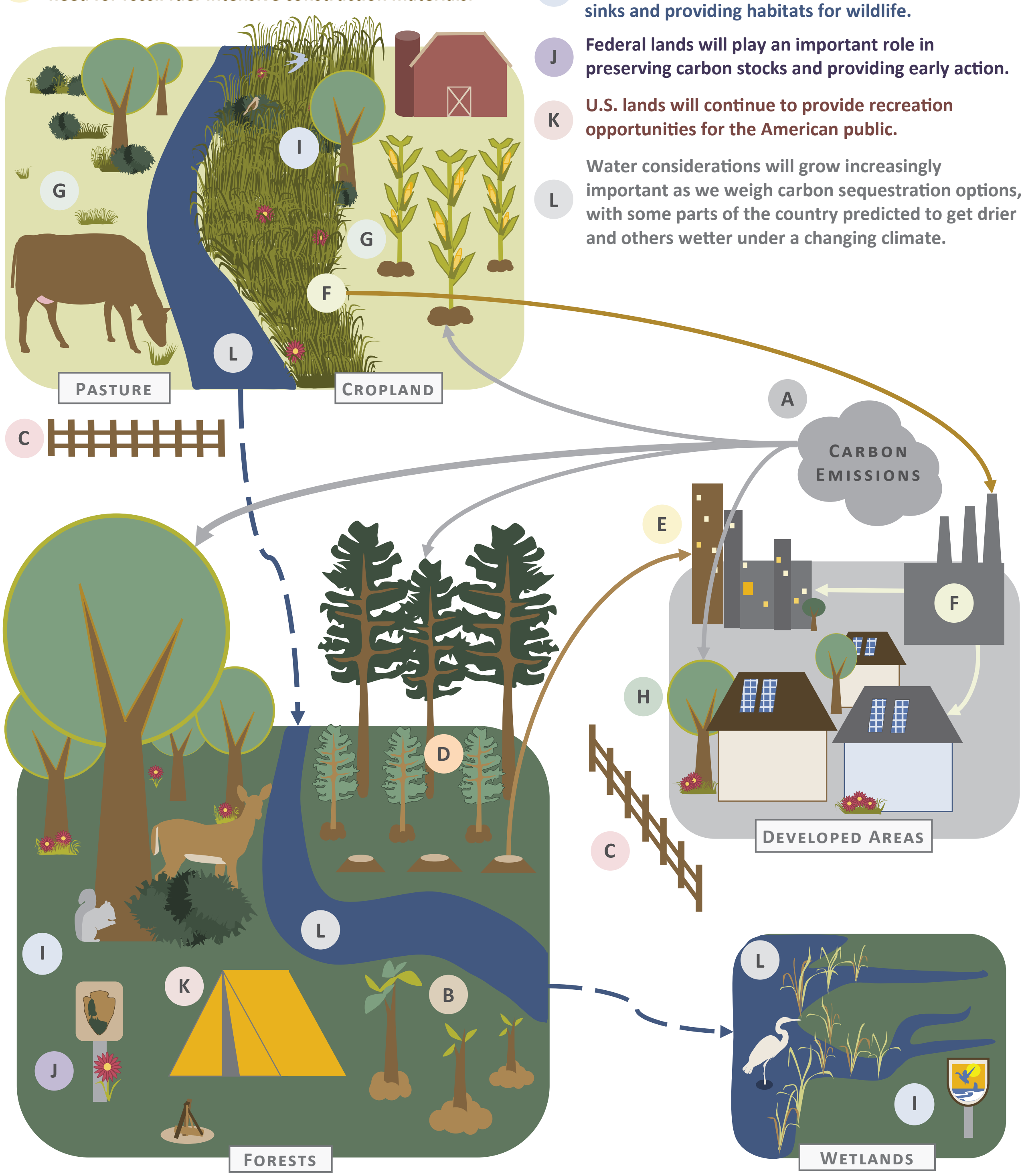
FIGURE 5.1: MCS NEGATIVE EMISSIONS SCENARIOS



1990-2014 land sink levels compared to 2050 projections for MCS Benchmark, No CO_2 Removal Technologies, and Limited Sink scenarios (GCAM). Historical data based on U.S. GHG Inventory (EPA 2016a).

FIGURE 5.2: ROLE OF U.S. LANDS IN THE MID-CENTURY STRATEGY

- **A** Carbon dioxide from all sectors of the economy is captured and stored by forests, agricultural lands, and urban trees.
- **B** Reforestation and afforestation will play a large role in enhancing the carbon sink.
- **C** Avoided forest conversion will preserve forest carbon.
- **D** Improved forest management can increase carbon sequestration in existing forests.
- **E** Tall wood buildings will store carbon and reduce the need for fossil fuel-intensive construction materials.
- **F** Perennial grasses grown on marginal or underutilized land and other carbon-beneficial forms of biomass will help us meet renewable energy demand.
- **G** Carbon storage in cropland and pasture can be increased through practices like no-till, cover crops, management intensive grazing, agroforestry, and other innovations.
- **H** Planting urban trees can increase carbon sequestration, even in developed areas.
- **I** Protecting natural landscapes and avoiding disturbances will be key to maintaining carbon sinks and providing habitats for wildlife.
- **J** Federal lands will play an important role in preserving carbon stocks and providing early action.
- **K** U.S. lands will continue to provide recreation opportunities for the American public.
- **L** Water considerations will grow increasingly important as we weigh carbon sequestration options, with some parts of the country predicted to get drier and others wetter under a changing climate.



In this chapter, we discuss how U.S. lands can help us achieve our deep decarbonization goals by storing more carbon in forests and soils and delivering carbon beneficial forms of biomass feedstocks for low-carbon energy generation (with or without CCUS), while also continuing to support key products like food, fiber, and wood products and creating economic opportunities for farmers, ranchers, and foresters. We look at these issues through four key landscapes: forests, croplands and grazing lands, developed areas, and wetlands. Finally, we identify policy and programmatic priorities that would: (1) bolster incentives for land carbon sequestration, (2) quickly mobilize federal lands, (3) increase land use efficiency and protect sensitive landscapes, and (4) fill key research and data gaps policy makers and stakeholders need to inform future climate and energy policy. These key issues and their connections are highlighted in Figure 5.2.

A set of principles found throughout this chapter are important to highlight at the outset:

- Mirroring the incentive to reduce carbon in the energy sector, finding efficient ways to structure carbon-based incentives in the land sector will be important. For example, carbon-based payments to farmers, ranchers, and forest owners would incentivize many of the activities described below. Funding these incentives will be an important consideration for future climate action, as well as putting in place the appropriate institutions to administer such incentives to ensure they are efficiently supporting our long-term climate goals.
- U.S. lands are managed by a diverse group of stakeholders for a wide variety of objectives. Achieving the land sector goals of the MCS will require developing partnerships and other forms of close cooperation with millions of private landowners, private sector corporations, and non-governmental organizations, as well as tribal, local, state, and federal government agencies.
- Using carbon reporting, accounting, and monitoring tools can help ensure we are supporting the most cost-effective land-based mitigation investments, while maximizing flexibility for stakeholders to make decisions about what strategies will work for them.
- Timing of land sector action is critical. Delivering significant land carbon sequestration by 2050 requires initiating investments soon.
- Some aspects of the MCS vision have the potential for large-scale land use changes. Putting in place policy "check points" over time that assess the effects of deep decarbonization activities in the land sector can help further tailor climate policies to ensure we are avoiding unintended impacts and appropriately modifying incentives and policies to reflect the latest science.

Climate action in the land sector can build upon existing policies and programs like the U.S. Department of Agriculture's (USDA) Building Blocks for Climate Smart Agriculture and Forestry. The USDA Building Blocks, launched in 2015, are designed to help farmers, ranchers, forest landowners, and rural communities respond to climate change. The ten Building Blocks span a range of technologies and practices to reduce GHG emissions, increase carbon storage, and generate clean energy, including actions to promote:

- **Soil Health**
- **Nitrogen Stewardship**
- **Livestock Partnerships**
- **Conservation of Sensitive Lands**
- **Grazing and Pasture Lands**
- **Private Forest Growth and Retention**
- **Stewardship of Federal Forests**
- **Promotion of Wood Products**
- **Urban Forests**
- **Energy Generation and Efficiency**

Through the suite of existing USDA programs and authorities, the Building Blocks look to reduce emissions by more than 120 million tons of CO_2 annually by 2025, with half of this supported through renewables and energy efficiency in rural areas, a quarter from reducing agricultural non-CO_2 emissions, and the remainder through bolstering the carbon sink. The Building Blocks are an important first step towards achieving our 2050 goals. Realizing these goals will, like the other programs and priorities outlined in this chapter, require an increasing commitment of resources, research and development support, outreach, and partnering with farmers, ranchers, forest owners, commodity groups, environmental organizations, and others.

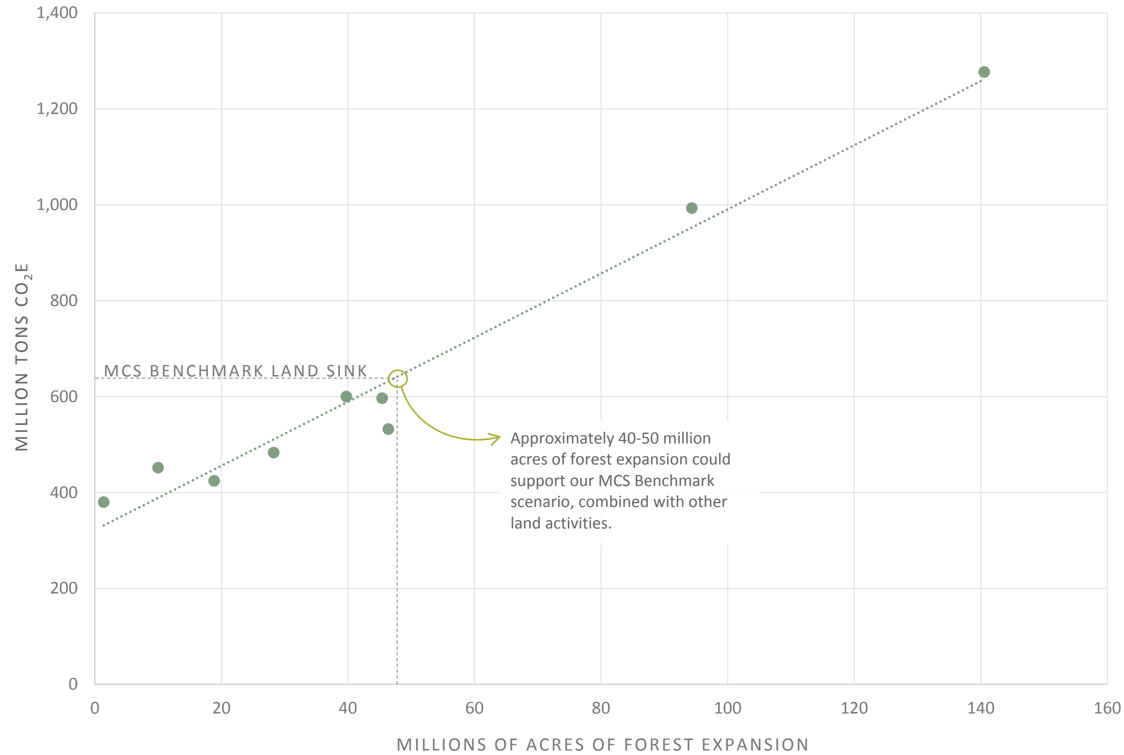
FORESTS

Forests account for more than 90 percent of today's U.S. carbon sink (EPA 2016b). Opportunities to increase GHG benefits of U.S. forests include afforestation and reforestation; avoided conversion of forests to other land uses; improved forest management; increasing resilience to natural disturbances; and wood products to offset fossil fuel-intensive construction materials.

AFFORESTATION AND REFORESTATION

Forests comprise one-third of total U.S. land area, down from covering half the country prior to European settlement (Oswalt et al. 2014). Through this historical lens, much of the U.S. forest expansion opportunity will be "reforestation." To capture both terms, we simplify to "forest expansion." The scale of potential and economic feasibility of forest expansion is well-studied (Van Winkle et al. in press). For example, Monge et al. indicates that 60 million acres of afforestation is economically feasible at $20 per ton CO_2 price (2016), while a 2005 EPA assessment indicated that at a $30 CO_2 price, 75 million acres could be converted to forest (Murray et al. 2005).

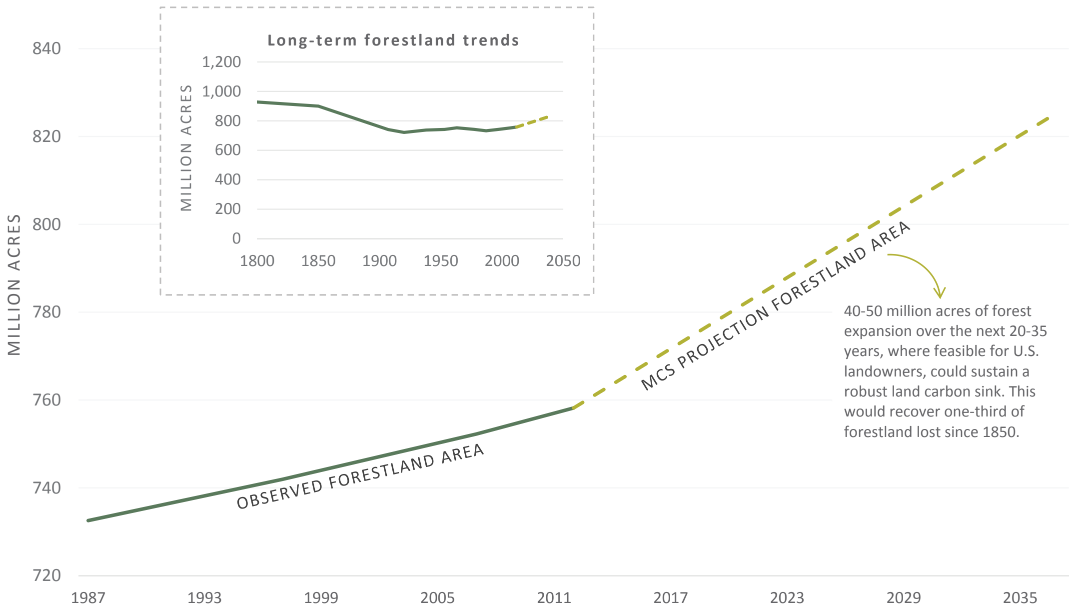
FIGURE 5.3: CUMULATIVE AFFORESTATION AND AVERAGE ANNUAL CO_2 STOCK CHANGE



This figure shows cumulative net forest expansion by 2050 (x-axis) and the average annual CO_2 stock change between 2015 and 2050 (y-axis) across three models used to assess MCS land sector dynamics (GCAM, GTM, and USFAS). Each dot represents a distinct land carbon sink scenario developed by one of the three models, with nine scenarios developed in total. These estimates do not reflect all possible forest sink projections.

Figure 5.3 explores the relationship between levels of net forest expansion and average annual forest sink levels out to 2050 from three different models, informing the level of effort required to maintain and possibly enhance the U.S. land carbon sink. While these models—GCAM, the Global Timber Model (GTM), and the U.S. Forest Assessment System (USFAS)—differ in terms of model type and function (economy-wide integrated assessment model, a dynamic partial equilibrium global timber model, and a set of interlinking models that consider biophysical and economic drivers, respectively), there is a linear trend between higher cumulative forested acres and greater annual CO_2 sequestration. Note that average annual carbon stock changes represented on the y-axis are driven by other factors in addition to cumulative forest expansion, including reduced forest conversion to developed land uses, forest management intensification, and regular management practices, such as replanting after harvest. Nonetheless, Figure 5.3 shows a strong correlation between the extent of net forest expansion and total forest carbon outcomes.

FIGURE 5.4: RECENT HISTORICAL FOREST EXPANSION COMPARED TO MCS FOREST EXPANSION



Historic data from 1630 to 2007 based on Kellogg (1909) and Oswalt et al. 2014. To account for uncertainty in observed forest expansion after 2007, this figure shows an average annual increase in forest area from 2007-2012 that reflects a longer-term average trend based on three separate data sources, including the FIA (1987-2007) as found in Oswalt et al. 2014, the 2007 USDA Major Land Use Database (1992-2007) (Nickerson et al. 2011), and the 2015 FAO Global Forest Resources Assessment (1990-2015) (FAO 2016). The resulting average annual increase for the 2007-2012 period is 1.2 million acres/year. 2017-2035 projection based on analysis of forest expansion that could support the MCS Benchmark scenario. MCS forest expansion is estimated to occur before 2035 in order to achieve desired 2050 carbon sink levels.

Based on the Figure 5.3 trend line, approximately 40-50 million acres of cumulative net forest expansion could support the 2050 land sink levels reflected in the MCS Benchmark scenario.

Trees planted before 2035 will sequester and store more carbon by 2050 than trees planted after 2035. This means tree planting efforts need to begin quickly to influence 2050 sink levels. An estimated 2.7 million acres of forest expansion annually up to 2035 could be consistent with achieving the MCS Benchmark forest expansion estimates in Figure 5.3.

This forest expansion rate will require additional effort in order to scale up beyond recent historical levels (Figure 5.4). U.S. forests expanded by approximately 1 million acres annually over 1987 to 2012. This trend has been driven by changing markets and policies, as well as federal programs, which supported tree planting on over 300,000 acres annually over 2006-2011.[20] An increase of resources for these efforts will be needed to scale up forest expansion rates and help achieve MCS goals.

Pursuing forest expansion as a carbon mitigation strategy will require addressing a variety of issues related to land use competition, site suitability, and water and fertilization requirements. Some stakeholders have expressed concerns that a forest expansion program could create competition for agricultural production. Other stakeholders are concerned about potential ecological, economic, and social impacts of such land use changes. Designing an appropriate strategy will require careful consideration of appropriate scale and location of forest expansion. Existing USDA programs have laid an important foundation for this cooperation, including the Agricultural Conservation Easement Program, the Conservation Reserve Program, and the Forest Legacy Program, as well as forward-looking Building Blocks that seek to support millions of acres of tree planting and forest retention on public and private lands by 2025.

As discussed below, there are a number of additional options to further enhance land carbon sequestration, such as agroforestry and soil carbon sequestration. The implementation of these options could reduce the need for forest expansion to some degree. For example, research indicates the potential for creating tree cover on over 50 million acres of agricultural land through agroforestry practices without impacting existing agricultural production (Nair and Nair 2003, Udawatta and Jose 2011). These opportunities are discussed further in the agroforestry section below.

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[20] Based on internal analysis by USFS and NRCS

AVOIDED FOREST CONVERSION

While U.S. forests on balance are a net emissions sink, conversions to other land uses could result in reduced forest carbon sequestration and greater emissions from release of stored carbon. The largest driver of forest loss in the United States in recent decades has been residential development, with a smaller role played by conversion of forest to cropland and pasture (Coulston et al. 2015). Nationwide, more than 57 million acres of rural forestland are projected to experience a substantial increase in housing density from 2000 to 2030 (Stein et al. 2009). USFAS modeling for the MCS indicates that reducing land development by 13 million acres compared to a future higher development scenario could avoid the loss of approximately 40 million metric tons CO_2 of annual sequestration by 2050, in addition to avoiding the loss of existing forest carbon stocks.

IMPROVED FOREST MANAGEMENT

Improved forest management (IFM) encompasses a variety of practices that can result in higher rates of forest carbon sequestration, including replanting following harvest (especially in areas that rely on natural regeneration) or natural disturbance, denser tree planting, increased fertilization and irrigation to increase forest growth rates, controlling competing vegetation, and using faster-growing tree species or varieties, including species developed through breeding (Fox et al. 2007). For example, tree breeding has increased southern pine wood growth by 10-30 percent from 1950 to 2000 (McKinley et al. 2011). All of these options should be assessed for potential impacts on biodiversity, N_2O emissions, and water resources.

Managing harvest rotation lengths and intensity in commercial forests can also be a tool for increasing the forest carbon sink (McKinley et al. 2011). However, the overall effect of changing harvest intensity or rotation lengths on net CO_2 sequestered depends on other management practices employed, forest growth rates, end use of harvested material, risk of increased harvesting in other areas (leakage), and other considerations (see Box 5.2).

There have been fewer assessments that attempt to quantify IFM mitigation potential compared to forest expansion, likely due to the complexity of analysis and the variety of IFM practices (Van Winkle et al. in press). Most available estimates indicate the scale of mitigation potential is likely lower for IFM than for forest expansion at a given carbon price, while other studies indicate IFM potential could be more than double that of forest expansion (Van Winkle et al. in press, Jackson and Baker 2010, Alig et al. 2010, Im et al. 2010). Differences in modeling methodologies impact these estimates.

MINIMIZE CARBON LOSS DUE TO NATURAL DISTURBANCES

As climate change impacts increasingly manifest, public and private lands in the United States are likely to be progressively impacted by related natural disturbances such as wildfire, flood, drought, pest and disease infestation, and extreme weather events. Natural disturbance may have already reduced carbon sequestration rates in the more arid regions of the West (Coulston 2015). However, studies indicate that in other parts of the United States and globally, carbon sequestration rates may increase due to CO_2 fertilization (Norby et al. 2005, Boisvenue and Running 2006, Thomas et al. 2010). These effects could nonetheless be dampened by water constraints or other limiting factors (Reich et al. 2014).

BOX 5.1: BALANCING LAND SECTOR CLIMATE MITIGATION AND ADAPTATION

Deep decarbonization strategies in the land sector must be adaptive to future climate impacts. While increasing temperatures and CO_2 levels might expand the growing season and increase plant productivity, changes in precipitation, extreme events, plant pests and diseases, and sea level rise could severely impact U.S. landscapes (Gill et al. 2013, EPA 2016a). When undertaking land sector mitigation efforts, stakeholders must consider the range of climate risks that could arise in the coming decades and plan accordingly. Priorities include developing resilient crop breeds, wisely choosing tree species for forest expansion efforts, and promoting genetic diversity in forests and other landscapes that allow plants to adapt to changing environments. Water in particular could become a growing challenge, especially in drier areas of the western United States.

Land carbon mitigation can also help to increase resiliency in the face of increasing climate impacts. Maintaining larger, more contiguous natural areas can support genetic resilience in the face of climate change while also preserving high-carbon landscapes (Gill et al. 2013). Urban forests can help to reduce flooding by increasing uptake of water into soil and preventing runoff (Oberndorfer et al. 2007). Farmers and ranchers taking up agroforestry or perennial crops to increase carbon storage can also increase water retention in drought-prone areas (FAO 2013). Taking advantage of mitigation opportunities that boost climate resilience will be key to delivering robust carbon sequestration in 2050 and beyond.

Treatments to reduce the severity of disturbances in forest systems include mechanical tree thinning, prescribed burning, and pesticide application. The net carbon impacts of these treatment decisions could be positive, neutral, or negative depending on their effectiveness in mitigating disturbances, their immediate carbon emissions (if any) ensuing effects on biomass regrowth potential, and many other variables. For example, there is significant debate on the net carbon effects of thinning trees in fire-prone areas to reduce wildfire severity (Stephens et al. 2012, Loudermilk et al. 2013, Hurteau et al. 2016, Law et al. 2013, Mitchell 2015). When managing to minimize ecological, social, and economic impacts from climate-related disturbances, land managers should include carbon as a consideration for maintaining and enhancing landscape health in order to avoid undermining carbon mitigation efforts elsewhere.

WOOD PRODUCTS TO OFFSET FOSSIL FUEL-INTENSIVE CONSTRUCTION MATERIAL

Harvested wood products (HWP) can help reduce net CO_2 emissions by substituting for carbon-intensive products such as steel and concrete (Sathre and O'Connor 2010). In the United States, new HWPs can be deployed in place of carbon-intensive concrete, steel, and aluminum products in non-residential and high-rise construction. Cross-laminated timber and other innovative wood products have enabled the construction of tall wood buildings over 10 stories, which are starting to be deployed in several U.S. cities (Bowyer et al. 2016). Buildings like shopping malls and hospitals could also begin to utilize wood products to reduce steel, concrete, and aluminum use. USDA has set a goal to increase the number of wood building projects supported annually through technical assistance from 440 in 2015 to 900 in 2025 as part of its Promotion of Wood Products Building Block (USDA 2016).

BOX 5.2: SETTING CONSISTENT CARBON PRICE SIGNALS FOR LAND SECTOR MITIGATION OPTIONS

To ensure climate policies are achieving intended outcomes and maximizing efficiency of any carbon credit or payment program, economic actors should face the same incentive per unit of GHG reduction across land management and market options. This means, whether it is planting trees on marginal pasture, lengthening harvest rotation periods, or selling material into bioenergy or wood products markets, stakeholders can make management choices with consistent carbon values.

Carbon accounting frameworks are needed to calculate net carbon effects from land-based activities in order to promote consistency and reliability. For example, the California cap-and-trade program has established offset protocols for measurement, monitoring, and verification of emissions reductions from afforestation, improved forest management, and avoided forest conversion, with additional protocols under development. Landowners and project developers use these protocols to generate emissions reductions credits (ARB 2016).

In another example, the U.S. EPA's Draft Framework for Assessing Biogenic CO_2 Emissions from Stationary Sources outlines an approach for calculating the net CO_2 emissions from utilizing diverse biomass feedstocks for energy (EPA 2014). Policymakers can use tools like the EPA Framework to assess net carbon implications of using biomass for energy.

To ensure that protocols or frameworks reflect our best assessment of the total CO_2 emissions or removals associated with various land uses and land management practices, the most up-to-date scientific understanding, data, and quantitative tools must be utilized. Accounting principles in these frameworks should include, but need not be limited to:

- Time and spatial scales over which carbon dynamics are being measured.
- Effects of management and harvesting practices. Any loss and regrowth of carbon should be accounted for accordingly, including timing between loss and regrowth, and across major carbon pools (living biomass, dead biomass, litter, soil organic matter, and HWP).
- Direct land use change or emissions from converting land use to or from a higher carbon density (such as forest) to lower carbon density (such as cropland).
- Indirect land use change or leakage. For example, converting land away from food crop production to energy crop production can result in higher food crop prices and incentivize land conversion in other areas to support crop production, creating potential for carbon losses.
- For activities that result in a product, such as paper or timber, the type of product needs to be considered in order to understand how quickly carbon could return to the atmosphere.
- Market dynamics. For example, increasing demand for forest products has the potential to drive increasing productivity and afforestation to support greater supply.

The application of such carbon accounting frameworks or protocols within policies and programs should be done with consideration of other existing policies or carbon credit programs to avoid double counting of emissions or sequestration across sectors.

Increasing wood product demand also has the potential to stimulate increased tree planting and afforestation, which can result in a larger carbon sink over the longer term (Lubowski et al. 2006, Beach et al. 2002, Alig et al. 2010, Miner et al. 2014). Additional analysis of the direction and scale of this management response, looking at empirical regional and market-specific effects, can provide further insights into forest carbon mitigation potential with stronger wood products markets. Additional research on the potential of tall wood buildings and low-rise commercial buildings to achieve state-of-the-art energy efficiency can also support these efforts.

BIOMASS FOR ENERGY

Biomass can be an important option for decarbonizing the energy sector, with higher biomass availability generally allowing for lower-cost mitigation than if biomass is restricted (IPCC 2014). Efforts to promote biomass should focus on those sources of biomass that result in net reductions of CO_2 emissions to the atmosphere, or "carbon beneficial forms of biomass." Policies that promote biomass use for energy should have safeguards to ensure actual emissions reductions to the atmosphere, based on the most up-to-date science and in accordance with the accounting principles described in Box 5.2, and must be managed with consideration of many land sector objectives, including maintaining and enhancing the carbon sink, minimizing competition with food crops and other commodities, and protecting wildlife habitat, ecosystem health, and high-value conservation areas. For MCS analysis, we applied constraints on 2050 biomass consumption in an attempt to reflect these factors.

We see multiple pathways to deliver the amounts of carbon beneficial forms of biomass envisioned in the MCS, with Figure 5.5 showing two assessments of potential 2050 biomass supply. The U.S. Department of Energy recently estimated 2040 U.S. biomass availability in the Billion-Ton Report (BT16) (2016). BT16 projections indicate the United States can produce between 1.2 and 1.5 billion dry short tons of biomass by 2040 (DOE 2016), while the MCS Benchmark scenario uses less than 1 billion dry short tons.

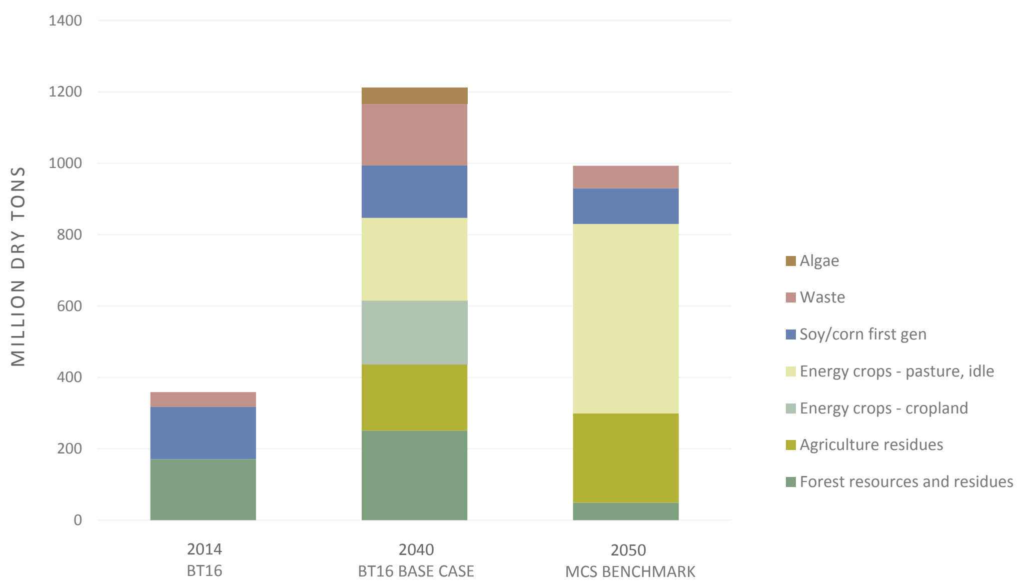
There are differences in how BT16 and MCS scenarios were constructed and in the models and assumptions used. The BT16 analysis was based on individual sectoral analysis of biomass feedstock categories (energy crops, agricultural residues, forestry resources) using specific assumptions about land use change and considering scale of supply under various biomass prices, yield improvements, and competing markets. It did not consider the net biogenic emissions effects of various feedstocks or a particular climate policy context. Conversely, the MCS analysis utilized GCAM to assess feasible biomass consumption in a deep decarbonization policy context, considering competing opportunities on landscapes to support forests for carbon sequestration, food production, biomass production, and other options. GCAM does not allow for converting forestland or natural grassland for biomass production. Both BT16 and MCS analyses were constructed to meet demand for timber, food, and other crop commodities as priorities before production of biomass for energy.

The BT16 found an estimated 31 million acres, or about 7 percent, of existing U.S. pasture, could be used to produce energy crops (DOE 2016), while GCAM estimates 40 million acres of pasture and idle agricultural land could deliver energy crops in 2050. Supporting energy crop production in ways that align with improved agricultural practices and minimize land use conversion, including pasture-energy crop rotational approaches, grazing intensification, restoration of degraded lands, and precision agriculture on croplands, will be important. Additional assessment of the scalability of each of these approaches can increase confidence in the ability to deliver energy crops without impacting existing agriculture, forestlands, natural grasslands, and high-value conservation areas. This is an area where periodic policy "check points" can ensure innovative agricultural strategies are being employed in a way that is both ecologically and economically sustainable.

Much of the energy crops utilized in 2050 are projected to be perennial grasses. Perennial grasses can support multiple environmental co-benefits including increased soil carbon storage and avoided soil loss, improved water quality, reduced pollution and emissions from fertilizer, wildlife habitat, and beneficial insect and pollinator habitat (Meehan et al. 2013, Blanco-Canqui et al. 2004, Morandin et al. 2015), especially on marginal or underutilized cropland and pasture.

While not shown in Figure 5.5, results generated by GTM and USFAS models using MCS scenarios point to additional opportunities to deliver various sources of forest biomass for energy while maintaining and enhancing U.S. forest carbon sink levels. Particularly if bioenergy markets can help bolster incentives to expand forests and increase forest productivity, using forest biomass could

FIGURE 5.5: FUTURE BIOMASS SUPPLY ESTIMATES



Biomass supply estimates from DOE's Billion Ton Report 2016 (BT16) and MCS Benchmark scenario outputs from GCAM, with 2014 biomass consumption levels estimated in BT16 provided for additional context on potential increase under MCS.

provide an important opportunity for meeting multiple land use and carbon reduction objectives at once (Tian et al. 2016, Lubowski et al. 2006, Beach et al. 2002, Alig et al. 2010, Miner et al. 2014, Abt et al. 2014). As noted above, this market effect should be further assessed with empirical data to guide future policy.

The biomass amounts and types ultimately utilized in the coming decades will depend on the economics of delivering various biomass feedstocks, the competitiveness of bioenergy compared to alternative low carbon technologies across sectors, and the ability to minimize land carbon impacts and other potential environmental impacts of biomass production. As noted in Box 5.2, carbon accounting approaches, such as the U.S. EPA Draft Framework for Assessing Biogenic CO_2 Emissions from Stationary Sources, can help ensure that net carbon effects of using different biomass feedstocks for energy are taken into account, and inform future efforts to create carbon pricing signals that incentivize bringing carbon beneficial forms of biomass to market.

CROPLANDS AND GRAZING LANDS

The U.S. GHG Inventory shows agricultural lands to be a net source of carbon emissions from soils, reaching over 66 million tons CO_2 in 2014 (EPA 2016b). Substantial additional emissions of methane and nitrous oxide from other agricultural practices on these lands are discussed in Chapter 6. However, the potential to reduce GHG emissions and increase carbon sequestration on U.S. croplands and grasslands is substantial through practices that increase soil organic carbon and employ agroforestry.

SOIL CARBON

Agricultural management and land use changes have substantially reduced soil carbon levels on U.S. lands (Chambers et al. 2016, Smith 2012, Eagle et al. 2012). Reversing this trend and increasing carbon sequestration on cropland and grazing lands represents a potentially large mitigation opportunity. Importantly, due to modeling constraints and uncertainty, soil carbon storage is not included in MCS modeling results, so these activities can deliver additional emissions reductions even beyond those envisioned in the MCS Benchmark and other scenarios. Increasing uptake of key soil carbon-enhancing practices to more than 70 percent of U.S. cropland and ensuring that the practices are implemented to maximize carbon storage benefits could result in an increased soil carbon sink of over 270 million metric tons CO_2e per year by 2050 (Chambers et al. 2016). Additional sequestration could be achieved by mobilizing pasture and rangeland (Bosch et al. 2008, Oates and Jackson 2014, Eagle et al. 2012).

Sequestering carbon in cropland soils can be achieved through a wide variety of activities, including no till or reduced till, cover crops, residue management, planting field borders and other areas with perennial grasses and other native plants, and crop rotations (Smith 2012, Eagle et al. 2012). No till, which causes the least soil disturbance and likely the highest soil carbon benefits of all tillage practices, involves drilling seeds directly through crop residues into untilled soil. Combining no till with the use of cover crops can further increase sequestration opportunities (Smith 2012, Eagle et al. 2012).

Management of intensive grazing is one activity that may increase soil carbon storage on working pasture lands (Bosch et al. 2008, Oates and Jackson 2014). Livestock are frequently rotated in small paddocks to prevent overgrazing and increase grass productivity. It also provides unoccupied paddocks longer "rest" periods for regrowth. Further research is needed to better understand the scale of mitigation potential, though early results indicate positive outcomes (Eagle et al. 2012). On drier rangelands, rotational grazing may be less effective due to precipitation constraints. However, reducing stocking rates (i.e., reducing the number of animals) on overgrazed rangeland, avoiding grazing during drought conditions, and improving the timing and frequency of grazing can increase rangeland soil carbon sequestration (Conant and Paustian 2002, Follett et al. 2001, Zhang et al. 2010, Svejcar et al. 2008).

Soil carbon dynamics vary across regions and even within a single field, depending on soil type, moisture, temperature, and many other issues (Post et al. 2012). Likewise, uncertainties remain regarding carbon sequestration dynamics at different soil depths (Eagle et al. 2012, Powlson et al. 2014, Baker et al. 2007). Additional research is needed to increase certainty of soil carbon gains across practices and reduce costs of verifying soil carbon improvements.

Minimizing reversal is key to lasting soil carbon mitigation. For example, it can take four to six years to improve soil structure and up to 10 years to see an increase in soil carbon sequestration from conservation or no till practices, but conventionally tilling untilled land even once can quickly reverse years of carbon sequestration gains (Eagle et al. 2012, Grandy and Robertson 2006, Smith 2012).

Looking ahead, agricultural innovation can support even greater soil carbon improvements. The potential for soil carbon storage is very large if roots access deeper soil profiles (Kell 2011, Kell 2012). The Advanced Research Projects Agency–Energy (ARPA-E) recently modeled potential for deep carbon storage if major commodity crops were able to double their root mass and shift root mass deeper in the soil. If these new crop breeds were taken up across the 400 million acres of U.S. cropland, the carbon sequestration potential ranges from 0.25-1.2 Gt CO_2 by mid-century (Figure 5.6). In order to realize this large carbon sink, ARPA-E is launching two programs: Transportation Energy Resources from Renewable Agriculture (TERRA) and Rhizosphere Observations Optimizing Terrestrial Sequestration (ROOTS). The goals of these programs are to drive rapid increases in sustainable farm productivity by increasing the accuracy and quantity of genetic tools to drive crop improvement.

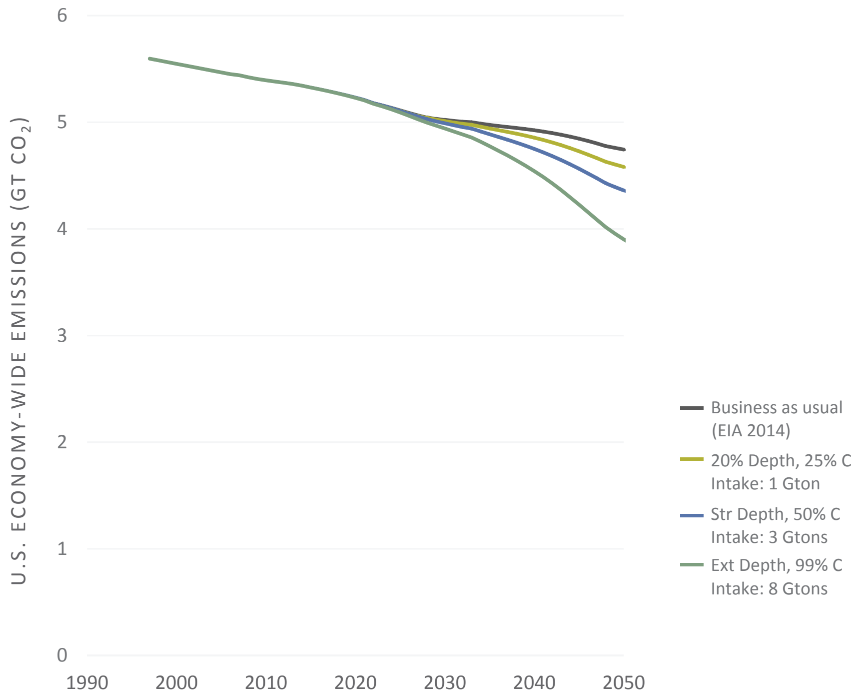
Researchers are also looking at the potential to develop perennial breeds of traditional food crops like wheat, with the potential to revolutionize cropland ecology and vastly reduce tillage and other agricultural inputs (Glover et al. 2010). More research to assess and develop these and other innovations should be a component of U.S. deep decarbonization.

AGROFORESTRY

Agroforestry refers to any land management approach that integrates trees, shrubs, or other woody plants with agricultural crops or livestock (FAO 2015). This includes forested conservation borders and buffers along crop fields, forested waterways and wind barriers, and tree plantings on underutilized farmland. In diversifying plant species and processes above- and belowground and reducing soil disturbance, agroforestry systems enhance soil structure, soil carbon sequestration, biodiversity conservation, water quality, and nutrient cycling (Nair 2011, Schoeneberger et al. 2012, Udawatta and Jose 2011). Agroforestry near crop fields can also improve air quality by capturing airborne soil particles and reducing wind-driven soil erosion.

While agroforestry is not currently included in the U.S. GHG Inventory, several analyses indicate both current agroforestry and the scale of additional potential are quite large, with the potential to create tree cover on over 50 million acres without impacting agricultural production (Nair and Nair 2003, Udawatta and Jose 2011). Creatively integrating agroforestry into cropland and pasture, where ecologically and economically viable, can help avoid land use competition sometimes associated with forest expansion.

FIGURE 5.6: ANNUAL IMPACT OF ARPA-E "ROOTS" SCENARIOS ON U.S. EMISSIONS



Increased root mass and depth in commodity crops generate significant emissions reductions by mid-century. Note: A simulation of soil carbon sequestration after stochastic state-by-state adoption of indicated crops was done based on the results presented in Paustian et al. 2016. If 100 percent national adoption were to occur by 2050, cropland would reach a new soil carbon equilibrium in the second half of the century, resulting in decreasing annual fluxes over time.

BOX 5.3: U.S. FOOD CROP PRODUCTION IN 2050

UN estimates indicate global food crop demand could increase by 60 percent by 2050, while other estimates indicate demand could double from current levels, driven by increasing global population, economic growth, and dietary preferences (FAO 2009, Tilman et al. 2011). Keeping cropland area constant, yield increases consistent with historical growth rates would deliver only a 50 percent increase in global crop production across primary crops (corn, rice, wheat, and soy) by 2050 (Ray et al. 2013). Minimizing conversion of forests and grasslands to cropland can support MCS goals by maintaining carbon storage while freeing up land for other productive uses and conservation.

A number of policy and research priorities can help ensure that U.S. food production continues to increase for growing domestic and international consumers, while keeping cropland expansion to a minimum, including:

- Renewed investment in ambitious food crop yield improvement programs within the federal government, universities, and the private sector, particularly in order to increase the climate resiliency of key commodity crops;
- Support for other countries in improving crop yields and climate resilience, especially in areas exhibiting the largest yield gaps;
- Reductions in food waste, which accounts for over one-third of global calories, requiring both better infrastructure to transport and store food as well as shifting social perceptions (FAO 2016); and
- Reductions in pollution like tropospheric ozone and particulate matter, which significantly impact crop yields (Shindell et al. 2012).

Looking ahead, growing demand for organic and locally produced foods, developments in vertical and urban agriculture, and other innovations and trends are quickly emerging. Identifying how these developments can align with growing global food demand and deep decarbonization goals will be important.

Agroforestry also has benefits for climate change adaptation. The co-benefits of incorporating trees in agricultural systems—namely, increased water infiltration and water and nutrient retention—include greater resilience to droughts or floods. Trees also create microclimates that can keep soils cooler and create more favorable conditions for crops and livestock (Schoeneberger et al. 2012).

URBAN AND SETTLEMENT AREAS

Over the coming decades, expansion of developed land will be driven by a growing U.S. population, increasing economic growth, and infrastructure development. USDA's projections of developed area growth by 2050 range from 17 million acres under a low development scenario to 49 million acres under high development (USDA 2016). Other estimates put this number even higher; for example, the USFS Resource Planning Act Assessment suggests 69 million acres of developed area expansion is possible by 2060 (Oswalt et al. 2014). Using smart growth and zoning policies to intensify urban development can reduce conversions of forestland, cropland, and grassland (Ewing et al. 2008).

Furthermore, improved urban planning can enable multi-use neighborhoods, higher quality of life, reduced transportation demand, and other co-benefits that support deep decarbonization (Marcotullio et al. 2013, Gudipudi et al. 2016). The most well-documented co-benefit is decreases in vehicle miles traveled (VMT) when residences and businesses are closer together (Sullivan and Yeh 2013). Compact development has the potential to reduce VMT by 20 to 40 percent, saving on commute times and reducing transport-related CO_2 by 10 percent or more by mid-century (Ewing et al. 2008, Cambridge Systematics Inc. 2009).

Urban and settlement areas can also contribute to carbon sink goals through urban trees and urban forests. U.S. urban trees currently sequester 90 million metric tons CO_2 annually, more than 10 percent of the annual carbon sink, yet urban tree cover is currently on the decline (Nowak et al. 2013). Studies indicate the potential for delivering additional mitigation may be limited by activities like mowing and intensive management requirements (Nowak et al. 2013). The impacts of individual trees can be maximized through careful selection of species, giving preference to species with long lifespans, high wood density, and high tolerance to stresses which may be experienced in urban settings, a practice which is not currently widespread (Scharenbroch 2012). In the coming years, urban trees can help reduce the carbon impacts of urbanization.

WETLANDS

Large stocks of carbon accumulate within wet organic soils, where they can be held in place for hundreds to thousands of years; however, if disturbed, these areas can become emissions sources (EPA 2016c). In 1989, the United States adopted an overarching policy of "no net-loss" of wetlands to mitigate future losses by restoring or creating wetlands. This policy, largely implemented under the Clean Water Act, is now the cornerstone of U.S. wetland conservation (Mitsch and Gosselink 2015). Nevertheless, future development and land use change can impact the ability of wetlands to store and sequester carbon.

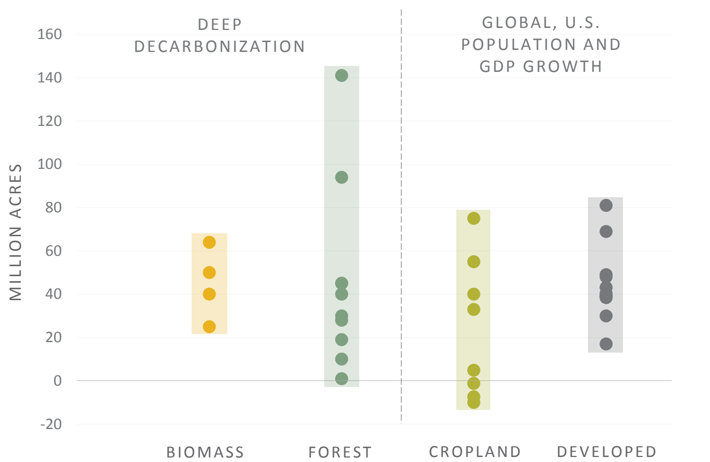
Inland wetlands cover over 97 million acres of the conterminous United States and 144 million acres in Alaska (Bridgham et al. 2007). Other than those areas used for rice cultivation and peat production, and some seasonally wet areas that are used predominately for crop production and grazing, many of these wetlands have not yet been fully integrated in the U.S. GHG Inventory. Efforts are underway to include all managed wetlands in the future. When wetlands are drained for agriculture or other development, stored carbon stock in the soil undergoes rapid decomposition and is released to the atmosphere as CO_2 (IPCC 2006). When wetlands are restored, long-term carbon storage resumes, reversing impacts of wetland drainage (Wickland et al. 2014). However, for freshwater wetlands, this can also increase methane emissions, depending on water levels, temperature, and vegetation (Badiou et al. 2011, Tangen et al. 2015, Macdonald et al. 1998, Bridgham et al. 2013, Bansal et al. 2016). This dynamic creates complexity surrounding the net GHG effects of freshwater wetland restoration (Waddington and Price 2000, Gleason et al. 2008, Gleason et al. 2009). Given the ecological significance of freshwater wetlands in supporting water quality, fish and wildlife habitat, and other benefits, better understanding this complexity can inform methods of freshwater wetland restoration that provide climate benefits.

Nearly half of all continental U.S. wetlands are in coastal zones (C-CAP 2010), and of these, nearly 10 percent are tidally influenced. Though a small percentage of the U.S. land base, the tidally influenced wetlands—specifically seagrasses, marshes, and mangroves—are some of the most efficient carbon sinks in the world (McLeod et al. 2011, Morris et al. 2012). Saline wetlands are a particularly robust carbon sink as the presence of seawater limits the production of methane, thus avoiding substantial GHG emissions that limit the carbon sequestration benefits in freshwater wetlands (Poffenbarger et al. 2011). As we work to include coastal wetland dynamics in the U.S. GHG Inventory, initial estimates suggest intact coastal wetlands sequester 8 million tons of

BOX 5.4: EVOLVING LANDSCAPES TOWARDS 2050

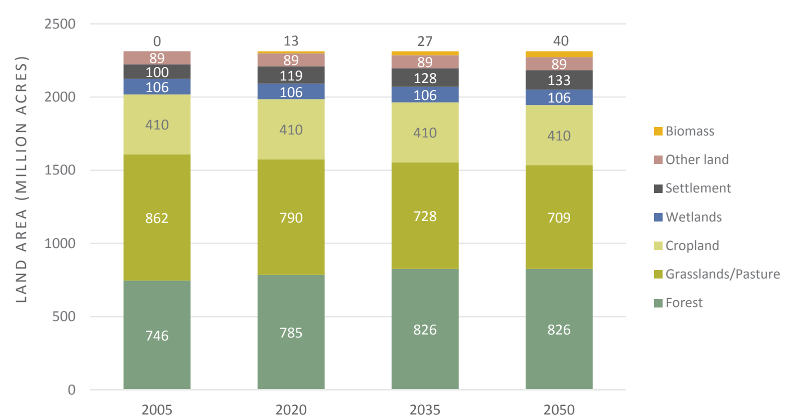
There will be multiple drivers of land use change over the coming decades, with population and GDP growth stimulating more demand for housing and developed land, greater food production, and possibly cropland expansion. At the same time, our deep decarbonization efforts could be supported by continued forest investments and afforestation to bolster the carbon sink and biomass production for carbon beneficial forms of bioenergy and BECCS. To give a broader perspective on the different possible land use outcomes in the future as a result of these drivers, we evaluated different estimates across the literature and the MCS analytical outputs (see Figure A). This evaluation shows there are a wide range of estimates on the degree of land use change that could occur as a result of these drivers by 2050, with some estimates illustrating the potential for large-scale impacts if we do not prioritize efforts to minimize land use change.

FIGURE A:



Range of 2050 land use change estimates produced by different research and modeling exercises for four key land use change drivers: carbon beneficial biomass production to decarbonize the energy sector, forestland expansion to increase carbon sequestration, cropland expansion in response to growing global food demand assumptions, and developed land expansion due to U.S. population growth. Note that not all four elements are represented in each model/study included here. Each dot represents a single literature or model-based estimate of additional cumulative acreage of the respective land use type by 2050. It is important to note that these scenarios and models contain different parameters, input data, and assumptions so the results are not directly comparable. They are compiled here to illustrate the range of possible outcomes in 2050 using different analytic approaches and assumptions. The estimates represented here were generated across 10 studies and modeling exercises with 24 distinct scenarios (USDA 2016, Radeloff et al. 2012, Oswalt et al. 2014, Sands et al. 2014, DOE 2016, EPA 2009, MCS, including GCAM, USFAS, and GTM).

FIGURE B:



Potential land use outcome in 2050 as drawn from the evaluation of the broader selection of different studies and analyses discussed in Figure A. The results presented here exemplify a potential future U.S. land use scenario that could be consistent with the U.S. MCS vision. The illustrative results above—reflecting 50 million acres of net afforestation to maintain and enhance the land sink and 40 million acres of biomass production to support carbon beneficial forms of bioenergy, all compared to 2015 areas—are consistent with estimates from Figures 5.3 and 5.5 above. This figure further reflects 17 million acres of developed land expansion from 2015, consistent with USDA estimates for low developed land expansion (2016), and constant cropland levels.

Achieving 2050 land use outcomes that allow us to meet our MCS goals will need to be managed carefully. However, there is reason to believe that land use outcomes like the one reflected in Figure B are ecologically and economically feasible. For example, between 1950 and 1990 forestland area declined by approximately 50 million acres (Alig et al. 2003)—recovery of a similar scale of forest cover over a similar time period could occur with the right set of policies and incentives. Between 1920 and 1950, 70 million acres of agricultural cropland was diverted from feeding work animals, which powered the early-20th century economy, as fossil-powered machinery took over (Baker 1937, U.S. Census 1950). Once again devoting a portion of our agricultural landscape to support the energy sector would be well within the range of historical land use. An estimated 27 percent of cropland, or 7 million acres, in Iowa alone may be economically marginal in crop production but well suited to perennial grasses (Brandes et al. 2016). Additional potential suitable areas include field borders, riparian strips, and highly erodible acres. Focusing on these areas nationally to produce carbon beneficial forms of biomass for energy or grow trees can potentially increase farm and forest owner income and value, deliver environmental benefits (such as reduced nutrient and sediment runoff), and reduce potential trade-offs between alternative land uses.

CO_2 annually, after accounting for existing methane emissions (Crooks et al. 2016). Currently, this annual carbon sequestration capacity of U.S. coastal wetlands is largely negated by annual emissions from already drained or eroded coastal wetlands (Crooks et al. 2016). Left unaddressed, human impacts, particularly in the Mississippi Delta, are projected to continue to erode coastal wetlands (Couvillion et al. 2013). Preliminary estimates indicate that nationwide conservation and restoration of coastal wetlands could avoid emissions and increase sequestration by 6-11 million metric tons of CO_2 per year through 2050 (Crooks et al. 2016).

PRIORITIES FOR POLICY, INNOVATION, AND RESEARCH

Achieving our 2050 goals will require implementing a number of policy, innovation, and research priorities which span four components: (1) bolstering incentives for land carbon sequestration; (2) quickly mobilizing federal lands; (3) supporting efficient land use through increasing productivity of forests, crops, and carbon beneficial forms of biomass, promoting smart urban growth, and protecting wetlands; and (4) identifying research and data priorities to inform policy and stakeholders. The first two components are key drivers of ambitious carbon reductions, while the latter two components ensure deep decarbonization efforts are aligned with broader environmental priorities, are based in the latest science, and have manageable impacts on land use.

BOLSTERING INCENTIVES FOR LAND CARBON SEQUESTRATION

Policies that drive deep decarbonization in the energy sector will impose an implicit or explicit price on carbon emissions, whether through an economy-wide carbon price, sector-specific regulation, or both. It will be difficult to fully integrate the land sector into such a system, due to the scale, complexity, and non-point source nature of U.S. land-based economic sectors. However, it will be important to harmonize the economy-wide cost of carbon emissions with incentive structures to encourage farmers, ranchers, and forest owners to take up the activities discussed throughout this chapter. Ensuring land carbon sequestration opportunities are being taken up efficiently across the economy will help maximize the net economic benefits of deep decarbonization.

Supporting land sector carbon outcomes at a scale that can support our 2050 goals will require additional financial resources. An important next step in this direction, consistent with previous Administration proposals, is to continue improving crop insurance and related programs in order to further incentivize producers to choose production practices that minimize climate change impacts and that achieve multiple strategic carbon, conservation, and water goals for every dollar of federal investment. Looking ahead, comprehensive climate policy can provide additional resources for land carbon incentives. An economy-wide carbon price can raise funds that in turn can be used to fund pay-for-performance programs or practice-based payments in the land sector as well as negative emissions technologies like BECCS.

Appropriately implementing and guiding land sector incentives will also require the right policy and administrative structures to ensure that payments are having the desired impact for lasting, additional carbon sequestration consistent with our long-term climate goals. Putting in place the carbon accounting protocols discussed in Box 5.2 and administrative support for monitoring and verifying carbon outcomes against those protocols will be important.

Carbon incentives for the land sector can be structured in different ways. One approach, practice-based payments, is already used under USDA conservation programs, including the Environmental Quality Incentives Program, the Regional Conservation Partnership Program, the Conservation Reserve Program, and other Farm Bill programs. These programs provide landowners technical assistance along with a portion of the funding required to implement a wide variety of voluntary conservation practices. While not an objective of existing conservation programs, they are estimated to support 50 million tons of CO_2 sequestration annually (U.S. Department of State 2016). These and other existing agricultural programs could be further leveraged by prioritizing and rewarding activities that generate carbon benefits.

Another approach is pay-for-performance or market-based payments, wherein landowners are compensated on the basis of how much carbon they can sequester, in some cases generating tradeable carbon credits. This can be implemented through crediting or offsetting programs like the California GHG cap-and-trade system, wherein landowners can sell carbon credits generated on their land to fossil fuel-emitting sectors. Alternatively, direct payments can be made to landowners through pay-for-performance structures, if appropriate funding sources can be developed. As new policies and programs are developed, it will be important to consult with diverse stakeholders and identify the range of complementary policy structures that can combine to most efficiently and effectively deliver carbon outcomes at scale.

In the coming years, USDA conservation programs can do more to increase soil health and forest growth, helping to scale carbon sequestration with more effective incentives and technical assistance for farmers, ranchers, and forest owners. Additionally, these efforts can link landowners to emerging carbon markets and programs. USDA's Natural Resources Conservation Service, for example, is currently testing many of these approaches through the Conservation Innovation Grant and Regional Conservation Partnership Program, with potential to scale up support in the coming years. These efforts can inform evolution of existing federal support programs, to advance more pay-for-performance approaches and ensure conservation dollars are advancing key strategic priorities.

QUICKLY MOBILIZING FEDERAL LANDS

Covering 28 percent of U.S. land and comprising nearly 20 percent of the annual U.S. carbon sink, federal lands provide an important opportunity to quickly sequester carbon at scale while programs to support carbon sequestration on private lands are gaining momentum (Zhu and McGuire 2016; Zhu, Zhiliang, and Reed 2012, 2014). Building on important progress over the past several years, federal agencies can both begin to track carbon dynamics on federal lands as part of their agency-wide GHG inventories and put in place management guidance to increase carbon sequestration potential.

Federal grassland and forest carbon fluxes are reported in the U.S. GHG Inventory, and federal agencies have begun to incorporate carbon sequestration and emissions estimates into land management plans. The Council on Environmental Quality has also issued updated guidance for assessing greenhouse gas impacts as part of National Environmental Policy Act (NEPA) analysis, ensuring federal agencies account for and consider mitigation options for greenhouse gas and carbon sequestration outcomes for project-level decision-making and planning processes on federal lands (CEQ 2016). Agencies are also required to track their GHG emissions under Executive Order 13693 – Planning for Federal Sustainability in the Next Decade, which requires all agencies to reduce GHG emissions by 40 percent by 2025. Using existing data from USFS, USGS, and other agencies, the five land management agencies (USFS, FWS, NPS, DOD, BLM) can include land use, land-use change, and forestry (LULUCF) reporting consistent with our national GHG Inventory to allow for annual tracking of land carbon on federal lands.

These data and federal processes can provide the foundation for developing and implementing guidance to include land carbon sequestration as one of the management priorities for federal lands. Research and data-supported management practices for carbon sequestration and resilience can be integrated into long-term strategic plans, such as BLM Resource Management Plans and National Forest System Land Management Planning.

Management priorities could include replanting understocked forests, promoting forest expansion where ecologically sound, and promoting agroforestry in federal grassland and pasture where appropriate. Federal lands could also support carbon beneficial forms of biomass production, such as energy crops. Western federal lands are also at risk for increasing natural disturbances like wildfire. As wildfire risk and other disturbances increase, regional and local strategies are needed for managing public safety, potential economic impacts, ecological viability, and long-term carbon storage on disturbance-prone lands. Land managers should include carbon as a consideration for maintaining and enhancing landscape health in order to avoid undermining carbon mitigation efforts elsewhere.

New resources will be required to implement this work at a scale sufficient to meet the MCS goals. Forest restoration work needed on federal lands far exceeds current budgets. In addition, the current funding model for fighting wildfires pulls money from restoration work in years with high firefighting costs, with severe wildfire seasons expected to increase as a result of climate change. To meet MCS goals, we will need to address these budget challenges to ensure federal agencies have the resources to fight wildfires and other natural disturbances as well as to implement restoration work that will increase forest resilience and carbon sequestration capacity. Addressing these budget constraints can also support research and monitoring to ensure our wildfire risk reduction and forest restoration efforts are aligned with our climate goals based on the best available science.

To date, there has not been an assessment of additional carbon sequestration potential on federal lands. As management guidance is developed, assessing the full potential contribution of federal lands to our 2050 goals can help guide future policy priorities.

SUPPORTING EFFICIENT LAND USE AND PROTECTING SENSITIVE LANDS

Managing land use and land use change will make it easier to achieve our climate goals, reduce impacts to natural landscapes and high-value conservation areas, and reduce risk of impacting global forests through agriculture and forest commodity "leakage." There are a number of policy, innovation, and research priorities that can help our working lands increase productivity, ensure smart urban growth, and protect sensitive areas like wetlands.

Increasing forest productivity and assessing supportive markets

Enhancing forest productivity, including IFM practices, genetic tree breeding, targeted fertilization, more rapid planting following harvest, and other strategies, could be an important component of maintaining and growing our carbon sink. While some forestry models include the potential for productivity improvements, there has been less discussion about what these activities would look like in practice and how we can guide forest management in this direction, especially in ways that protect and promote healthy working lands.

A renewed focus on research is needed to better understand the potential for increased forest productivity, assess the potential advantages and negative impacts, and develop recommendations for further RD&D and policy support. Of key importance is better understanding the role that forest products markets, including the production and use of carbon beneficial forms of woody biomass for energy and the potential for non-residential low-rise and high-rise wood buildings deployment, can play in incentivizing enhanced forest productivity and increased carbon storage. New research can take advantage of emerging market dynamics, providing real-world data on the effects of forest products markets on forest management decisions and planting activity.

Improving food crop yield and delivery

Increasing crop yields beyond historic rates, which will be important for avoiding conversion of forests and grasslands to cropland, requires renewed RD&D investment. Research that indicates across 24–39 percent of global crop-growing areas, yields are not improving or declining (Ray et al. 2013). Increasing U.S. crop yield research support and developing a strategic global plan can help deliver on global climate goals and increase access to affordable nutrition.

Reducing food waste is another tremendous opportunity to increase food supply without impacting land use. Led by USDA and EPA, with a full range of partners, the U.S. Food Waste Challenge has set a goal to reduce food waste in the U.S. by 50 percent by 2030. Major global efforts by governments, the private sector, and civil society are striving to achieve the Sustainable Development Goal 12.3 to halve food waste globally by 2030 (UN 2016). Progress in this area would significantly reduce the land, fertilizer, energy, and water required for food production and reduce emissions from agriculture, transportation, and landfills.

Investing in energy crop yields and advanced biomass supplies

Increasing energy crop yields is an important strategy for reducing land use impacts of dedicated biomass production and increasing supplies of carbon beneficial forms of biomass. The DOE Sun Grant Initiative has to date focused on building a database of energy crop yield measurements from around the country, informing our understanding of yield potential. New RD&D efforts through USDA and DOE can support continued improvement in energy crop yields, innovative biomass production approaches, and emerging biomass opportunities like micro- and macroalgae.

There are also opportunities for using cropland and pasture more efficiently to allow for growing energy crops without increasing land use competition and land use change. A significant percentage of national cropland may be economically marginal in crop production due to poor hydrology, poor soils, or operational constraints. These acres are important candidates for supporting production of energy crops (Muth 2016). While quantification of these types of "marginal" acres has been undertaken at the state level in Iowa (Brandes et al. 2016), which indicates up to 27 percent of cropland acres are under-producing or unprofitable, a more detailed analysis of national availability is needed. Expanding use of precision agriculture technology, which helps to track inputs and production on a fine spatial scale across fields, can empower farmers to identify these areas themselves. Policies that encourage markets for carbon beneficial forms of biomass would help create a higher value use for these acres.

Advances in micro- and macroalgae and other emerging forms of biomass can also significantly increase biomass supplies with minimal land use pressures, generating significantly higher yields than land-based energy crops per unit of area and time (DOE 2016). Ongoing RD&D will be needed to address logistical challenges and lower costs.

Smart urban planning

Cities around the United States, including Portland, Seattle, and Denver, are already implementing policies to promote smart development, utilizing market-based approaches through urban growth limits and tradeable development rights. These market incentives for smart planning can simultaneously support our land preservation and carbon sink goals, reduce emissions from transportation, and enable higher urban quality of life through mixed-use neighborhoods (Marcotullio et al. 2013, Gudipudi et al. 2016). Complementary policies for appropriate zoning, mixed-used neighborhoods, and provision of low-income housing are needed to avoid undesired consequences of limiting urban expansion, such as increasing land prices and rental rates. Additional financial signals in the form of conservation easements, forest products markets, preferential current use taxation policy, and cost-share incentives can also help to maintain undeveloped areas and forests.

The federal government already supports urban planning through programs like Housing and Urban Development (HUD) regional planning grants and the HUD-DOT-EPA Partnership for Sustainable Communities. Looking ahead, additional federal incentives are needed to support communities in managing urban expansion and promoting conservation easements and other tools. Targeting smart planning efforts in areas at highest risk of forest loss can enhance the carbon mitigation potential of these programs.

Maintaining intact wetlands

Protecting existing wetlands and restoring previously degraded wetlands can help maintain and grow carbon benefits from U.S. natural lands. Programs should look to maximize natural ecosystem resilience to climate change, implement strong adaptation measures allowing for wetland restoration and migration, and limit future development in areas at risk, currently or in the future from coastal flooding. Continued attention to data needs while also considering issues of scale will help refine and support the implementation of these strategies. Future federal research should focus on (1) providing regional- and local-scale GHG emissions estimates for coastal wetlands to help coastal managers better manage the carbon stocks, and (2) innovative, low-cost approaches to measuring and modeling GHG fluxes for linking climate mitigation and adaptation through wetland conservation and restoration. Better quantification of U.S. seagrass beds is another research priority, as these habitats are thought to provide substantial carbon sequestration benefits (Fourqurean et al. 2012).

RESEARCH AND DATA FOR INFORMING POLICY AND STAKEHOLDERS

The United States has taken great strides in improving our knowledge of U.S. land carbon dynamics, improving the land use, land-use change, and forestry (LULUCF) component of our national GHG Inventory, and developing new projections of the U.S. carbon sink (EOP 2015). As we seek to guide policy that can support our 2050 climate goals, future research, inventory improvements, and data collection efforts will provide policy makers with a strengthened foundation for decision making.

Mitigation hot spot mapping

Avoided forest conversion, forest expansion, and other forest management practices will play a significant role in maintaining and growing the U.S. carbon sink. Programmatic funding for these activities should be targeted in areas where it will have the largest mitigation impact. Developing "hot spot" maps for areas at high risk of forest loss, areas in need of reforestation or restoration, and those capable of supporting highly productive forests would allow for targeting incentives to high-priority areas. When carbon pricing or carbon markets drive mitigation activities, hot spot maps could support private sector project developers in targeting high carbon potential regions. This mapping effort could build on existing forest monitoring and inventory programs like the Forest Inventory and Analysis (FIA) database and Landsat data, translating data on forest loss, forest regeneration failure, and forest productivity into spatially explicit geographic areas qualifying for priority forest carbon incentives. Expanding this approach to agroforestry and soil carbon-enhancing strategies should also be considered. This effort can feed into decision-support tools that allow stakeholders to apply this data to project development and investment decisions.

Increasing certainty, decreasing costs, and innovation for soil carbon projects

Scaling up soil carbon sequestration on cropland and grassland through carbon incentives could be challenging for multiple reasons, including regional and local uncertainty of sequestration potential, cost of verification of soil carbon sequestration, and concerns regarding the permanence of stored soil carbon and risk of reversal. There are also potential opportunities to incentivize enhanced soil carbon in forests, but similar scientific and methodological uncertainties present barriers to program design and measurement of performance. Additional research, data collection, and monitoring frameworks can help improve existing measurement and estimation tools and models and reduce verification costs.

Through federal research efforts such as USDA's Soil Health Initiative, the federal government can support a national research program to significantly improve the ability of soil carbon models and satellite data to estimate current and potential future soil carbon gains across variable soils, climates, and activities. This program would fund consistent implementation and monitoring of soil carbon activities across the country using high-accuracy measurement systems. Such a research program can help increase certainty of soil carbon gains and lower execution risk for landowners and the private sector, reducing barriers to soil carbon mitigation.

Innovative research programs to massively expand soil carbon potential, like ARPA-E's ROOTS and TERRA programs, and efforts to develop perennial commodity crops should also be an ongoing priority. These efforts can unlock previously unimagined mitigation opportunities with minimal impacts to land use competition and natural landscapes.

Monitoring and data improvements for U.S. GHG Inventory

We need a full understanding of emissions and removals to target mitigation policies and incentives most effectively, and to track the results of our actions. The United States continues to improve its ability to quantify its land sector emissions and removals, including as part of its GHG inventory submission to the UNFCCC. In the coming years, we will do even more to improve inventory accuracy, including incorporating remote sensing input with ground plot data, reconciling definitions and metrics in different federal datasets, using new data to better estimate and represent the carbon benefits of our conservation programs, enhancing estimates of carbon in aboveground grassland biomass, and more fully integrating data from wetlands and from interior Alaska. However, there is still significant uncertainty and variability in our land sector estimates.

Looking ahead to mid-century, we can envision growing use of satellite data and remote sensing to provide more detailed, real-time, and accurate data. Greater coordination across federal agencies, including USGS, USDA, USFS, and EPA, will be necessary, along with continued Federal investments.

LAND SECTOR "CHECKPOINTS"

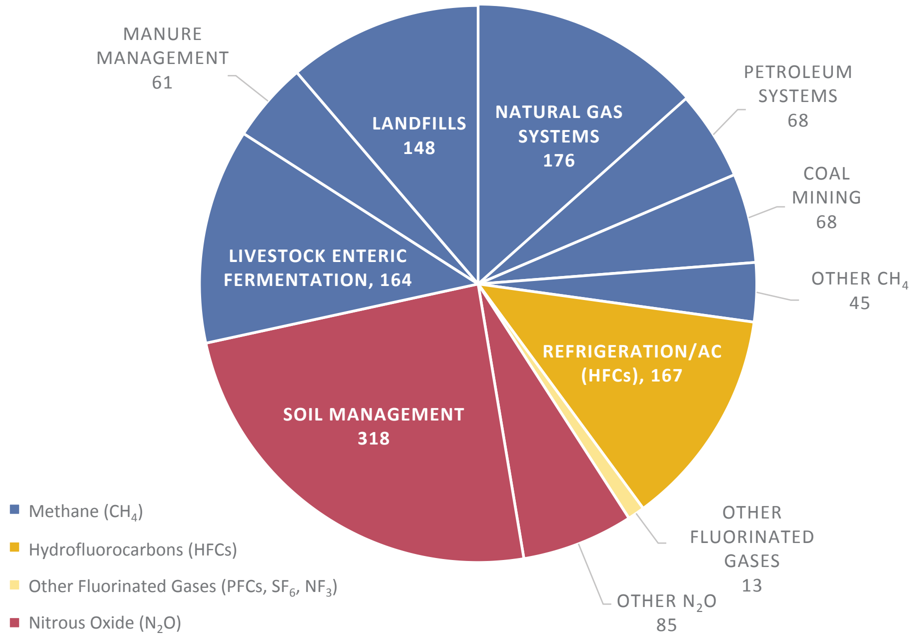
Most policies and programs are naturally subject to "checkpoints" throughout their implementation, or moments when the policy's effectiveness and impacts are assessed and decisions are made about whether to continue on the same path or to change course. The large-scale land-sector changes envisioned in the MCS, as with any long-term policy process, warrant checkpoints at which policy makers can assess climate and land policy effectiveness in achieving intended outcomes and avoiding negative or unintended impacts. The appropriate timing and structure for such checkpoints should be policy-specific and they should not be so rapidly paced as to undermine the ability for policies to function. Putting in place these processes can allow us to act quickly in the face of future uncertainty, while allowing for important adjustments over time to improve policy effectiveness. Both of these elements will support achieving deep carbon reductions by mid-century.

6 REDUCING NON-CO_2 EMISSIONS

While CO_2 accounts for four-fifths of U.S. greenhouse gas (GHG) emissions, the remainder are highly potent heat-trapping gases, many of which have near-term climate impacts due to their shorter "lifetimes" in the atmosphere. Figure 6.1 shows the contribution of non-CO_2 U.S. GHG emissions and their major sources, including methane (CH_4) (55 percent), nitrous oxide (N_2O) (31 percent), hydrofluorocarbons (HFCs) (13 percent), and other fluorinated gases such as PFCs, SF_6, and NF_3 (1 percent) (EPA 2016a).

Absent significant innovation and policy, non-CO_2 GHG emissions are projected to increase rapidly. For example, growing global demand for food would drive broader use of nitrogen fertilizer and increased livestock production, resulting in greater N_2O and methane emissions. A growing global population will also increase demand for energy and refrigerants, leading to greater emissions of methane and HFCs in the coming decades. Additional challenges to mitigating non-CO_2 GHG emissions include the diffuse nature of their sources such as individual cattle or air conditioners and the difficulty of detecting and monitoring leaks. Increased research, development, and demonstration (RD&D) is needed to address these challenges.

FIGURE 6.1: SOURCES OF U.S. NON-CO_2 GREENHOUSE EMISSIONS BY GAS, 2014 (MMT CO_2E)



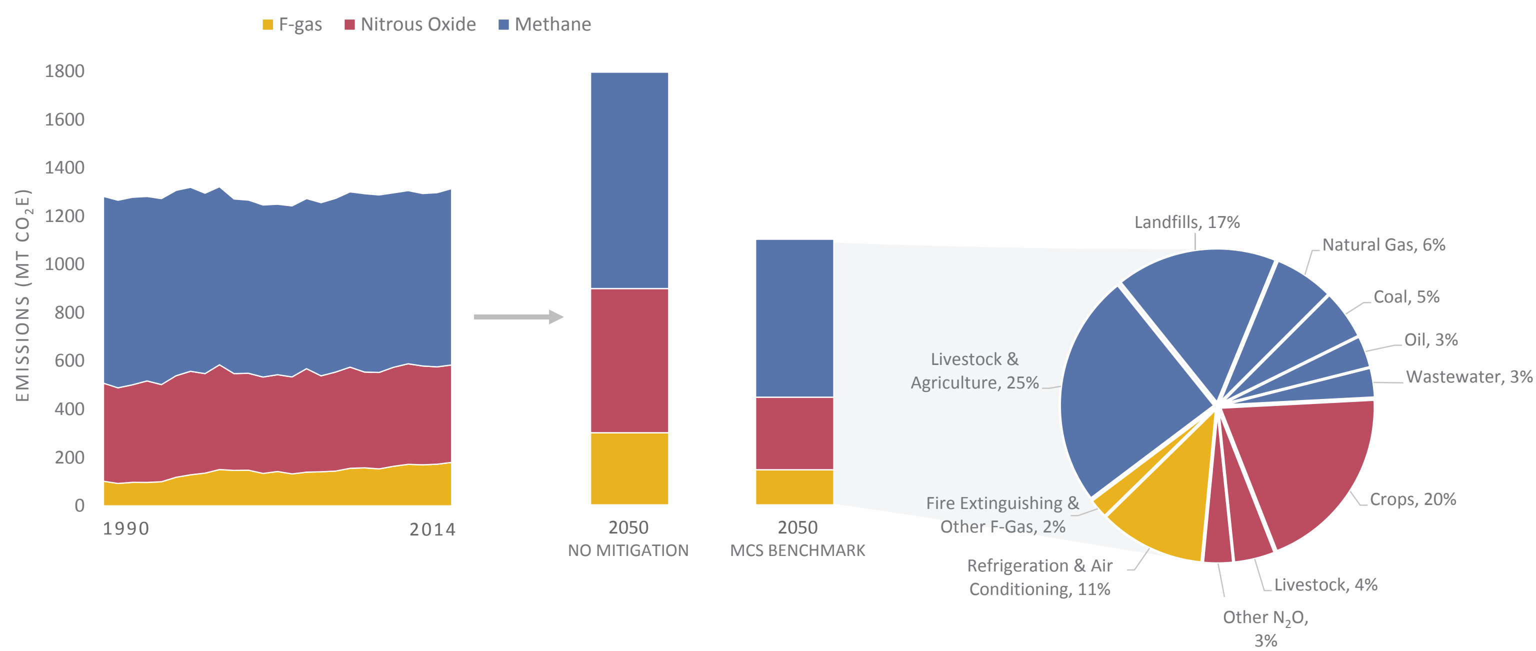
Note: These calculations use the U.S. GHG Inventory for 1990-2014 that assumes a 100-year GWP based on IPCC AR4 estimates. Source: EPA 2016a.

Figure 6.2 compares 2005 non-CO_2 GHG emissions to the 2050 MCS Benchmark scenario[21] as well as to projected 2050 emissions absent mitigation efforts (i.e., new policies and innovation). Figure 6.2 also displays the residual 2050 emissions consistent with the MCS Benchmark scenario. While total non-CO_2 emissions decline modestly compared to 2005 levels, they are 50 percent lower than a 2050 No Mitigation scenario.

The MCS analysis of non-CO_2 mitigation potential does not account for major technological advances that may be achievable with increased RD&D investment. The cost estimates used in the analysis assume only minor technological progress over the next few decades. With continued innovation and well-designed policies, we can achieve even deeper non-CO_2 reductions than those displayed in the MCS analysis.

[21] In generating these estimates, the MCS analysis relied on the Global Mitigation of Non-CO_2 Greenhouse Gases report (EPA Report 430R13011) to calculate country-level marginal abatement cost (MAC) curves for all non-CO_2 greenhouse gases by sector. The EPA MAC analysis is a bottom-up engineering cost analysis that constructs MAC curves from estimated abatement potential and average breakeven price calculations for each mitigation option. The mitigation options are ordered producing a stepwise curve, where each point reflects the average cost and reduction potential if a mitigation technology were applied across the sector within a given region. Cost and abatement potential data used in the EPA report are drawn from a variety of public sources and the peer-reviewed literature. In determining whether to undertake non-CO_2 reduction actions, the GCAM model used to generate the MCS compares the costs from the EPA MAC curves to the costs of other opportunities to reduce net GHG emissions, such as reductions in CO_2 from the energy sector.

FIGURE 6.2: NON-CO_2 EMISSIONS REDUCTIONS IN 2050 WITH MCS BENCHMARK SCENARIO



Emissions are down only modestly compared to 2005 emissions levels but are considerably lower than a projection of emissions in 2050 without mitigation efforts. Note: "MCS Benchmark" emissions are scaled to be consistent with EPA projections data used in the Global Mitigation of Non-CO_2 Greenhouse Gases report (EPA Report 430R13011) in order to reflect residual non-CO_2 emissions consistent with U.S. GHG Inventory data. These projections include distinct activity assumptions from those used in GCAM non-CO_2 results displayed in previous chapters. Source: "No Mitigation" estimates for each non-CO_2 gas are sourced from the Deep Decarbonization Pathways Project, with historical data from the U.S. GHG Inventory (Williams et al. 2014, EPA 2016a).

BOX 6.1: GLOBAL WARMING POTENTIAL

In order to compare the climate impacts of each greenhouse gas, scientists use a "global warming potential" (GWP) factor to convert the warming impacts from a non-CO_2 gas into carbon dioxide-equivalent (CO_2e). A GWP assumes a given time period, since different gases have different lifetimes in the atmosphere. Non-CO_2 greenhouse gases are more potent than CO_2 at trapping heat within the atmosphere, and thus have high GWPs. Using the IPCC AR5 GWP estimates for a 100-year time scale, methane is 28-36 times more powerful than CO_2, nitrous oxide is 265-298 times more powerful, and hydrofluorocarbons have GWPs as high as thousands or tens of thousands (EPA 2016b). Because methane and HFCs cycle out of the atmosphere more quickly than CO_2, their 10 and 20-year GWPs are even higher. This also means that near-term global actions on non-CO_2 GHG emissions can effectively reduce the rate of near-term warming.

As seen in Figure 6.2, the largest share of residual emissions in 2050 is methane from livestock, landfills, and fossil fuel production. Other major sources in 2050 include HFCs from existing equipment and appliances and N_2O emissions from crop production.

METHANE FROM FOSSIL FUEL SYSTEMS

Fossil fuels are not only the primary source of CO_2 emissions but also a major source of methane emissions. Methane is released across the supply chain as part of fossil fuel production, processing, transmission, storage, and distribution. These emissions are both intentional (venting) and unintentional (leaks). Current estimates attribute nearly one-third of total U.S. methane emissions to oil and natural gas systems. Coal mining also releases methane trapped in coal seams, accounting for 9 percent of U.S. methane emissions (EPA 2016a).

Decarbonizing the energy sector, including transitioning away from fossil fuels to low-carbon energy, will not only reduce CO_2 but will also reduce methane emissions associated with fossil fuel extraction and processing. However, fossil fuels will continue to play a role in the U.S. energy mix for some time. The MCS therefore envisions additional measures to reduce methane from oil and gas, including increasing the stringency of current standards and enhancing investments to improve methane emissions measurement, capture, and repair technology. Some of these methane reductions can be achieved highly cost-effectively with the recovery and sale of captured methane.

The United States has already taken action to better identify and reduce methane emissions from the energy sector. In 2014, President Obama released a national methane strategy targeting the largest sources of methane, including from oil and gas production and coal mines. The strategy also identifies opportunities to reduce methane from agriculture and landfills, which are discussed in subsequent sections. In 2015, the Obama Administration set a goal of reducing methane emissions from the oil and gas sector 40 to 45 percent below 2012 levels by 2025. Canada and Mexico have since also committed to this goal. In recent years, new information from studies of the U.S. oil and gas industry have indicated that methane emissions are much higher than previously understood. EPA updated the U.S. GHG Inventory with this information, resulting in a large increase in its estimates. In May of 2016, EPA finalized the first-ever standards for methane emissions from new and modified oil and gas facilities, and took the first steps in the process of developing emissions standards for existing sources.

Federal agencies are also coordinating a range of voluntary programs and supporting industry efforts and research initiatives to reduce methane emissions by recognizing leaders, through efforts like the Methane Challenge Program and the Oil and Gas Methane Partnership of the Climate and Clean Air Coalition. Additional federal programs are improving measurement and monitoring of oil and gas sector emissions, such as ARPA-E's MONITOR program, which has invested $30 million to help reduce the cost of detecting and quantifying natural gas leaks (DOE 2014).

Recent evidence indicates that a small fraction of sources may be responsible for a large portion of total oil and gas methane emissions (Brandt, Heath, and Cooley 2016; Zavala-Araiza et al. 2015). Therefore, developing and deploying monitoring capabilities to identify these sources may be particularly effective for targeting mitigation actions. However, doing so is currently challenging due to the fact that these high-emitting sources are dispersed across the United States and may emit intermittently. Continuous monitoring at a large spatial scale via remote sensing technologies could help identify these sources. Use of new satellite, aircraft, and drone capabilities coupled with on-site continuous monitoring and automated infrared imaging have the potential to greatly improve leak detection, monitoring, and repairs.

In coal mining, commercially available technologies can recover and reduce methane emissions. These mitigation technologies include drainage and recovery systems to remove methane from the coal seam before mining or from the area post-mining, destruction of ventilation air-methane, and end-use application for recovered gas (e.g., electricity generation or use as a process fuel for on-site heating).

METHANE AND NITROUS OXIDE FROM AGRICULTURE

Agricultural production contributes over 40 percent of U.S. non-CO_2 greenhouse gas emissions in the form of N_2O and methane. Agriculture, in particular the use of nitrogen-rich fertilizers to increase crop yields, is the source of three-fourths of annual U.S. N_2O emissions. Agricultural methane emissions are largely driven by livestock manure and enteric fermentation (EPA 2016a).

As discussed previously, global demand for food is projected to lead to greater global agricultural-related methane and N_2O emissions. In spite of this growth, the MCS analysis points to potential actions to reduce N_2O emissions significantly from 2005 levels by 2050. Still, without additional technological innovation, agricultural methane emissions will likely remain a significant GHG source in 2050.

Many technologies and practices are currently available that can reduce methane and N_2O emissions associated with agricultural operations. Farmers, ranchers, and land managers across the United States are already using many of these techniques. Through the Department of Agriculture and programs such as the Environmental Quality Incentives Program (EQIP), the United States has promoted increased education, dissemination of online tools, and technical assistance to help farmers manage livestock herds, improve manure management, modify animal diets, and adopt alternative techniques to fertilizer applications. These actions reduce emissions while also maintaining yields and decreasing costs. In 2015, the USDA announced its Building Blocks for Climate Smart Agriculture and Forestry, previously discussed in Chapter 5. Through the Building Blocks, USDA is working closely with farmers, ranchers, and rural communities to implement voluntary, incentive-based practices that improve environmental conditions while also preparing communities for the impacts of climate change. To address N_2O, USDA promotes efficient nitrogen stewardship to reduce over-application and nitrogen runoff into waterways through the principles of right timing, right fertilizer type, right placement, and right quantity. Adopting these techniques will enable farmers to maintain yield while decreasing expenses on fertilizer. Another Building Block supports livestock partnerships that use cost-share support and technical assistance to encourage broader deployment of anaerobic digesters, lagoon covers, composting, and solids separators to reduce methane emissions from cattle, dairy, and swine operations.

Building on these actions, greater emissions reductions can be achieved through broader uptake of these existing techniques, greater incentives to promote climate-smart practices, and technological innovation. Investments in animal genetics and breeding could improve the health and value of livestock while reducing feed demand and decreasing livestock-related emissions. Safe food additives like certain types of algae have the potential to significantly reduce methane production in livestock (Kinley and Fredeen 2014). Small-scale anaerobic digesters can capture methane from waste and supply renewable energy for electricity and on-farm equipment. Slow-release fertilizers and other precision agriculture techniques can reduce the amount of nitrogen that is applied to a field. USDA estimates that we can reduce non-CO_2 emissions from agriculture by 25 percent or more from current levels by 2050 by successfully expanding existing mitigation options, making new technologies standard practice, and expanding outreach and technical assistance efforts.[22] Over time, many of these mitigation solutions can lead to economic gains for farmers and ranchers, including lower fertilizer costs, and increasing health and productivity of livestock.

Addressing methane and N_2O from agricultural production will continue to be challenging. Risk aversion, highly competitive agricultural markets, and growing impacts from climate change can make new practices unattractive for farmers and ranchers. Achieving widespread adoption of these practices could require putting in place economic incentives to help overcome potential concerns about lower yields, lower profits, and any costs associated with new technologies and practices. Improved approaches for capturing these emissions reductions in the U.S. GHG Inventory are also needed. By no means are the opportunities laid out in this report exhaustive. The MCS envisions additional focus on policies, incentives, and innovative technologies to scale up non-CO_2 mitigation from agriculture.

METHANE AND NITROUS OXIDE FROM WASTE STREAMS

Landfills are the third largest source of methane emissions in the United States, contributing 11 percent of non-CO_2 emissions. As seen in Figure 6.2, landfill methane remains a significant share of non-CO_2 emissions in 2050 under the MCS Benchmark scenario. When organic materials, such as food waste, decompose in the absence of oxygen, methane is produced. Methane emissions are similarly generated from municipal and industrial wastewater treatment activities, although centralized aerobic wastewater treatment facilities limit the amount of methane released. Municipal wastewater is also a source of N_2O emissions—human sewage emits N_2O during both the nitrification and denitrification of urea, ammonia, and proteins.

In July 2016, EPA finalized stringent standards to reduce methane emissions from new and existing landfills that will result in reductions of 8 million metric tons annually in 2025. The standard requires the installation of gas collection systems that capture methane to either flare or put to productive use, such as powering on-site equipment. EPA also supports smaller landfills in implementing landfill gas capture through voluntary programs like the Landfill Methane Outreach Program.

The efficiency of biogas collection systems is currently around 85 percent (EPA 2008). This may be improved with technological advances and as new landfills are designed with gas collection in mind. Some of the remaining fugitive emissions from landfills could be reduced by installing and maintaining bio-based systems such as bio covers or bio filters that oxidize methane emissions.

While these measures can reduce methane once created, other actions can help prevent methane production entirely. For example, food waste reduction and diversion programs cut the amount of organic waste decomposing in landfills. Approximately 133 billion pounds of food end up in landfills because it is either deemed cosmetically unfit or will not stay fresh long enough to be shipped far distances, making it the single greatest contributor to municipal landfills (USDA 2015). In addition to exacerbating methane emissions, food waste contributes to excess fossil fuel and water use, while also putting increasing pressures on

[22] Based on internal USDA analysis.

cropland as global food demand grows. In September 2015, USDA and EPA, along with many private sector and food bank partners, announced a national target to reduce food waste 50 percent by 2030, including through encouraging farmers to donate more of their imperfect produce to the hungry (USDA 2015). Multiple states, including Massachusetts, Vermont, and Connecticut, have implemented regulations to reduce food waste from commercial sources (Perry 2014). Scaling up these waste diversion programs would help significantly reduce landfill emissions in the future.

Finally, 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.

HFCs FROM REFRIGERATION AND AIR CONDITIONING

Fluorinated gases are man-made and used in a range of applications. They are highly potent greenhouse gases, trapping hundreds to thousands of times more heat than carbon dioxide. The vast majority of fluorinated gases emitted are hydrofluorocarbons (HFCs). A substitute for ozone-depleting substances, HFCs are primarily used for refrigeration and air conditioning.

Absent regulation, emissions of HFCs in the United States and globally were expected to double between 2015 and 2030, due both to the phase-out of ozone-depleting substances under the Montreal Protocol on Ozone-Depleting Substances and the overall growth of air conditioning and refrigeration around the world (EPA 2012, Velders et al. 2009). Fortunately, HFC emissions reductions are achievable by preventing or reducing leaks and transitioning to the use of low-GWP alternatives. The Obama Administration has reduced HFCs through both international diplomacy and domestic actions.

Over the past several years, the Obama Administration announced a series of executive actions to address HFCs. Under the Significant New Alternatives Policy (SNAP), EPA lists acceptable alternatives used in aerosols, foam-blowing, refrigeration, and other sectors. In 2015 and 2016, EPA finalized two regulations to prohibit the use of certain HFCs and HFC-containing blends across a variety of end-uses where safer and more climate-friendly alternatives are available. In September 2016, EPA also finalized a regulation that would strengthen existing refrigerant management requirements and extend safe handling, reuse, and disposal requirements to HFCs.

Along with these regulatory measures, the White House announced a series of private-sector commitments to cut HFC usage. The combination of private-sector commitments and executive actions in the United States is estimated to reduce domestic reliance on HFCs and contribute to a reduction in cumulative global consumption by more than 1 billion $MtCO_2e$ through 2025.

Significant progress has also been made this year on the international front. In October 2016, the United States worked with nearly 200 other countries to adopt an amendment under the Montreal Protocol to phase down the production and consumption of HFCs. Under the Kigali Amendment to the Montreal Protocol, the United States and other countries listed under Article 2 of the Montreal Protocol committed to phase down production and consumption of HFCs by 85 percent by 2036, while the rest of the world committed to 80 to 85 percent reductions by 2047. The United States is also working with partners in the Climate and Clean Air Coalition to Reduce Short-Lived Climate Pollutants (CCAC), launched in 2012, to promote climate-friendly alternatives and standards for HFCs.

Achieving HFC reductions beyond those shown in Figure 6.2 will depend on addressing the existing stock of refrigerators and air conditioners, which already contain HFCs and have potential to leak into the atmosphere over the coming decades. For example, EPA can help to reduce or eliminate the leaking of HFCs from various types of refrigerant-containing equipment through targeted partnership programs such as its GreenChill program, which partners with food retailers to, among other things, lower refrigerant charge sizes and eliminate leaks. EPA can also scale up partnership programs such as the Responsible Appliance Disposal Program to prevent emissions through the proper disposal of appliances by ensuring recovery and reclamation or destruction of refrigerants and foam.

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, though private sector players are already leading the way on this front.

7 INTERNATIONAL CONTEXT

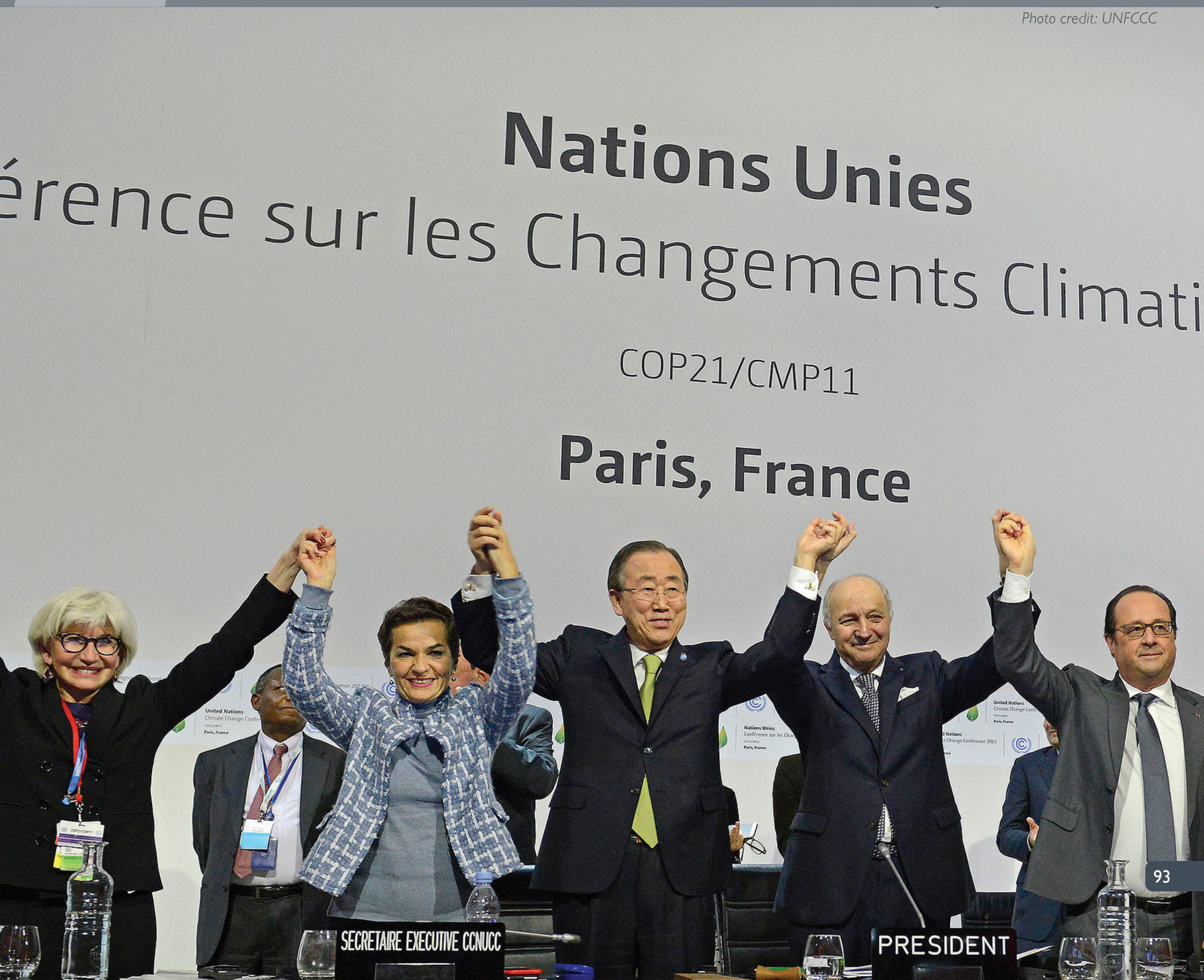


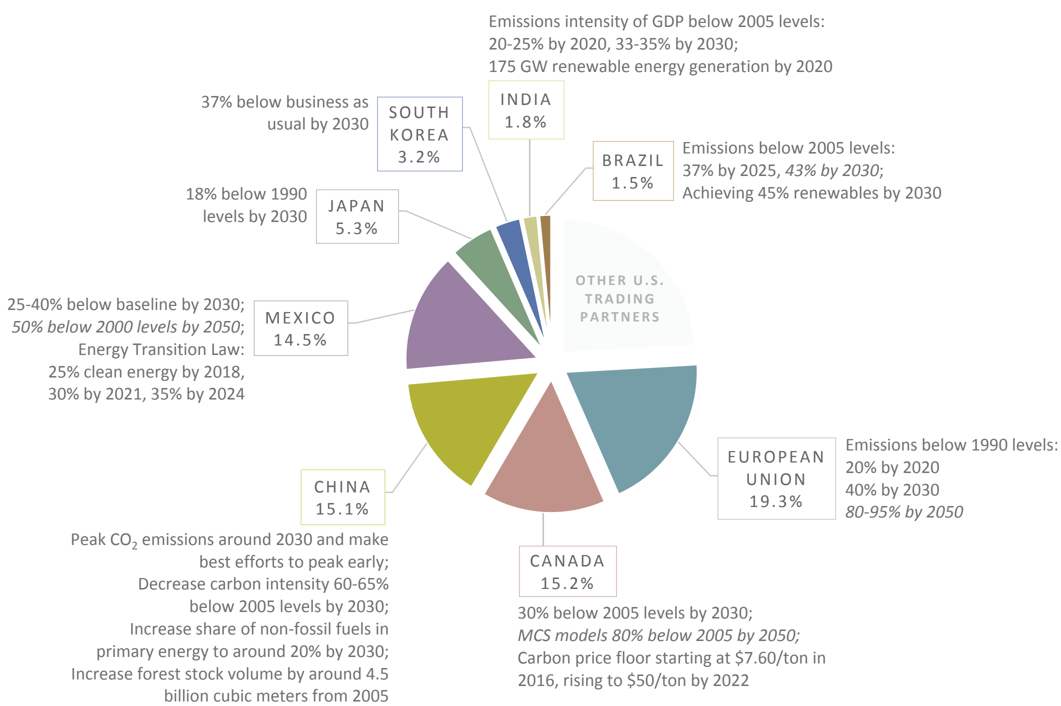
Photo credit: UNFCCC

While this report focuses on the United States' mid-century strategy (MCS), climate change is a global problem requiring a global solution. To this end, 195 countries, including all major economies, have adopted the Paris Agreement, which entered into force on November 4, 2016. The Paris Agreement aims to hold the global average temperature to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels. Consistent with this objective, Parties also aim to balance greenhouse gas (GHG) emissions sources and sinks in the second half of this century or, in effect, achieve net-zero global GHG emissions before 2100. The U.S. MCS is consistent with these global objectives, but strong international action will be critical to achieving them. International cooperation can also significantly lower the costs of decarbonization and create economic opportunities for people and businesses, all while reducing the risks and impacts of climate change.

THE NEED FOR GLOBAL ACTION

Achieving the long-term goals of the Paris Agreement will require ambitious action across the international community. According to the Intergovernmental Panel on Climate Change (2014), a pathway to limit warming below 2°C will require global annual GHG emissions to decline between 40 and 70 percent below 2010 levels by 2050, equivalent to lowering annual emissions by 20 to 35 billion metric tons of CO_2 equivalent (CO_2e). The United States is the world's second largest emitter of GHGs, but its total net emissions were just 6 billion tons CO_2e in 2014 (EPA 2016).

FIGURE 7.1: CLIMATE COMMITMENTS OF MAJOR U.S. TRADE PARTNERS



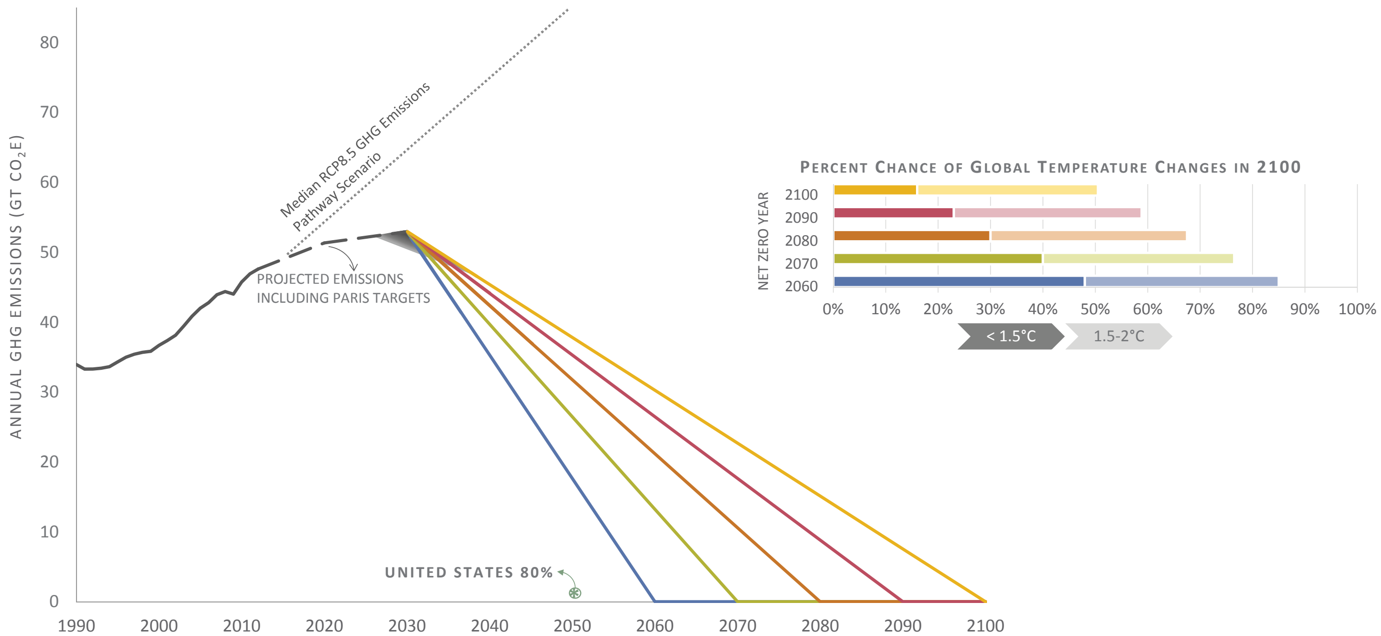
Note: Segment size represents country's contribution to U.S. total trade volume (U.S. Census Bureau 2016). Total trade equals the value of U.S. imports from a given country plus the value of U.S. exports to that country. Other trading partners, the majority of which have also developed NDCs, make up the remainder of the pie, of other trading partners, the large majority of which have also developed NDCs. Aspirational goals are indicated in italics.

Under the Paris Agreement, all countries have put forward strategies for domestic action. Specifically, each party will prepare and implement successive NDCs that chart a course for emissions reductions over time. To date, the vast majority of countries, including all major economies, have set their contributions for 2025 or 2030, with the U.S. NDC setting a target of 26-28 percent GHG reductions in 2025 from 2005 levels. The largest trading partners of the U.S. have all set near-term targets and have undertaken serious actions to deliver against them (Figure 7.1). For example, China's targets include expanding total energy consumption coming from non-fossil sources to around 20 percent by 2030. To achieve this goal, China will need to deploy more clean electricity generating capacity than all the coal-fired power plants that exist in China today and close to the total electricity generation capacity in the United States today.

At the same time, the international community will not achieve its climate goals without the United States. As the world's largest economy and the pacesetter in so many areas of international cooperation, the United States' continued leadership on climate change is needed to galvanize the international community. Indeed, the United States has been a key driving force behind the strong recent momentum toward global action on climate change, including rapid entry into force of the Paris Agreement.

The U.S. MCS is consistent with the ambitious goals of the Paris Agreement and puts the United States on track to achieve net-zero GHG emissions well before the rest of the world will need to. Figure 7.2 displays multiple pathways to global net-zero emissions this century, and the resulting probabilities of constraining global average temperature increases to 2°C and 1.5°C by 2100. If all countries follow the long-term emissions pathways implied by their NDCs under the Paris Agreement and implement rapid reductions starting in 2030, reaching net-zero global GHG emissions in 2080 would mean a roughly two-thirds chance of limiting warming to below 2°C. This MCS puts the United States on a trajectory to achieve net-zero emissions decades before that. Furthermore, applying the rate of U.S. decarbonization between 2020 and 2050 globally would allow for global net-zero GHG emissions by 2070 if rapid reductions begin in 2030.

FIGURE 7.2: GLOBAL GHG EMISSIONS AND TEMPERATURE CHANGES UNDER DIFFERENT NET-ZERO EMISSIONS SCENARIOS



The United States MCS puts the nation on a path consistent with a successful global outcome. Achieving the Paris Agreement temperature goals will require increasing ambition leading to 2030 and steep reductions to net-zero global GHG emissions following 2030. This figure shows the probability of staying below 2°C and 1.5°C across global scenarios by 2100. While there could be an overshoot of the Paris Agreement temperature objectives before 2100, achieving net-zero GHG emissions globally could bring temperatures below peak levels in 2100 and beyond.

Figure 7.2 also shows that following current NDCs will require extremely sharp reductions in global emissions after 2030 to put the Paris Agreement temperature goals within reach. This underscores the importance of increasing global action between now and 2030, as illustrated by the shaded triangle in the figure.

BENEFITS OF THE WORLD ACTING TOGETHER ON CLIMATE

Strong international action and coordination on climate change will directly benefit Americans and the global community in multiple ways, including reducing the costs of deep decarbonization and creating economic opportunities for U.S. businesses and entrepreneurs. Economists have long pointed to the benefits of internationally linked decarbonization policies in minimizing mitigation costs and maximizing advantageous trade opportunities, but ambitious domestic actions implemented separately by all countries will provide crucially important benefits as well, including (1) accelerating innovation in clean technologies and (2) avoiding emissions leakage.

Accelerating innovation in clean technologies. Support for innovation is a core pillar of the United States' MCS because it will reduce the costs and increase the pace of emissions reductions. For the same reason, countries around the world will make similar investments to improve low-carbon technologies, which are traded and deployed globally. The United States can greatly benefit from such "spillovers" of technological progress. Innovation both at home and abroad will increase the cost-effectiveness of emissions reduction efforts. More effort and more experience researching and deploying a technology typically leads to more efficient technologies (commonly referred to as the "learning-by-doing" effect), and rapid deployment also lowers costs through economies-of-scale (Duke 2002, Duke and Kammen 2000, Ueno 2007, Lacerda and van den Bergh 2014, Swanson 2006). In addition, strong international action on climate change will ensure large and growing markets for the new products and services that are developed in the United States. Technological spillovers will also likely be critical in enabling the poorest countries of the world to take action.

Avoiding emissions leakage. Emissions leakage occurs when emissions reductions in one place result in an increase in emissions elsewhere. For example, implementing ambitious climate policies in one country could cause high-emitting producers to relocate to a country with less ambitious regulations. Similarly, leakage can occur when the supply of a high-carbon product declines in one country and production increases elsewhere to satisfy global demand for the product.

The risk of emissions leakage is highest in commodity markets with a high degree of international trade, such as certain manufacturing, agricultural, and forestry products. In the land sector, international cooperation under the UNFCCC Reducing Emissions from Deforestation and Forest Degradation (REDD+) framework is already helping to ensure that reductions in unsustainable logging in one country are not negated by increased logging elsewhere. More work remains to put in place domestic policies consistent with the international REDD+ framework in countries around the world, and additional policies will be required for activities that do not result in deforestation but that impact agriculture and forestry products. Other energy-intensive, trade-exposed sectors also require further attention.

Working to ensure that all countries are acting on climate change, including in trade-exposed sectors, helps to ensure that leakage will not occur. This will benefit Americans in at least two ways. First, U.S. emissions reductions will have their intended effect of lowering global emissions (and thus reducing climate change) because they will not be offset by emissions increases elsewhere. Second, when our international trading partners have comparably stringent regulations, we avoid creating an uneven playing field for businesses operating in different countries.

Fortunately, the United States' most important economic allies are acting in concert on climate change, as shown in Figure 7.1. This is an excellent first step in minimizing emissions leakage.

ROLE OF MID-CENTURY STRATEGIES IN COORDINATING GLOBAL ACTION

The Paris Agreement "[I]nvites Parties to communicate, by 2020, to the secretariat mid-century, long-term low greenhouse gas emission development strategies in accordance with Article 4, paragraph 19, of the Agreement, and requests the secretariat to publish on the UNFCCC website Parties' low greenhouse gas emission development strategies as communicated." [23]

The inclusion of mid-century strategies in the Paris Agreement has roots dating back many years in previous meetings of the Conference of the Parties (COP). The 2010 Cancun outcome encouraged parties to "develop low carbon development strategies or plans in the context of sustainable development," while the 2011 Durban outcome, with its call for "financial and technical support by developed country Parties for the formulation of these strategies," helped shape U.S. cooperation with developing country partners through the Enhancing Capacity for Low Emission Development Strategies (EC-LEDS) program and LEDS Global Partnership.

Mid-century strategies, while separate from the process of developing successive NDCs, will help to put near-term emissions reduction goals in a longer-term context. For example, the NDCs set for 2025 and 2030 include important and significant pledges to reduce emissions, yet in total, the current NDCs are insufficient to achieve the long-term Paris Agreement temperature

[23] 4.19. All Parties should strive to formulate and communicate long-term low greenhouse gas emission development strategies, mindful of Article 2 taking into account their common but differentiated responsibilities and respective capabilities, in the light of different national circumstances.

objectives, as shown in Figure 7.2 (Fawcett et al. 2015). Mid-century strategies can help to ensure that future NDCs lay the groundwork for more ambitious long-term action consistent with the Paris Agreement.

Mid-century strategies are also important in sending clear signals to the private sector that economies are headed to a low-emissions future. Such signals can provide confidence to investors and entrepreneurs that markets for low carbon technologies will continue to rapidly expand, thus fostering innovation in low carbon solutions.

ALIGNING DEVELOPMENT OF MID-CENTURY STRATEGIES

In June 2015, President Obama, Canadian Prime Minister Trudeau, and Mexican President Peña Nieto declared the three countries' common vision with a historic North American Climate, Clean Energy, and Environmental Partnership. Among many other important areas of cooperation, this included the alignment and coordination of mid-century low-GHG strategies.

The United States is working closely with allies outside of North America as well. This includes a series of technical exchanges on mid-century strategies with China, the world's most populous country and largest emitter of GHGs. In a joint outcomes document with the United States in September 2016, China announced it will publish its own MCS as soon as possible. India, another major emerging economy and GHG emitter, has also committed to developing an MCS. Germany has similarly engaged in robust long-term modeling and agenda-setting with its "Climate Action Programme 2020" document, released in 2014, which lays out a strategy for Germany's contribution to the EU-wide goal to reduce emissions 80 to 95 percent by 2050. Germany is also submitting its MCS to the UNFCCC in November 2016. Other countries like Norway and the United Kingdom are carrying out similar analysis. We expect and encourage more countries to take up the Paris Agreement invitation to develop these mid-century strategies.

While every country has unique situations to consider, the U.S. MCS can serve as an example for other nations as they develop mid-century strategies, and the United States stands ready to share its experiences and engage with other nations in developing ambitious, rigorous, and transparent mid-century strategies.

BOX 7.1: THE MID-CENTURY STRATEGIES OF CANADA AND MEXICO

The United States is pleased to release its MCS alongside its North American allies. Indeed, we have worked closely with our counterparts in Canada and Mexico in developing our respective strategies. We are acting in concert on climate change in other ways as well, including an ambitious target to increase clean power to 50% of the electricity generated across North America by 2025. The following provides brief summaries of the mid-century strategies of Canada and Mexico:

Canada's mid-century low greenhouse gas emissions strategy outlines key principles and pathways consistent with Canada achieving net greenhouse gas emissions reductions in 2050 that respect the 1.5-2°C global temperature goal. A few key factors are identified as paramount to low-GHG outcomes in Canada: non-emitting electricity generation; the electrification of certain end-use applications; low-carbon fuels; energy efficiency; and the importance of sequestration from forests. The necessity of reducing non-carbon dioxide emissions is also highlighted. The strategy includes the key message that significant emissions reductions are possible with today's technology, while innovation and research and development will ease and accelerate the deployment of clean technologies and clean energy options—where the role of carbon pricing is paramount in this respect. Canada's strategy also links long-term low greenhouse gas objectives to infrastructure and investment planning.

Mexico's mid-century strategy provides the vision, principles, goals, and key actions to build a climate resilient society and to achieve low emissions development. The strategy is in line with Paris Agreement objectives, with additional efforts indicated for the more ambitious 1.5°C goal. The need for action is identified in five areas: (1) the clean energy transition; (2) energy efficiency and sustainable consumption; (3) sustainable cities; (4) reduction of short-lived climate pollutants; and (5) sustainable agriculture and protection of natural carbon sinks. Mexico's strategy identifies critical crosscutting issues for long-term climate policy, including the need for market-based approaches to price carbon, increased innovation, more research and development of new technologies, and the need to build a climate culture with mechanisms for social and private sector participation. More broadly, Mexico's long-term climate strategy aims to catalyze a profound transformation of its economy, addressing climate change as well as the national priorities of sustainable and more inclusive development.

The United States strongly encourages countries that are developing mid-century strategies to include a basic set of elements that will help them stand up to the scrutiny of the international community, including:

- **Mid-century emissions visions.** An MCS should include an economy-wide, quantitative vision for emissions reductions in 2050 that captures all of the nation's emissions sources and sinks. If objectives are provided in terms of reductions below current or historical emissions levels, the assumed "base year" should be explicitly stated. Exploring multiple scenarios can be useful, but all should be consistent with an ambitious mid-century vision.
- **Quantitative projections supported by appropriate analytical tools.** While recognizing the considerable uncertainties associated with long-term projections, an MCS should use analytical tools to display the sectoral and technological dynamics underlying the strategy. Using a scenario approach can help to straddle competing desires to display the feasibility of a particular objective without prescribing a specific pathway for achieving that objective.
- **Policy and technology assumptions.** When presenting projections of emissions or other quantitative analyses, an MCS should be transparent about the associated technology and policy pathways. For example: What low carbon technologies are expected to provide the country's energy needs? What assumptions have been made about land use, biomass use, and productivity? What new technologies and improvements in existing technologies are assumed to be available? What policies and regulations are expected to lead to these outcomes?
- **Consultation with a broad cross-section of stakeholders.** Mid-century strategies are meant to be comprehensive and reflect viable futures across all economic sectors. Procuring input from stakeholders can help inform technological, economic, and political viability of various mid-century pathways and help identify strategies that can garner the broadest support. Stakeholders can also help inject creativity and strengthen political will in the MCS development process, helping to develop more ambitious visions for the future.

Of course, any mid-century strategy will represent a snapshot in time, bounded by the limited knowledge possessed at that moment. As circumstances change and technologies evolve, mid-century strategies should be revisited and revised as necessary.

The Paris Agreement provides for recurring five-year cycles, wherein parties will revisit and revise their NDCs. Given the important linkages between near-term NDCs and long-term planning, the United States intends to use the same five-year cycles to guide its long-term planning and vision setting, and encourages other countries do the same.

If all countries engage in periodic, rigorous, and transparent long-term planning exercises consistent with the ambition of the Paris Agreement, and take critical steps to implement those plans, the world will succeed at limiting climate change and thus avoid unacceptable risks to our health, our environment, and our economy for generations to come.

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