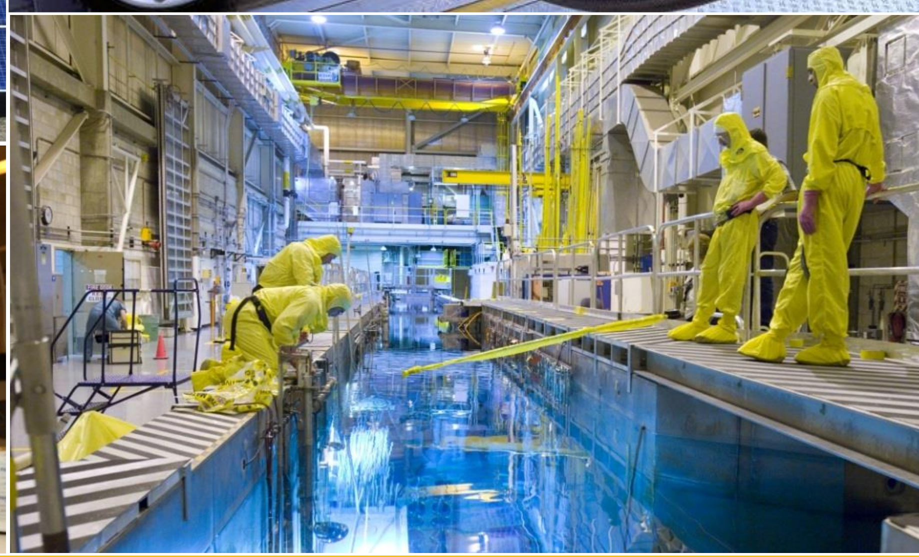
Energy CO_2 Emissions Impacts of Clean Energy Technology Innovation and Policy





U.S. DEPARTMENT OF ENERGY

January 2017

ACKNOWLEDGEMENTS

The U.S. Department of Energy's Office of Energy Policy and Systems Analysis (DOE-EPSA) produced this report and underlying analysis with the cooperation and support of several other DOE offices, including the Office of the Undersecretary for Science and Energy, the Office of the Chief Financial Officer, the Office of Energy Efficiency and Renewable Energy, the Office of Electricity Deliverability and Energy Reliability, the Office of Nuclear Energy, the Office of Fossil Energy, and the Energy Information Administration. Modeling was completed by OnLocation Inc., and Caitlin Murphy, Carla Frisch, Elke Hodson, and Aaron Bergman authored the report.

The authors are grateful for extremely helpful technical reviews and other contributions provided by several individuals. Technical input was provided by Department of Energy, National Laboratory, and contractor staff including Sam Baldwin, Hoyt Battey, Gil Bindewald III, Nicholas Bleich, Alicia Birky, Erin Boedecker, Matt Bowen, Erin Boyd, Lauren Boyd, Steve Capanna, Joe Cresko, Stuart Cohen, Mindi Farber-DeAnda, Paul Donohoo-Vallett, Sarah Garman, Kristin Gerdes, Patrick Gilman, Michael Goff, David Gohlke, Judi Greenwald, Marcos Gonzales Harsha, Zia Haq, Rebecca Jones-Albertus, Fred Joseck, Jordan Kislear, Alison LaBonte, Eric Lantz, Valri Lightner, Alicia Lindauer, Seungwook (Ookie) Ma, John Maples, Cara Marcy, Jack Mayernik, Colin McMillan, Jim Moore, Chris Namovicz, Rachael Nealer, Valerie Nubbe, Tien Nguyen, Franklin Orr, Bill Parks, Kara Podkaminer, Daniel Rabon, Timothy Reinhardt, David Rosner, Aymeric Rousseau, Ann Satsangi, Sunita Satyapal, Tarak Shah, Sharon Showalter, Cody Taylor, Jim Turnure, Rich Tusing, Brian Walker, Anna Wall, Jacob Ward, Brad Williams, Timothy Welch, Frances Wood, Charles Zelek, and others.

Several people reviewed the draft report and provided helpful comments to improve it, including Sam Baldwin, Steve Capanna, Paul Donohoo-Vallett, David Feldman, Judi Greenwald, Joe Hezir, Jordan Kislear, Trieu Mai, Colin McMillan, Ian Mead, Ann Satsangi, Rich Tusing, and Brad Williams within the Department of Energy and its National Laboratories; and Professor Laura Diaz Anadon at Harvard University, Professor John Weyant at Stanford University, and Professor Erin Baker at the University of Massachusetts, Amherst, among others. These reviewers helped to make this report as technically sound as possible; however, any remaining errors or omissions are those of the authors.

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference therein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views of the authors do not necessarily reflect those of the United States Government or any agency thereof.

This report was supported by a DOE American Association for the Advancement of Science Fellowship, administered by the Oak Ridge Institute for Science and Education, which is managed by Oak Ridge Associated Universities under DOE contract number DE-AC05-06OR23100.

Table of Contents

ACRONYMS

AEO	Annual Energy Outlook
AMO	Advanced Manufacturing Office
ARPA-E	Advanced Projects Research Agency–Energy
ATB	Annual Technology Baseline
BETO	Bioenergy Technologies Office
BEV	battery electric vehicle
BTO	Building Technologies Office
CCUS	carbon capture, utilization, and storage
CO_2	carbon dioxide
CP10	an initial carbon price of $10, starting in 2017 and increasing at a rate of 5% per year in real dollars
CP20	an initial carbon price of $20, starting in 2017 and increasing at a rate of 5% per year in real dollars
CPP	Clean Power Plan
CSP	concentrating solar power
DOE	U.S. Department of Energy
EERE	Office of Energy Efficiency and Renewable Energy
EIA	U.S. Energy Information Administration
EPSA	Office of Energy Policy and Systems Analysis
EV	electric vehicle
FCTO	Fuel Cell Technologies Office
FE	Office of Fossil Energy
FEMP	Federal Energy Management Program
FY	fiscal year
GDP	gross domestic product
GHG	greenhouse gas
HDV	heavy-duty vehicle

ITC	Investment Tax Credit
kW	kilowatt
kWh	kilowatt-hour
LCOE	levelized cost of energy
LDV	light-duty vehicle
MEL	miscellaneous electric load
MMT	millions of metric tons
NE	Office of Nuclear Energy
NEMS	National Energy Modeling System
NETL	National Energy Technology Laboratory
NGCC	natural gas combined cycle
NREL	National Renewable Energy Laboratory
O&M	operating and maintenance
OE	Office of Electricity Delivery and Energy Reliability
OWIP	Office of Weatherization and Intergovernmental Programs
PHEV	plug-in hybrid electric vehicle
PTC	Production Tax Credit
PV	photovoltaic
RDD&D	research, development, demonstration, & deployment
VTO	Vehicle Technologies Office
WIP	Weatherization and Intergovernmental Programs Office

EXECUTIVE SUMMARY

This report presents the results of an assessment by the U.S. Department of Energy (DOE) of the impact that meeting or exceeding Departmental energy program goals would have on carbon dioxide (CO_2) emissions from the energy sector in the United States. The focus of this report is on the impact that technology innovation—both alone and in combination with additional policies that incentivize reductions in energy CO_2 emissions[a]—could have on transitioning to a decarbonized energy sector.

The report addresses the following questions:

1. What level of U.S. energy CO_2 emissions reductions could be achieved if all current DOE program goals, including cost and performance goals, are met?
2. What level of U.S. energy CO_2 emissions reductions could be achieved if more ambitious program goals could be attained, supported by additional research, development, demonstration, and deployment (RDD&D), such as what could be enabled by Mission Innovation?
3. What level of U.S. energy CO_2 emissions reductions could be achieved by combining the attainment of DOE program goals with additional policies that reduce CO_2 emissions?

The need to reduce greenhouse gas (GHG) emissions is supported by international scientific consensus, which suggests that the United States will need to reduce economy-wide GHG emissions by 80% by mid-century. [1, 2] This report focuses on CO_2 emissions emitted by our energy system, which are the dominant net source of GHGs.[3] An 80% reduction in economy-wide GHG emissions by mid-century is consistent with keeping global temperatures below a 2 degrees Celsius (°C) increase from pre-industrial levels. This temperature threshold is considered by the scientific community to be a tipping point below which we are more likely to avoid an unmanageable degree of climate change. Note that throughout this report, references to a level of emissions reductions that would mitigate the worst impacts of climate change imply an 80% reduction in economy-wide GHG emissions by 2050.

The impact of a changing climate will be felt both domestically and internationally, lending urgency to the development of national emissions targets that will require deep reductions in emissions by mid-century. Most recently, the Paris Agreement set both a 2 °C goal and a further aim to limit warming to 1.5°C.[4] Thus far, 118 of 197 Parties to the United Nations Framework Convention on Climate have signed the Agreement. The costs of inaction and the objectives of modernizing and enhancing the U.S. energy infrastructure are further motivations and opportunities for reducing GHG emissions in the energy sector.[5, 6]

There are many pathways for reducing energy CO_2 emissions, many of which can be broadly categorized as "technology push" or "policy pull" approaches. "Technology push" is defined as facilitating reductions of CO_2 emissions through advances in technology, i.e., facilitating market adoption of cheaper and better performing clean energy technologies through research, development, demonstration, and deployment (RDD&D). "Policy pull" is defined as market-based policy, tax policy, standards, and/or other mechanisms that create market signals, or mandates that encourage the adoption of low-emissions technologies and strategies.

[a] Other greenhouse gases (GHGs) are also very important to reduce; however, they are not discussed in this report due to modeling limitations.

Government investment in energy innovation has a long history of success.[7, 8, 9, 10, 11] Mission Innovation, an effort to dramatically accelerate global clean energy innovation, is an important first step in expanding innovation. Mission Innovation will help to increase clean energy options and reduce costs for producers and consumers, create new domestic jobs and commercial opportunities in clean energy, improve U.S. competitiveness in the rapidly expanding market for clean energy, and address global climate change.[12] [13] Through the initiative, 22 countries and the European Union have committed to doubling their respective investments in clean energy research and development over the next 5 years.[14]

This report considers both "technology push" and "policy pull" approaches for achieving significant reductions in CO_2 emissions from the energy sector, with an emphasis on the "technology push" approach. DOE examined two technology cases—an Advanced Technology Case and a Stretch Technology Case—which align with questions 1 and 2, respectively, based on technology cost and performance inputs that were provided by the DOE program offices. In addition, the report examines the combination of the "technology push" and "policy pull" cases by applying a proxy for a market-based policy (i.e., a carbon price, to the two technology cases, which aligns with question 3). Combining the "technology push" and "policy pull" approaches offers many benefits and can accelerate the transition to a decarbonized energy sector.

The analysis presented in this report is rooted in a modeled projection of what changes might occur in the energy sector, given a specific set of assumptions about energy resources, conversion, transport and distribution, end-use consumer behavior, and many other factors, as well as about the particular analytical methodologies used. There are inherent limitations to any modeling effort, as all modeling relies on simplified representations of the energy sector. This analysis attempts to estimate the impacts of the portfolio as a whole, so when interpreting the results, one should keep in mind the difficulties inherent in the process. As the history of innovation clearly shows, many individual technology goals included in this analysis may not be realized. At the same time, unforeseen research breakthroughs or major changes to the energy system as a whole may occur and cannot be anticipated in the modeling analysis. Nonetheless, the portfolio as a whole may achieve comparable results.

Finally, it is important to note that this analysis is not a prediction of the future energy system, as there are inherent and significant uncertainties surrounding the future of the U.S. energy sector (e.g., uncertainties in energy price projections and market penetration rates). Rather, the purpose of this analysis is to assess how different sets of internally consistent assumptions about energy supply, demand, and technologies impact energy CO_2 emissions. In turn, this analysis can inform efforts to determine how current and future clean energy RDD&D, as well as how additional policies might support an acceleration of the ongoing transition to a low-carbon U.S. energy sector. Many limitations and simplifications exist, but the present modeling effort is still useful as a guide for policy analysis, particularly when comparing cases against each other to see the impacts of policy and technology change, as was done in this analysis.

Key Results

This analysis indicates that DOE's clean energy RDD&D can contribute to significant progress toward current U.S. climate and energy goals (Figure ES-1). In particular, successful RDD&D activities that drive advancement of clean energy technologies, supported by deployment activities that reduce or eliminate specific market barriers, can result in significant reductions in energy CO_2 emissions. Specific key results are presented in the list below, which includes a corresponding description of how each finding is represented in Figure ES-1:

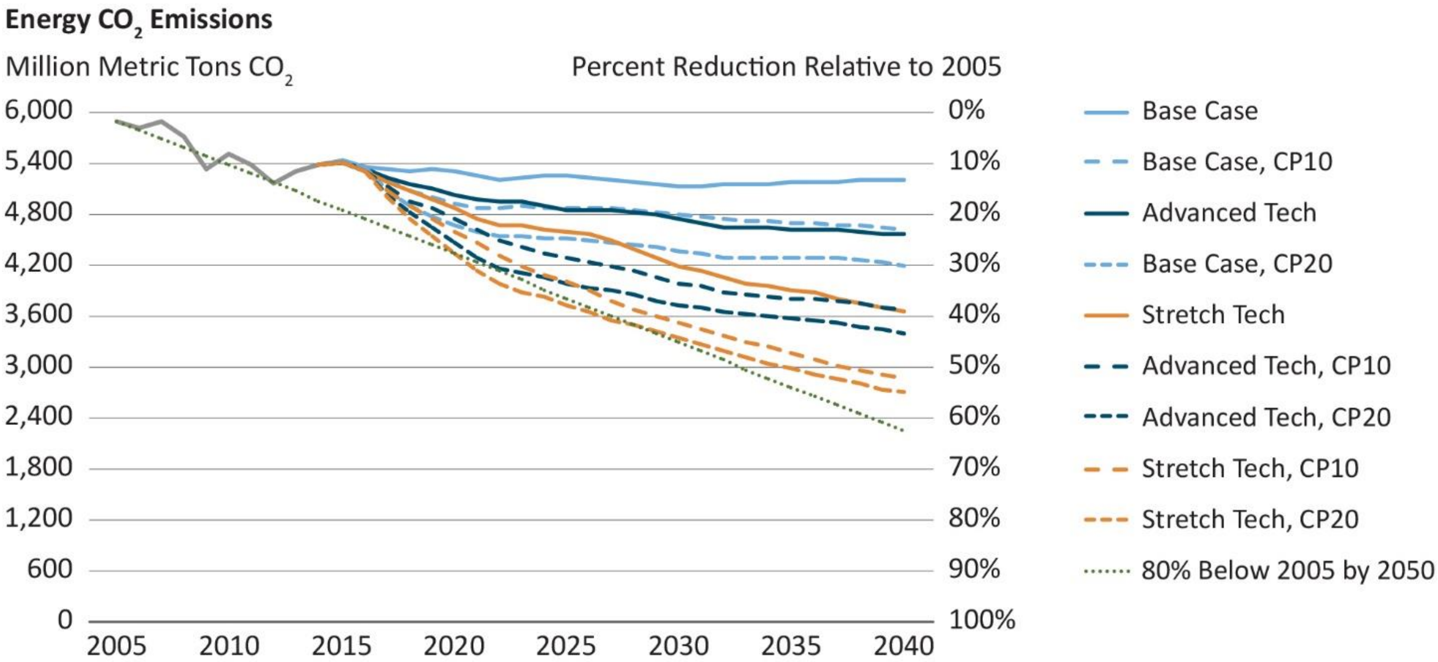


Figure ES-1. Projected U.S. energy CO_2 emissions under various technology (Base, Advanced Technology, and Stretch Technology) and policy (CP10 or CP20: carbon prices of \$10 or \$20 per tonne of CO_2, starting in 2017 and increasing at a rate of 5% per year in real dollars) assumptions. Also included is a dotted straight line indicating energy-sector reductions that are consistent with an economy-wide 80% reduction from 2005 levels by 2050. Historical energy CO_2 emissions are shown for 2005–2014 based on data from the U.S. Energy Information Administration (EIA).[15]

1. *Current levels of RDD&D investment in clean energy technologies, sustained over the next two decades and achieving stated goals, can facilitate reductions in energy CO_2 emissions beyond business as usual projections.* (This result can be seen by comparing the solid black and solid blue lines in Figure ES-1.)

   The Advanced Technology Case projects double the energy CO_2 emissions reductions that are projected in the Base Case by 2040 as compared to 2005. This result demonstrates that successful achievement of DOE's clean energy RDD&D goals (Advanced Technology Case), as modeled, could drive down energy CO_2 emissions beyond those projected under current policies, measures, and projections for technology advances (Base Case).

2. *Opportunities exist for greater energy CO_2 emissions reductions through more ambitious advancements in clean energy technologies and systems, such as what could be enabled by additional support for clean energy RDD&D (e.g., through Mission Innovation).* (This result can be seen by comparing the solid orange and solid blue lines in Figure ES-1.)

   The Stretch Technology Case is projected to drive triple the energy CO_2 emissions reductions in 2040 relative to 2005, compared to those projected in the Base Case (see solid orange line in Figure ES-1). This result indicates that while deployment of current low-carbon technologies is important, additional and ongoing successful clean energy RDD&D can enable additional reductions in energy CO_2 emissions. For example, Mission Innovation is an initiative to dramatically accelerate public and private global clean energy innovation to increase clean energy options and reduce costs for producers and consumers, create new domestic jobs and commercial opportunities in clean energy, improve U.S. competitiveness in the rapidly expanding market for clean energy, and address global climate change.

3. *Achieving DOE's current program goals can reduce the cost of additional policies needed to achieve a level of carbon reductions that would mitigate the worst impacts of climate change.* (This result can be seen by comparing the solid black and dotted blue lines in Figure ES-1.)

   This analysis explores the individual and combined impacts of successful clean energy RDD&D and additional policies that incentivize reductions in energy CO_2 emissions. This analysis shows that the level of emissions reductions that could be achieved if DOE successfully meets all of its current program goals, as modeled, is roughly equal to the emissions reductions that could be achieved in 2040 when applying a $10 carbon price (starting in 2017 and rising at a rate of 5% per year in real dollars) to an otherwise business as usual case.

4. *The combination of additional policies and clean energy technology advances and penetration can drive greater emissions reductions than the sum of each approach on its own.* (This result can be seen by comparing the solid black, solid blue, dashed black, and dashed blue lines in Figure ES-1.)

   This analysis shows that successful clean energy RDD&D and policies that incentivize reductions in energy CO_2 emissions are synergistic policies; the CO_2 emissions reductions achieved through a combined "technology push + policy pull" approach are greater than the sum of the CO_2 emissions reductions achieved under each individual approach. When applied separately to an otherwise business as usual case, both innovation and policy each yield significant CO_2 reductions; however, emissions reductions in the innovation and policy combined cases were greater than the sum of each alone.

   Moreover, early deployment of existing technologies, combined with ongoing innovation to further reduce costs and improve performance of technologies, is key to realizing the largest CO_2 emissions reductions enabled by investment in innovation in this analysis. In particular, these results show early and sustained investment in low-carbon generation and end-use efficiency can leverage the availability of already low-cost generation options in the power sector while reducing costs to consumers and the required pace of the build-out of a low-carbon generation supply. Note that applying a carbon price primarily reduces CO_2 emissions from electricity generation because of the wide array of available low-cost substitution options in the power sector, making it the least-cost method for reducing energy-sector emissions.

5. *Current policies and U.S. RDD&D clean energy technologies program goals, if they are met, are not projected to achieve the level of GHG emissions reductions from the energy sector that are needed to mitigate the worst impacts of climate change.* (This result can be seen by comparing all lines with the dotted green line at the bottom of Figure ES-1.)

   Projected reductions in energy CO_2 emissions that would result from the successful attainment of DOE's program goals—in isolation or coupled with a carbon policy—are insufficient to reach an 80% reduction in GHG emissions from 2005 levels by 2050. With additional successful RDD&D plus a carbon policy, further emissions reductions are possible. Ultimately, cost-effectively achieving an 80% economy-wide reduction by 2050 would require both increased innovation and new policy.

   This analysis shows that additional policy and technology innovation can drive significant reductions in the electricity sector CO_2 emissions through a cleaner electricity generation mix and improved efficiency of end-use electricity consumption. However, the projected emissions reductions from end-use sectors in this analysis fall short of the levels needed to mitigate the worst impacts of climate change. There is significant opportunity for additional emissions reductions from the industrial and transportation sectors through targeted technology innovation and/or additional policies.

Market forces and structures, additional state and local policies, and factors that are not explicitly represented in this analysis could also drive deeper reductions in energy CO_2 emissions. One example is the future prices of fossil fuels, which are highly uncertain and have a strong impact on projected energy CO_2 emissions. In this analysis, higher natural gas and oil prices drive greater CO_2 emissions reductions from the electricity and energy end-use sectors.

It is important to note that this analysis was performed from the bottom up, and it was not designed to achieve a specific level of energy CO_2 emissions. This is in contrast to other studies that explicitly set out to identify pathways for achieving specific levels of CO_2 emissions, consistent with mitigating the worst impacts of climate change.[16,17,18] These studies demonstrate that, with appropriate incentives, decarbonizing the U.S. economy at the pace that is required to mitigate the worst impacts of climate change is feasible but will require a significant transition from current technologies and systems.[b] Within this context, this analysis suggests that innovation is a necessary condition for achieving deep levels of emissions reductions, and that additional policies, market-based incentives, and/or targeted technology innovation will ultimately be needed to accelerate the transition towards clean energy technologies and practices in end-use sectors, particularly industry and transportation.

[b] These studies also explored related topics that are not covered in this report, such as the costs, benefits, and savings to the economy that are associated with technology innovation and additional policies.

INTRODUCTION

This report examines how the U.S. Department of Energy's (DOE's) clean energy research, development, demonstration, and deployment (RDD&D) activities can contribute to national climate and energy goals. This objective is accomplished by performing energy sector analyses of the impacts of current clean energy RDD&D activities, as well as representative analyses that explore the potential impacts of additional RDD&D and/or additional policies that incentivize reductions in energy carbon dioxide (CO_2) emissions. The outputs of these analyses indicate how the collective effects of success across the DOE portfolio can impact national electricity generation, energy consumption, and energy CO_2 emissions.

The analysis underlying this report captures DOE goals as components of an overall portfolio approach and estimates the potential aggregate impact of these goals on CO_2 emissions from the U.S. electric power and end-use (i.e., buildings, industry, and transportation) sectors. This analysis and the outcomes underscore the importance of success in supporting the development, commercialization, and deployment of clean energy and energy efficiency technologies for continuing the nation's transition towards a decarbonized energy sector, which will require some level of private sector investment and is necessary to mitigate the worst impacts of climate change.

This report begins by describing the current state of U.S. energy sector emissions and related policies and the projected energy CO_2 emissions based on current technology trends and policies. It then presents the results of an analysis of multiple scenarios that explore the impacts of DOE's clean energy RDD&D activities on energy CO_2 emissions in the United States, which depend on a variety of factors, such as the price of natural gas and the extent to which additional policies are implemented. Finally, this report includes an illustrative scenario of the potential impact that significant new investments in DOE's clean energy RDD&D activities could have on U.S. energy CO_2 emissions.

Current U.S. Energy Sector Emissions and Policies

The electric power sector, which has historically been the largest source of CO_2 emissions in the United States, accounted for approximately 36.5% of energy sector CO_2 emissions in 2015 (Table 1).[19] Coal and natural gas together fueled 65.8% of U.S. electricity generation in 2015 and accounted for 98% of U.S. electricity-related CO_2 emissions. Nuclear power is currently the largest source of carbon-free generation in the United States, constituting roughly 20% of all generation in 2015 and approximately 60% of zero-carbon electricity generation. In 2015, renewable energy provided 13% of all utility-scale generation, primarily from hydropower (6%), wind (5%), and solar (1%). In recent years, shifting of generation to low-cost natural gas, slow electricity demand growth, and increased deployment of renewable electricity generation sources have resulted in reduced U.S. power sector emissions.[20, 21] It is also likely that this trend will continue into the future, with wind and solar energy making up 68% of all new electricity generating capacity additions in the United States in 2015.[22]

Direct fossil fuel use is another important source of CO_2 emissions from the U.S. energy end-use sectors. For example, CO_2 emissions from the U.S. transportation sector accounted for 35.5% of U.S. CO_2 emissions in 2015, almost all of which (99.8%) were due to direct combustion of fossil fuels (Table 1). In addition, direct fuel use in buildings was responsible for 10% of U.S. CO_2 emissions, while direct fuel use and processes in the industrial sector accounted for an additional 18% in 2015 (Table 1).[23]

Many policies have been designed and implemented to mitigate climate change through CO_2 emissions reductions, either directly or indirectly. A "policy pull" approach mitigates CO_2 emissions through regulations, standards, or mandates. One recent example that is represented in this analysis is the U.S. Environmental Protection Agency's Clean Power Plan (CPP), which requires states to adopt and implement plans to limit CO_2 emissions from existing fossil fuel-fired power plants. The CPP leaves it up to each state to determine which suite of technologies and policies it wants to employ to meet its target.[24]

Table 1. Direct and Indirect (Electricity-Related) Emissions of Energy CO_2 by Sector, 2015.[25]

Emissions Source	Direct Emissions	Indirect Emissions
Transportation	1,860 MMT CO_2	4 MMT CO_2
Buildings	540 MMT CO_2	1,421 MMT CO_2
Industry[c]	946 MMT CO_2	494 MMT CO_2
Electricity Generation	1,919 MMT CO_2	--

Direct emissions are due to the combustion of fossil fuels, either for electricity generation at a power plant or to provide on-site energy in the energy end-use sectors. Indirect (electricity-related) emissions reflect emissions from electricity generation that have been attributed to each energy end-use sector based on the amount of electricity consumed.[d] MMT = millions of metric tons.

Mitigating CO_2 emissions can also be an indirect impact of policies that do not directly address emissions. For example, the U.S. Federal Renewable Electricity Production Tax Credit (PTC) and Investment Tax Credit (ITC) were designed to accelerate the deployment of renewable electricity projects and, in turn, accelerate cost and performance improvements in clean electricity generating technologies. As an indirect impact, they have driven significant emissions reductions from the U.S. electricity sector. Going forward, a recent National Renewable Energy Laboratory (NREL) study estimates that the December 2015 extension of the ITC and PTC, among other factors, will drive increased incremental renewable electricity capacity additions with the largest deployment of 53 gigawatts projected to occur in 2020. In turn, the corresponding new renewable electricity generation will help to avoid between 540 and 1,420 MMT CO_2-equivalent by 2030, where the range reflects the uncertainty associated with other market factors, such as the price of natural gas.[26]

Technology innovation is another policy approach to reducing energy CO_2 emissions, by improving the cost and performance of clean energy technologies through successful clean energy RDD&D.[e] This approach is referred to in this report as "technology push," and it is highly complementary to the previously described "policy pull" approach. Ongoing RDD&D activities by the DOE's program offices represent one example of the "technology push" approach, which will be the focus of this report.

Perhaps the most prominent current example of a "technology push" proposal is Mission Innovation, which was announced in November 2015 at the United Nations Framework Convention on Climate Change's 21st session of the Conference of the Parties. Mission Innovation is an initiative to dramatically accelerate public and private global clean energy innovation to address global climate change, provide affordable clean energy to consumers, and create additional commercial opportunities in clean energy. Through the initiative, 22 countries and the European Union have committed to double their respective clean energy research and development investments over the next 5 years.[27]

[c] Table 1 shows only combustion-related CO_2 emissions. It does not include non-energy or process-related emissions, which account for approximately half of industrial greenhouse gas emissions.

[d] The difference between the sum of each row for direct emissions and total U.S. energy CO_2 emissions in 2015 (5,264 MMT CO_2) is due to rounding. In addition, Figures ES-1 and 1 show historical emissions through 2014, with projections beginning in 2015, which explains the apparent discrepancy between Figure ES-1, Figure 1, and Table 1.

[e] For simplicity, this report refers to technology investments facilitated by policy as a technology approach.

APPROACH AND PROCESS

This analysis attempts to represent DOE's innovation and technology advancement efforts to the maximum extent possible in an integrated model of the U.S. energy system. Offices across DOE were involved in gathering information on current and expanded clean energy technology program goals, as well as translating that information into model inputs.

The analysis presented in this report is rooted in a modeled projection of what changes might occur in the energy sector, given a specific set of assumptions and methodologies. There are inherent limitations to any modeling effort (described in the following sub-section), as all modeling relies on simplified representations of the energy sector. The results presented in this report are strongly influenced by the underlying input assumptions about energy resources, conversion, transport and distribution, end-use consumer behavior, and many other factors, as well as about the particular analytical methodologies used, which are based on economic analysis and observed responses but may not reflect as well future responses.

Moreover, the underlying assumptions for this analysis interact with one another and have a strong impact on energy CO_2 emissions, so all results should be interpreted with the technology and policy inputs in mind. Breakthrough technological advances are also difficult to anticipate and represent in a model, so the present analysis does not reflect disruptive technologies that would dramatically impact the energy sector.

It is also important to note that this analysis is not a prediction of the future energy system, as there are inherent and significant uncertainties surrounding the future of the U.S. energy sector. Rather, the purpose of this analysis is to assess how different sets of internally consistent assumptions about energy supply, demand, and technologies impact energy CO_2 emissions. In turn, this analysis can inform efforts to determine how current and future clean energy RDD&D, as well as additional policies, might support an acceleration of the ongoing transition to a low-carbon U.S. energy sector. Many limitations and simplifications exist; however, the present modeling effort is still useful as a guide for policy analysis, particularly when comparing cases against each other to see the impacts of policy and technology change, as was done in this analysis.

The Model

This analysis was completed by DOE's Office of Energy Policy and Systems Analysis (EPSA), and explores energy CO_2 emissions using a version of the National Energy Modeling System (NEMS). In order to meet U.S. climate goals, other greenhouse gases (GHGs) are also very important to reduce, but they will not be discussed in this report due to modeling limitations.

This analysis uses a version of NEMS, which is an integrated energy system model, with modifications that differ from the version maintained by EIA. As a result, the model is referred to as EPSA-NEMS throughout the report. EPSA-NEMS was run by OnLocation, Inc., with input assumptions determined by EPSA and informed by the DOE program offices. According to the EIA, "NEMS projects the production, imports, conversion, consumption, and prices of energy, subject to assumptions on macroeconomic and financial factors, world energy markets, resource availability and costs, behavioral and technological choice criteria, cost and performance characteristics of energy technologies, and demographics." Further documentation of NEMS can be found on EIA's website at www.eia.gov/forecasts/aeo.

The benefit of using EPSA-NEMS is that it is an integrated energy system model and explicitly represents demand for electricity and fuels for direct use, fuel supply, and transformation sectors such as refining and electricity generation.[f] By solving these sectors simultaneously and finding an economic equilibrium, EPSA-NEMS is able to capture interactions across the energy sectors. Furthermore, it includes detailed representations of generation and end-use demand energy technologies and is updated annually by the EIA. Another important property of EPSA-NEMS is that, in every year, when making generating capacity expansion decisions it looks 30 years into the future. Because of this, there are no issues with boundary conditions. For example, in 2040, the model looks out to 2070 even though 2070 is not an output year. However, many of the technology price projections used as inputs to this effort do not continue to drop past a certain year, which can bias the results.

However, as with all models, EPSA-NEMS does not capture all of the details about the energy sector. For example, certain technologies are not represented (such as marine hydrokinetic power or fusion energy), which might become relevant in the future. In addition, for most electricity generating technologies, only a single technology type is available in the model, meaning that, in a given year, only one type of advanced nuclear technology is available or one option for solar photovoltaics. In the model's representation of the energy end-use sectors (i.e., buildings, transportation, and industry), multiple technologies are available with different efficiencies; however, there are still some gaps regarding potential future technologies, such as battery-electric heavy duty vehicles (HDVs) and heating, ventilation, and air conditioning sensors and controls in buildings. There is also only a limited representation of hydrogen production for transportation. Finally, the model is not set up to represent the array of different financing mechanisms that exist for different technologies (e.g., power purchase agreements).

Development of Technology Inputs

Technology inputs for the Base Case follow a methodology that is similar to the one used in the *Annual Energy Outlook* (AEO), which is described in the assumptions documentation for the annual report.[28] In general, the Base Case technology assumptions were developed by applying a standard technology learning curve to cost and performance metrics that were current at the time of the analysis and do not explicitly take current DOE technology program goals into account. Such an approach may underestimate advances that are projected to be driven by technology innovation; however, it provides a useful baseline against which to compare different input assumptions about technology improvements and additional policies. The specific assumptions modified for the Base Case from the AEO 2015 report[29] are shown in Table 2 (included at the end of this section).

The process for developing technology inputs for the cases with additional technology innovation (the Advanced Technology Case, and the Stretch Technology Case) was performed in collaboration with DOE's technology programs and is related to the regular budget planning process. DOE has a long history of examining the achieved and projected impacts of its clean energy RDD&D investments. Impact analyses are required by several directives to agencies, including the Government Performance and Results Act.[30, 31, 32, 33, 34]

As part of the regular budget planning process, the Undersecretary of Science and Energy and the Chief Financial Officer engage with each technology program in DOE, including the Office of Energy Efficiency and Renewable Energy, the Office of Electricity Deliverability and Energy Reliability, the Office of Nuclear Energy, and the Office of Fossil Energy. Each office and sub-office explores activities that would be possible at different budget levels and develops detailed RDD&D plans.

[f] Note that EPSA-NEMS allows for economic retirement of the existing generating capacity.

As part of this planning process, DOE and laboratory experts assess the potential impact of program activities on technology characteristics (e.g., capital cost). An example of this type of activity is the analysis underpinning DOE's SunShot Initiative,[g] here future cost targets are linked to specific elements of technology program RDD&D support. The Building Technologies Office used similar analysis to develop its overarching building efficiency goals, which are linked to specific elements of technology RDD&D. DOE technology offices also assess potential market deployment for energy efficiency, electric generation, transportation, and grid technologies (e.g., resulting from the identified RDD&D-driven changes in technology characteristics paired with technology office deployment activities).

The analysis described in this report attempts to estimate the impacts of the portfolio as a whole. Results of technology and sector-specific deployment modeling were input into the EPSA-NEMS model, which allows consideration of macro-economic factors and avoids double-counting among the sectors. This analysis is a best attempt at representing as many goals as possible; however, in interpreting the results, one should keep in mind the difficulties inherent in the process. While the uncertainty associated with the following technology inputs is not quantifiable, the range of technology assumptions described in the rest of this section (and in Appendix C) provides some insight into the potential magnitude of emissions reductions that could be achieved through various levels of successful clean energy technology innovation.

Two sets of inputs were developed for this analysis: the Advanced Technology Case and the Stretch Technology Case. The Advanced Technology Case is an ambitious but feasible case, which represents an energy future in which all established federal clean energy RDD&D goals are met.[h] The Stretch Technology Case incorporates more aggressive clean energy RDD&D goals that are thought to be achievable if significant new investments are made in successful clean energy RDD&D, such as those that could be enabled by Mission Innovation.[i]

The Advanced Technology inputs were based on information that is publicly available in DOE's fiscal year 2017 (FY 17) budget request. The analyses for these inputs are based on detailed budget planning and are supported by peer-reviewed and/or national laboratory analysis, as described in Appendix C. The Stretch Technology inputs were developed as part of the FY 18 budget planning process, and, as of the time of this report, do not have the same level of supporting technical analysis underlying the development of the technology goals as the Advanced Technology inputs.

Each program goal was translated into a model input to the maximum extent possible, but it is not always possible to directly translate program goals into modeling inputs. For example, much of the work performed by the Office of Electricity Delivery and Energy Reliability is focused on improving the ability to manage the electric grid, which is not fully represented in EPSA-NEMS. However, one can still model the predicted impact of these improvements (e.g., in enabling higher variable renewable energy penetration). Work performed by DOE's Advanced Projects Research Agency–Energy (ARPA-E) includes breakthrough technologies that were not included due to modeling constraints but could play an

---

[g] SunShot is a collaborative national initiative to make solar energy cost competitive with other forms of energy by 2020. See https://www1.eere.energy.gov/solar/sunshot/index.html.

[h] The technology goals included in the Advanced Technology Case are based on detailed underlying analysis conducted to support the fiscal year 2017 (FY 17) budget planning process mainly from U.S. national laboratories. This analysis did not attempt to harmonize technology goals to be consistent amongst technologies in either case, meaning the goals are not consistent relative to a standard statistical metric.

[i] The Stretch Technology Case is based mainly on expert judgment. This analysis did not attempt to harmonize technology assumptions to be consistent amongst technologies. Especially for the Stretch Technology Case, some potential technology breakthroughs that could be enabled through RDD&D support are not captured in the results. In other cases, significant deployment impacts are included in the program goals that influence the results.

important role in achieving the level of emissions reductions that are needed to mitigate the worst impacts of climate change. Due to these modeling constraints, ARPA-E impacts were excluded from this analysis.

Finally, it is important to note that this analysis made no attempt to represent possible complementary investments in infrastructure and systems integration (e.g., micro-grids, newly emerging digital demand technologies, widespread car battery charging, new business models that sellers of cars or mobility services might offer, and the use of waste heat from industrial processes for district heating or industrial clusters), which could lead to an understatement of the rate at which new clean energy technologies might be introduced and proliferated into the energy system.

As the history of innovation clearly shows, many individual technology goals may not be realized. At the same time, unforeseen research breakthroughs, such as those that could be facilitated by ARPA-E's work, or major changes to the energy system as a whole may occur and cannot be anticipated in the modeling analysis. Nonetheless, the portfolio as a whole may achieve comparable results, underscoring the need for diversification. This analysis is one attempt to model this potential at the portfolio level; while it does not represent the significant uncertainty regarding individual technologies, it is informative to look at the broad conclusions.

Development of Policy Inputs

All existing U.S. policies that mitigate climate change through CO_2 emissions reductions (either directly or indirectly) and were final at the time of this analysis are included herein. A complete description of policy inputs can be found in the assumptions documentation for the 2016 AEO.[35] For example, one representation of the CPP and the most recent extension of the federal production and investment tax credits (which, at the time of this publication, was in December 2015) were included, among others.[j]

States will ultimately determine how to comply with the CPP; however, the Base Case achieves the broad emissions reductions required by the rule, consistent with U.S. Environmental Protection Agency analysis. The Base Case assumes that states use the CPP mass-based state goal approach with all sources covered,[k] and assumes national emissions trading among the states. The Base Case does not allow for either banking or borrowing[l] of CPP allowances or credits, and it does not model the Clean Energy Incentive Program because the program was not final at the time of analysis.

In order to represent additional economy-wide policy that reduces CO_2 emissions, a carbon price was employed in this analysis and serves as a proxy for any number of potential policies. Outside of this carbon price, no other additional policies are included in the modeling beyond the policies described above. The use of a carbon price, which is an effective and efficient economy-wide policy for reducing CO_2 emissions, is intended to show the scale of the potential impacts of "policy pull," and is in lieu of a detailed analysis of any specific policy to incentivize GHG emissions reductions. For example, the modeled price on carbon could serve as a proxy for other policies designed to reduce CO_2 emissions, such as emissions regulation, clean energy standards, and sectoral policies, among others.

[j] A detailed discussion of current policies that mitigate climate change through CO_2 emissions reductions at the time of this analysis is presented in the forthcoming 2016 Quadrennial Energy Review Greenhouse Gas Baseline.

[k] This is called the "New Source Complement" and is one of the options available in the CPP for states to counteract "leakage." Note that existing combustion turbines are not covered under the New Source Complement.

[l] In other words, compliance must be achieved by meeting or exceeding the goal in every year. Due to modeling constraints, this analysis does not allow allowances to be used in subsequent years ("banking"), and it does not allow allowances from later years to be used for compliance in earlier years ("borrowing").

Analysis Cases

This analysis focuses on a comparison between a Base Case, which is rooted in current policy and technology projections, and two technology cases—the Advanced and Stretch Technology Cases—which provide a starting point for understanding the potential for energy sector CO_2 emissions reductions if significant technology advances are made. Each of these technology-driven cases is also combined with a price on carbon in order to represent a future that couples advances in technology with policies that incentivize energy CO_2 emissions reductions. The assumptions associated with each case are provided in Table 2, and a detailed list of technology assumptions for the Advanced Technology and Stretch Technology Cases is provided in Appendix C. Detailed results from the High Natural Gas and Oil Prices Side Cases are presented in Appendix B, and discussed throughout the report.

Table 2. Description of Analysis Cases

Base Case: Started with EIA's AEO 2015 High Oil and Gas Resource Case,[36] with modifications, including one potential implementation of the CPP, wind and solar tax credit extensions,[37] updated carbon capture, utilization, and storage (CCUS) cost and performance estimates,[38] and updated solar and wind technology cost and performance estimates that are consistent with AEO 2016.
Advanced Technology Case: Current DOE energy program goals overlaid on top of the Base Case. Major changes from the Base Case to the Advanced Technology Case include: changes to cost and performance of new and retrofitted coal and new natural gas combined cycle units with CCUS, a representative advanced nuclear plant, central and distributed solar, land-based and offshore wind, geothermal and hydropower, and enhanced transmission capacity and load shifting to reflect modernization of the electric grid. Significant changes to costs and adoption of efficient methods in industrial, buildings, and transportation technologies are also included. The Case assumes all current goals are met, though this outcome is uncertain.
Stretch Technology Case: Stretch DOE energy program estimates (including more ambitious cost, performance, and deployment goals) enabled by additional RDD&D support (e.g., through Mission Innovation and overlaid on top of the Advanced Technology Case). Major changes from the Advanced Technology Case include: changes to costs for a representative advanced nuclear plant, new and retrofitted coal and new natural gas combined cycle CCUS plants, land-based and offshore wind, central and distributed solar, hydropower plants, and geothermal sites; increased hydropower and geothermal resource availability; reduced costs for advanced biofuels processing; improved light-duty vehicle (LDV) battery, light-weighting, and electric drive systems; increased efficiency for HDVs; reduced cost of fuel cells and hydrogen; improved manufacturing and industrial motor system efficiency; increased efficiency for building shells and appliances; and increased maximum percentage of variable generation allowed in the EPSA-NEMS model, to reflect what could be enabled by advances in grid modernization.
Carbon Price (CP) Cases: Base Case, Advanced Technology, and Stretch Technology Cases coupled with initial carbon prices of \$10 or \$20 per tonne of CO_2, starting in 2017 and rising at a rate of 5% per year in real dollars (2013\$).
High Natural Gas and Oil Prices Side Cases: The Base Case and Advanced Technology Case modeled using AEO 2015 Reference Case assumptions (instead of the AEO 2015 High Oil and Gas Resource Case assumptions), which represent lower resources and, hence, higher natural gas and oil prices. All other inputs, as explained for the Base and Advanced Technology Cases, are the same.

RESULTS

This section explores the projected impacts of clean energy technology innovation, additional policy, and the combination of technology innovation and additional policy. It starts with the cumulative effect on energy CO_2 emissions and then explores the structure, energy demand, and CO_2 emissions of the U.S. energy sectors—buildings, transportation, industry, and electric power—by comparing the results of the various analysis cases. Wherever the analysis is available, this section also discusses the impact of future natural gas and oil prices on these results.

Cumulative Energy CO_2 Emissions

This section discusses the results from all analysis cases for projected energy CO_2 emissions, which is the most important metric for assessing progress towards mitigating the worst impacts of climate change. Under business as usual assumptions, and assuming no new policies beyond those that were final at the time of this analysis, it is projected that energy CO_2 emissions will remain roughly flat over the next two decades (Figure 1), and slightly below 2005 levels (Table 3). This business as usual trajectory is largely the result of a cleaner electricity generation mix (driven by the CPP, renewable tax credits, and improved cost and performance of low- and zero-carbon generation sources), as well as relatively flat energy demand from the end-use sectors due in part to existing fuel economy and efficiency standards.

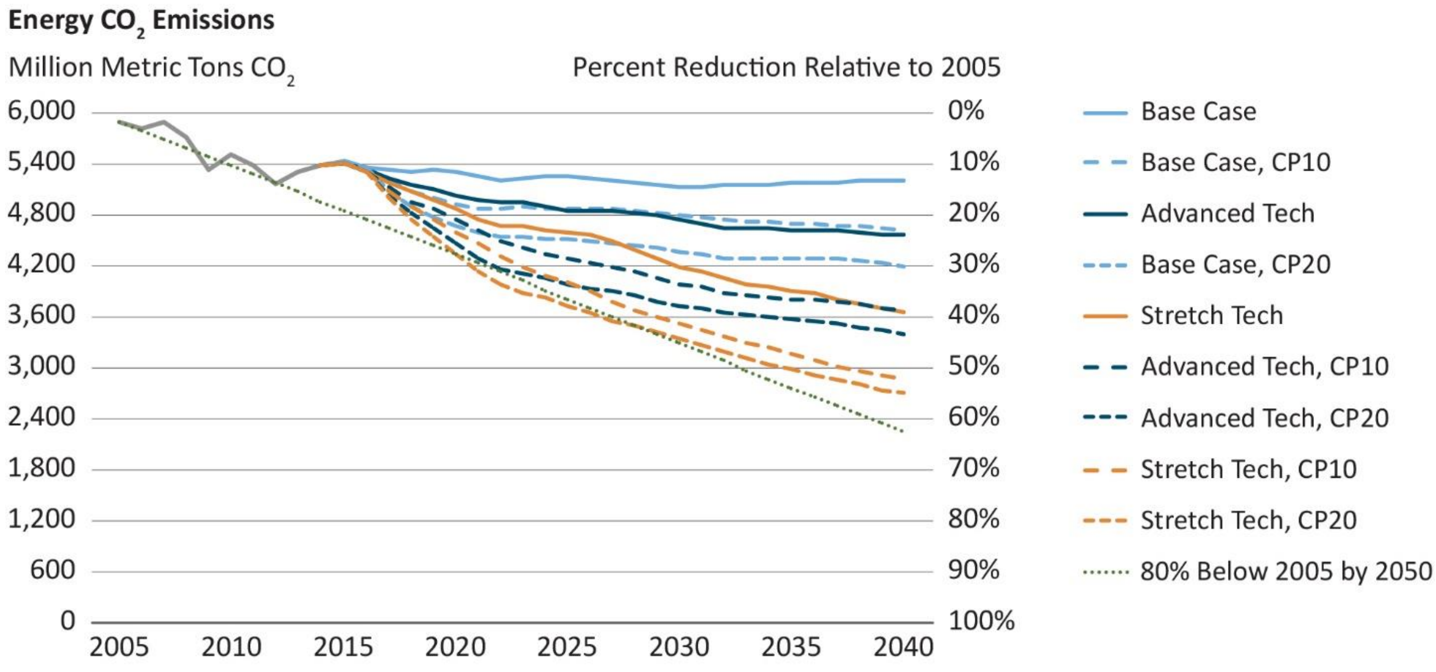


Figure 1. The projected impact of clean energy technology innovation and additional policies on U.S. energy CO_2 emissions (see Table 2 for a description of cases). Also shown are historical energy CO_2 emissions (2005–2014), 39 and a dotted line indicating a straight-line trajectory towards an economy-wide 80% reduction from 2005 levels by 2050. By themselves, increases in successful clean energy RDD&D ("Advanced Tech" and "Stretch Tech") or a price on carbon (CP10 and CP20) can drive greater decreases in energy CO_2 emissions compared to a business as usual projection (Base Case). The combination of increased technology investments and a price on carbon is projected to drive even greater reductions in energy CO_2 emissions than the sum of each approach on its own, the magnitude of which begins to approach the linear path towards an economy-wide 80% reduction from 2005 levels by 2050 under our most ambitious analysis case (Stretch Tech, CP20).

Table 3. Projected Energy CO_2 Percent Emissions Reductions by 2040, Relative to 2005 Levels

Analysis Case	Low Natural Gas and Oil Prices	High Natural Gas and Oil Prices
Business as Usual		
Base Case	12%	16%
Impacts of Technology Innovation		
Advanced Technology	23%	27%
Stretch Technology	38%	--
Impacts of Additional Policy		
Base Case, CP10	22%	--
Base Case, CP20	29%	--
Impacts of Additional Policy + Technology Innovation		
Advanced Technology, CP10	38%	41%
Advanced Technology, CP20	43%	49%
Stretch Technology, CP10	52%	--
Stretch Technology, CP20	54%	--

All analysis cases project that energy CO_2 emissions will decrease over the next two decades. Technology advances can result in significant additional emissions reductions: established DOE program goals (Advanced Technology) double energy CO_2 emissions reduction, and more ambitious clean energy RDD&D goals (Stretch Technology) triple energy CO_2 emissions reductions in this analysis. The impact of an initial $10 carbon price, starting in 2017 and increasing at a rate of 5% per year in real dollars (Base Case, CP10), is similar to that of meeting established DOE technology program goals (Advanced Technology) in 2040. The combination of "Additional Policy + Technology Innovation" achieves greater reductions (relative to the Base Case) than the sum of each approach on its own. Additional technology innovation can make it cheaper to achieve similar levels of emissions of reductions. Higher natural gas and oil prices drive greater reductions in energy CO_2 emissions over the long term.

Technology innovation can further accelerate and enhance energy CO_2 emissions reductions. In particular, the Advanced Technology Case results in double the energy CO_2 emissions reductions that are projected under the Base Case by 2040 (Table 3). This result demonstrates that successful achievement of DOE's clean energy RDD&D goals, as modeled, could drive down energy CO_2 emissions beyond the pull of current policies, measures, and projections for technology advances (Figures 1 and 2).[m]

---

[m] The CPP targets are constant after 2030, which leads to a flattening of power sector CO_2 emissions in the Base Case post 2030. The Advanced Technology Case achieves CO_2 reductions beyond the CPP, but also eventually flattens and begins to increase slightly as the technology cost and performance goals, as modeled, are met and remain mostly constant for the remainder of the projection. In the later years (2032–2040), the emissions intensity of electricity generation remains roughly constant (Appendix A), so the concurrent increase in electricity demand leads to a slight increase in electricity-related emissions during this time period.

Further opportunities exist for even greater energy CO_2 emissions reductions through more ambitious advancements in clean energy technologies and systems, such as what could be enabled by additional support for clean energy RDD&D (e.g., through Mission Innovation). In particular, the Stretch Technology Case is projected to drive triple the energy CO_2 emissions reductions in 2040, compared to those projected in the Base Case (Table 3, Figure 1). This result indicates that additional and ongoing successful clean energy RDD&D can enable additional reductions in energy CO_2 emissions.

The difference in the emissions trajectories for the Base Case, Advanced Technology Case, and Stretch Technology Case demonstrates the significant impact that improvements in the cost and performance of clean energy technologies could have on energy CO_2 emissions. In particular, the steeper trajectories demonstrate the important impact that early deployment of clean electricity generating and efficient end-use technologies can have on energy CO_2 emissions (Figures 1 and 2). These factors result in a cleaner electricity generation mix and reduced end-use energy demand, respectively, which are the primary drivers of emissions reductions beyond what is required or incentivized by existing policies and measures.

Additional policy is also projected to have a major impact on energy CO_2 emissions. The impact of a purely "policy pull" approach to reducing energy CO_2 emissions can be seen in Figure 1, which shows that the addition of an initial $10 carbon price (CP10, representing a price of $10 per tonne of CO_2 in 2017, rising at a rate of 5% per year) to the Base Case drives energy CO_2 emissions reductions that are similar to those achieved under the technology advancements of the Advanced Technology Case alone in 2040. The addition of an initial $20 carbon price (CP20, representing a price of $20 per tonne of CO_2 in 2017, rising at a rate of 5% per year) to the Base Case achieves deeper reductions (Table 3, Figure 1).

A combined "technology push + policy pull" approach can be seen in the Advanced Technology and Stretch Technology Cases combined with the same initial carbon prices. The projected energy CO_2 emissions reductions in the Advanced Technology Case with an initial $10 carbon price are similar to those in the Stretch Technology Case without a carbon price, and both are significantly larger than projected emissions reductions under the Base Case with an initial $20 carbon price (Figure 1, Table 3). The most ambitious analysis cases (Stretch Technology, CP10 and CP20) show that the combination of increased technology investments and a price on carbon is projected to drive energy CO_2 emissions reductions that begin to approach the pathway to an economy-wide 80% reduction from 2005 levels by 2050 (Figure 1).

Finally, it is worth noting that these results are sensitive to the future prices of natural gas and oil, which are highly uncertain. While the uncertainty of the future prices of commodities is not quantified, this analysis explores their impact through sensitivity cases with higher natural gas and oil prices. The analysis cases with higher natural gas and oil prices project smaller near-term reductions in energy CO_2 emissions, primarily due to the increased reliance on coal in the electricity sector (relative to the Base Case). However, the analysis cases with higher natural gas and oil prices project larger long-term energy CO_2 emissions reductions (5-20% larger reductions), primarily due to an increase in the market share of renewables and a reduction in end-use demand for fuels for direct use (Appendix B).

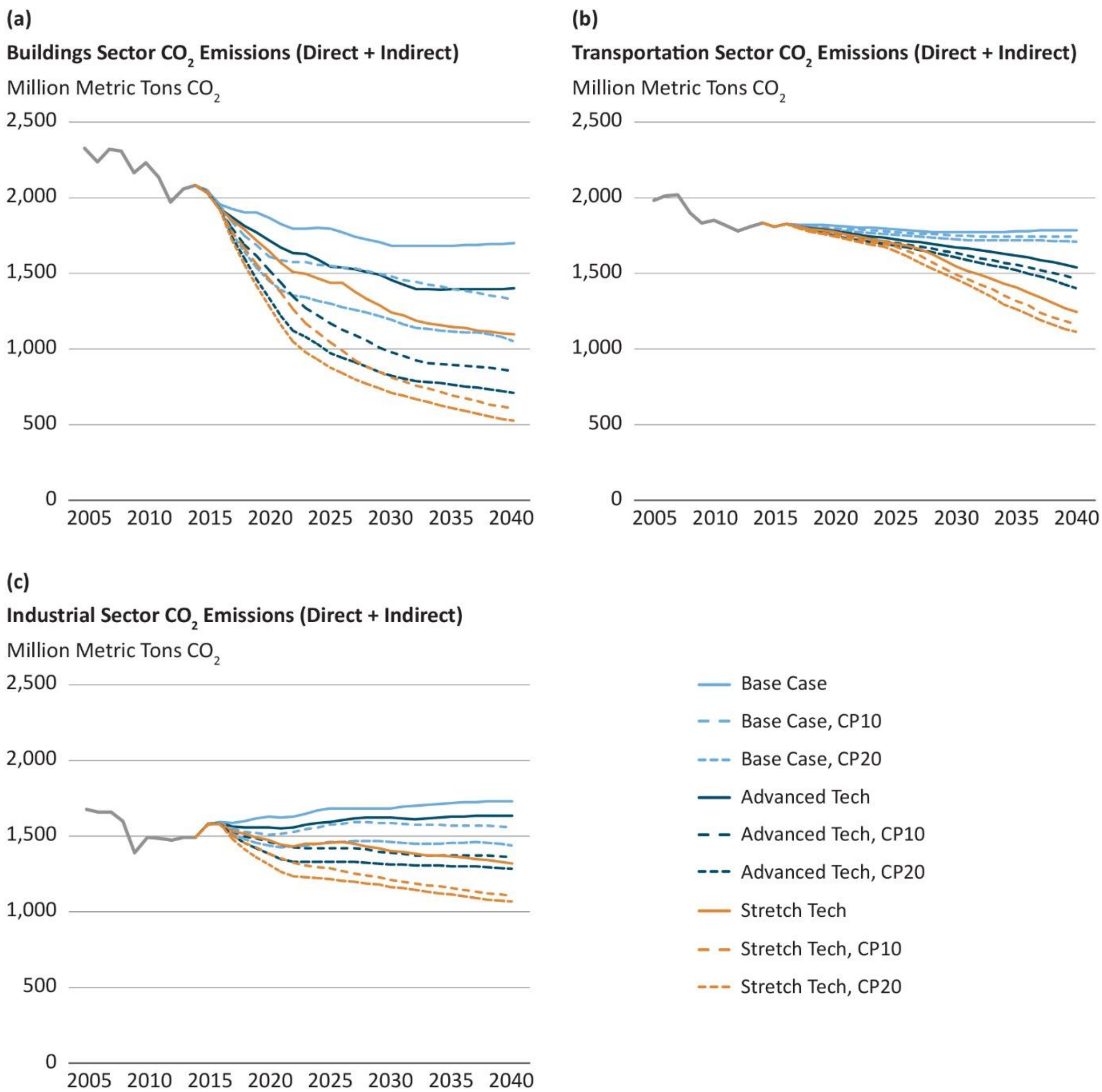


Figure 2. The projected impact of clean energy technology innovation and additional policies on total CO_2 emissions from the (a) buildings, (b) transportation, and (c) industrial sectors, including both direct and electricity-related (indirect) emissions. The relative amount of electricity-related (indirect) vs. direct emissions in each sector can be seen by comparing this figure with Figures 3 (buildings), 5 (transportation), and 7 (industry). Technology innovation is projected to drive reductions in CO_2 emissions from the buildings sector through a cleaner electricity generation mix, as well as lowered energy demand from faster deployment of more efficient appliances and equipment and better insulated buildings. In the transportation sector, technology innovation is projected to drive significant CO_2 emissions reductions through the improved cost and performance of electric and hydrogen-fueled LDVs, as well as better fuel-economy for LDVs and HDVs. However, a carbon price is not projected to drive significantly greater reductions in transportation CO_2 emissions. Additional successful clean energy technology innovation is projected to drive greater efficiency improvements in the industrial sector, and additional policy is also projected to reduce industrial CO_2 emissions.

Building Energy Consumption and Emissions

Under business as usual assumptions and assuming no new policies beyond those that were final at the time of this analysis, the energy intensity of U.S. buildings (i.e., energy consumed per square foot) is projected to decrease by 14% over the next 25 years. This is largely driven by existing federal, state, and local policies that support the development and deployment of more efficient buildings, including the building shell, appliances, equipment, and the design and operation of the building itself.

This analysis suggests that technology innovation can have a major impact on building energy demand. In particular, the successful achievement of DOE program goals, as modeled in the Advanced Technology Case, is projected to double the reduction in the energy intensity of U.S. buildings by 2040. The primary drivers of additional reductions in energy consumption are more efficient building shells and equipment, as lower costs for more efficient technologies in the Advanced Technology Case. In addition, the Advanced Technology Case includes faster adoption of highly efficient building technologies, which reflects the ongoing efforts in the Office of Energy Efficiency and Renewable Energy (EERE).[n] Finally, the Stretch Technology Case shows similar but enhanced results for the buildings sector, largely due to faster deployment of more efficient appliances and equipment and better insulated buildings, with a particular emphasis on reducing demand from miscellaneous electric loads (MELs).

Building energy demand is also sensitive to the price of fuels that are used in onsite combustion, which are a major energy source for space heating and water heating in the buildings sector. As a result, a price on carbon—both in isolation and in combination with technology innovation—is projected to drive down energy demand in the buildings sector due to reductions in direct fuel use. Higher assumed natural gas and oil prices have a similar effect of driving down energy demand in the buildings sector over the long term (Appendix B). In turn, a price on carbon and/or higher assumed natural gas and oil prices can drive significant reductions in direct CO_2 emissions from the buildings sector (Figure 3).

The previously described efficiency improvements for building services are also projected to drive significant reductions in direct CO_2 emissions from the buildings sector. These emissions benefits are more apparent in the later years, in part, because they are delayed by the long stock turnover times for buildings and building components. The relative trajectories for the Base Case and technology innovation cases demonstrate the important role that successful clean energy RDD&D can play in reducing emissions from the buildings sector. Moreover, this comparison suggests that early deployment of existing technologies can contribute to significant reductions in CO_2 emissions from buildings (Figure 3).[o]

The same building energy efficiency improvements lead to significant reductions in annual monthly household energy bills due to reduced demand (Figure 4). Note that this chart does not include any revenue returned to consumers in the modeled carbon price cases; however, it still shows that energy efficiency and reduced demand causes bills to decline significantly in the Advanced Technology and Stretch Technology Cases, including in the presence of carbon policy.

[n] Select programs that support deployment efforts existing within the Building Technologies Office, the Office of Weatherization and Intergovernmental Programs (OWIP), and the Federal Energy Management Program (FEMP).

[o] The projected reductions in emissions from direct fuel use in the buildings sector for the Advanced Technology Case and Stretch Technology Case are similar because the assumptions about additional technology improvements in the latter case were primarily focused on building services that are powered by electricity. Additional reductions under the Stretch Technology Case can be seen in Figure 2a, which shows the projected impact of additional clean energy innovation on total emissions from the U.S. buildings sector, because electricity-related (indirect) emissions are lower in the Stretch Technology Case.

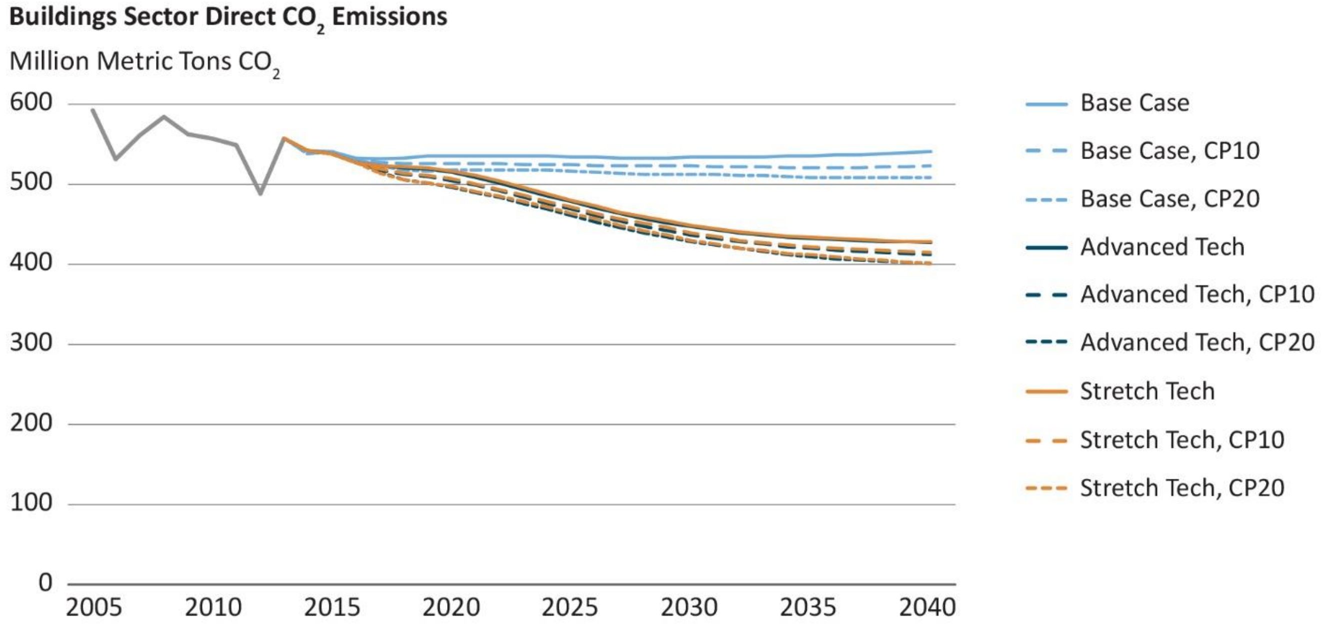


Figure 3. The projected impact of technology innovation and additional policies on CO_2 emissions from direct fuel combustion in the buildings sector. Lowered energy demand from better insulated buildings and the development and faster deployment of more efficient appliances and equipment play an important role in reducing direct CO_2 emissions from buildings. Reductions for the Advanced Technology and Stretch Technology Cases are similar because the former includes substantial efficiency improvements in buildings, and additional technology improvements in the latter case were primarily focused on building services that are powered by electricity (see Figure 2a). Additional policy (as represented by an initial $10 [CP10] or $20 [CP20] carbon price, starting in 2017 and increasing at a rate of 5% per year in real dollars) drives slight reductions in direct CO_2 emissions beyond those achieved through technology innovation alone.

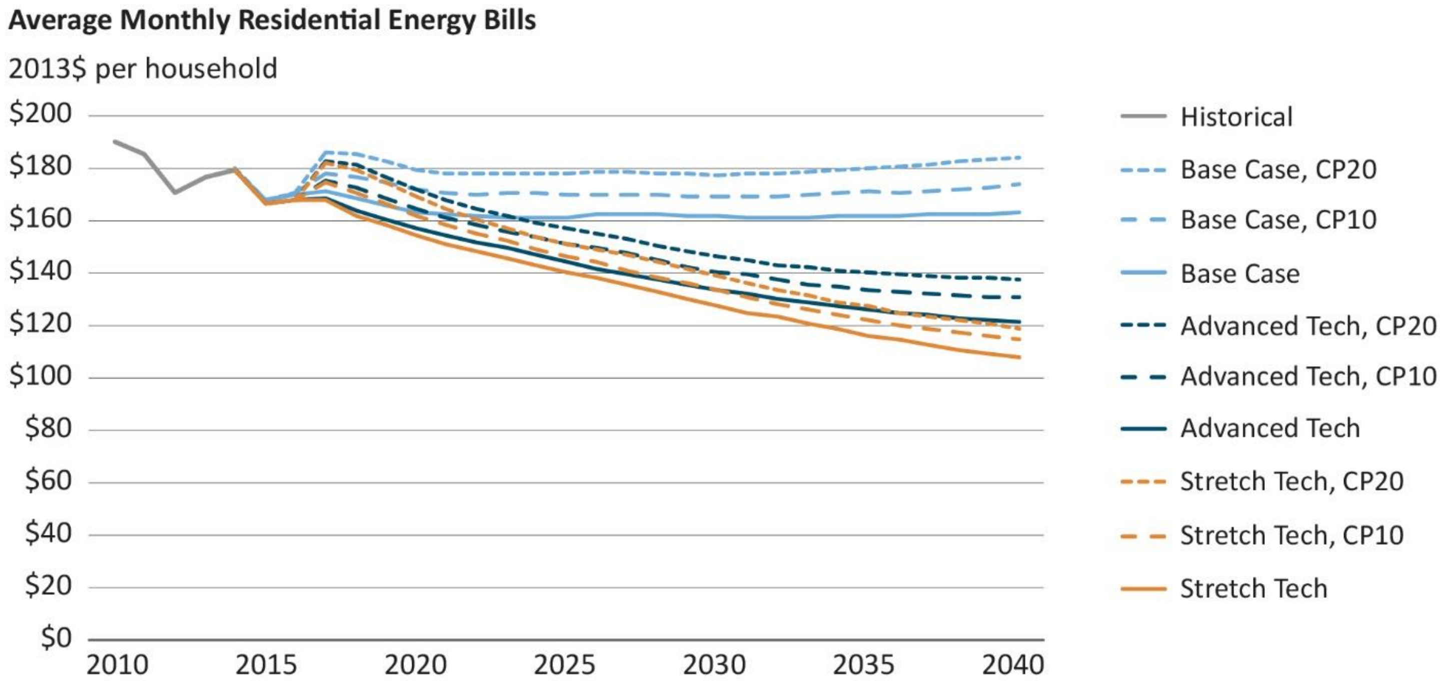


Figure 4. Projected impact of additional successful clean energy RDD&D on average monthly residential energy bills. Additional successful clean energy RDD&D (Stretch Tech) can further reduce average monthly residential energy bills beyond those projected under the Advanced Technology Case.

Transportation Energy Consumption and Emissions

Under business as usual assumptions, transportation energy demand is expected to remain relatively flat over the next two decades, assuming no new policies beyond those that were final at the time of this analysis. This result is due to a number of factors, including existing federal policies that drive improvements in the fuel economy of LDVs and HDVs, as well as current incentives that support consumer adoption of alternative fueled vehicles. Despite such incentives, electricity is projected to provide just 0.2% of transportation sector energy demand in 2040, and hydrogen is not adopted as an energy source in the transportation sector over this time period (Base Case).

This analysis suggests that there is significant opportunity to reduce transportation energy demand through technology innovation. Transportation energy consumption in the Advanced Technology Case is 10% lower than in the Base Case in 2040 due to further increases in the fuel economy of LDVs and HDVs, as well as the increased adoption of alternative vehicles, including battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), and hydrogen fuel cell electric vehicles (EVs). Alternative vehicles are projected to constitute over 20% of LDV miles traveled, and battery electric and hydrogen fuel cell vehicles comprise 18% of new light-duty car sales in 2040 in the Advanced Technology Case (not shown). In addition, electricity demand in the transportation sector is more than triple that projected for the Base Case in 2040, due to a more than 10-fold growth in transportation electricity demand between 2010 and 2040 in the Advanced Technology Case. Despite this growth, electricity consumption is a small (1.3%) but growing fraction of delivered energy to the transportation sector out to 2040 (Figure 5).

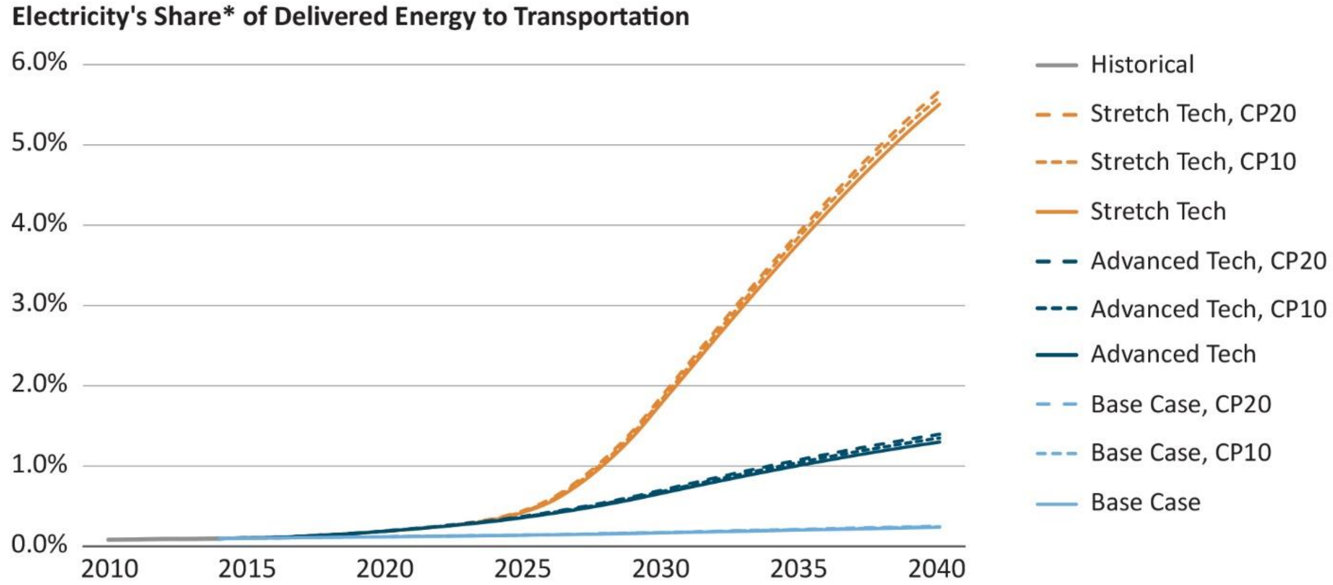


Figure 5. The projected impact of technology innovation and additional policies on electricity's share of delivered energy to the transportation sector, including hydrogen produced from electrolysis. All analysis cases project a small but growing shift towards electrification in the transportation sector. In the Advanced Technology and Stretch Technology Cases, technology innovation leads to increased market penetration of alternative fueled vehicles, including BEVs, PHEVs, and hydrogen fuel cell electric LDVs. In 2040, battery electric and hydrogen fuel cell vehicles comprise 18% of new light-duty car sales in the Advanced Technology Case and 40% of new light-duty car sales in the Stretch Technology Case (not shown). Despite this increased penetration, electricity is a small but growing source of delivered energy to the transportation sector, constituting over 5.5% by 2040 in the Stretch Technology Case. Finally, it is worth noting that the addition of a carbon price is projected to have only a modest impact on electricity's share of delivered energy to the transportation sector.

It should be noted that an approach similar to the previously described acceleration of consumer adoption for energy efficiency measures in the buildings sector was *not* made in the transportation sector in the Advanced Technology analysis. Moreover, the model used for this analysis (EPSA-NEMS) is conservative in its assumptions about consumers' willingness to adopt new types of LDVs (e.g., electric and hydrogen vehicles) in both the Base Case and Advanced Technology Case. The rate at which consumers adopt new clean energy technologies significantly impacts the reduction in energy demand and, in turn, direct CO_2 emissions from the transportation sector, as can be seen in the Stretch Technology Case (below).

The Stretch Technology Case also projects large reductions in transportation energy demand (relative to the Base Case) due to improved fuel economy for HDVs as well as a more efficient LDV fleet. The Stretch Technology Case differs from the other cases in that it assumes consumers continue to value the same features and performance metrics for a vehicle; however, they do not have a preference for conventional vehicles beyond the quantified features and performance metrics (as in the Base and Advanced Technology Cases). Thus, consumers are more willing to adopt alternative vehicle technologies in the Stretch Technology Case. As a result, battery and hydrogen fuel cell EVs constitute 40% of new light-duty car sales in 2040 in the Stretch Technology Case, thus leading to a greater combined market share for these (and other) alternative vehicles (not shown). The rate of adoption of advanced technologies was also accelerated in heavy-duty vehicles, leading to higher fuel economy in these vehicle classes as well.

The modeled carbon price has only a modest effect on transportation sector energy demand. In comparison to other sectors of the economy, the transportation sector has a limited number of comparatively low-cost options for reducing its carbon intensity, and there is also a long timeframe associated with the introduction and market penetration of new vehicle technologies.[40] In addition, consumers undervalue the savings of fuel economy relative to its expected present value when making vehicle purchase decisions.[41] Finally, the impact of a carbon price on the price of gasoline is relatively small, thus muting the impact on consumer adoption of more efficient and alternative fueled vehicles.[42]

Direct emissions from the transportation sector largely parallel changes in demand, since the transportation sector sources the vast majority of its energy from direct fuel use. In the Advanced Technology and Stretch Technology Cases, transportation direct CO_2 emissions are 15% and 33% lower, respectively, than in the Base Case in 2040 (Figure 6). These emissions reductions are largely due to the previously described energy demand reductions, as well as the increased reliance on electricity and other low-carbon fuels in the transportation sector.

The modeled carbon price has only a modest impact on transportation sector emissions beyond those achieved by the assumed technology advances—for the same reasons described above for energy demand—which is a result commonly shown in similar types of peer-reviewed studies.[43,44] However, due to its heavy consumption of natural gas and oil, the analysis cases that assume higher prices for natural gas and oil project lower transportation energy demand and CO_2 emissions. Under Base Case technology assumptions, the projected impact of higher natural gas and oil prices (as modeled in the High Natural Gas and Oil Prices Side Case) on transportation CO_2 emissions is of similar magnitude to that of an initial $20 carbon price (Appendix B).

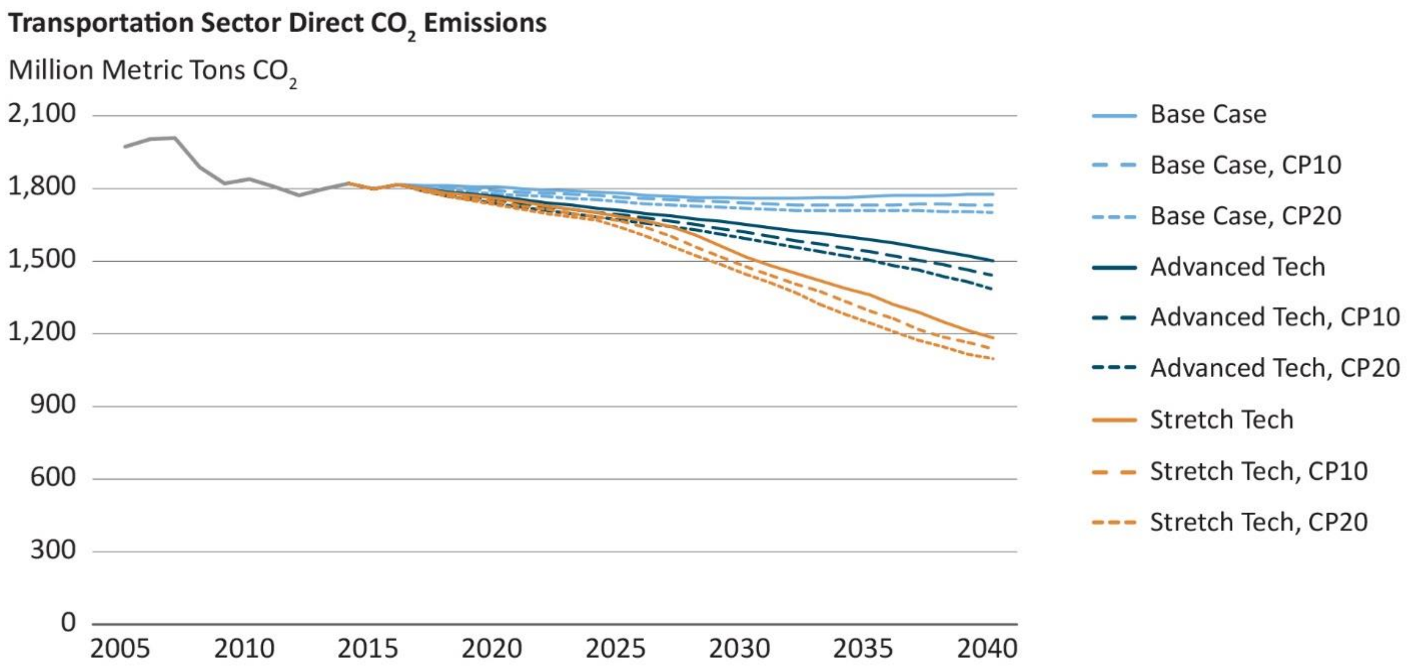


Figure 6. The projected impact of technology innovation and additional policies on CO_2 emissions from direct fuel consumption in the transportation sector. Projected CO_2 emissions reductions are achieved through improved fuel economy for LDVs and HDVs and improved cost and performance of electric and hydrogen-fueled LDVs in all cases, and through greater parity in consumer adoption of alternative and conventional vehicles in the Stretch Technology Cases. The modeled carbon price is projected to drive only modestly greater reductions in transportation CO_2 emissions.

It should be noted that there are additional opportunities for reducing transportation emissions that were not fully captured in this analysis. For example, more aggressive assumptions about drop-in (i.e., advanced) biofuels could drive additional reductions in the carbon intensity of fuels without requiring significant changes to existing fueling infrastructure or consumer vehicle choice. However, feedbacks between the energy sector and land use in the United States would have important implications for the penetration of biofuels in the transportation sector, and this interplay can only be fully captured in integrated assessment models that represent both the energy and land-use sectors.

Finally, it is also worth noting that the transportation sector represents a significant opportunity for additional emissions reductions through targeted technology innovation. Additional electrification (Figure 5) and replacement of traditional fuels with hydrogen or low-carbon biofuels will be essential for further reducing emissions from the transportation sector, particularly in the context of a deeply decarbonized electricity sector. With current policies, market conditions, infrastructure, and costs and performance of alternative fueled vehicles, it is not clear which combination of low-carbon fuels (i.e., electricity, hydrogen, and/or advanced biofuels) will ultimately succeed in achieving deep market penetration in the United States. Clean energy RDD&D will play a critical role in improving the cost and performance of alternative-fueled vehicles, which will be essential for defining the path forward for decarbonizing the transportation sector.

Industrial Energy Consumption and Emissions

Industrial energy demand changes vary depending on changes in the efficiency, productivity, and structure of the industrial sector. Under business as usual assumptions and assuming only current policies and measures with relatively low future prices for natural gas and oil, industrial energy demand is projected to increase slightly, reflecting growth in the economy and an increase in industrial production. It is worth noting that gross domestic product grows at a similar rate in all of the analysis cases.

Opportunities exist for significant demand reductions from the industrial sector through technology innovation. In the Advanced Technology Case, the majority of reductions are due to greater efficiency in petroleum refining processes, which contributes to over 0.6 quads of fossil energy savings in 2040. A shift to greater production of biofuels and reduced refining requirements (due to lower demand for petroleum products) also contribute to these fossil energy savings. Additional energy savings arise from reduced demand in the cement and lime and iron and steel industries, as well as greater adoption of combined heat and power in most industries. Altogether, technology improvements represented in the Advanced Technology Case drive a 6% reduction in industrial direct emissions relative to the Base Case in 2040 (Figure 7).

More aggressive assumptions about the energy efficiency potential for manufacturing processes and industrial motor-driven systems result in lower industrial sector energy demand in the Stretch Technology Case, demonstrating that efficiency can be an important aspect of achieving emissions reductions in the industrial sector. As in the buildings sector, additional policy (as represented by an initial $10 [CP10] or $20 [CP20] carbon price, starting in 2017 and increasing at a rate of 5% per year in real dollars) in the industrial sector drives only slight reductions in direct CO_2 emissions beyond those achieved through technology innovation alone (Figure 7). Most of the emissions reductions in the industrial sector that are driven by additional policy occur due to a cleaner electricity generation mix (Figure 2c).

Higher assumed natural gas and oil prices are projected to drive additional reductions in demand and direct CO_2 emissions from the industrial sector (Appendix B), largely due to a pronounced reduction in direct fuel use. Additional policy, both in isolation and in combination with technology innovation, is projected to have a similar effect (Figure 7). It is worth noting that only the Stretch Technology cases (both with and without additional policy) project industrial sector direct CO_2 emissions that are below current levels in 2040, and that such reductions occur even while the economy (as represented by gross domestic product) is projected to grow by 74%–79% between 2016 and 2040 (depending on the analysis case).

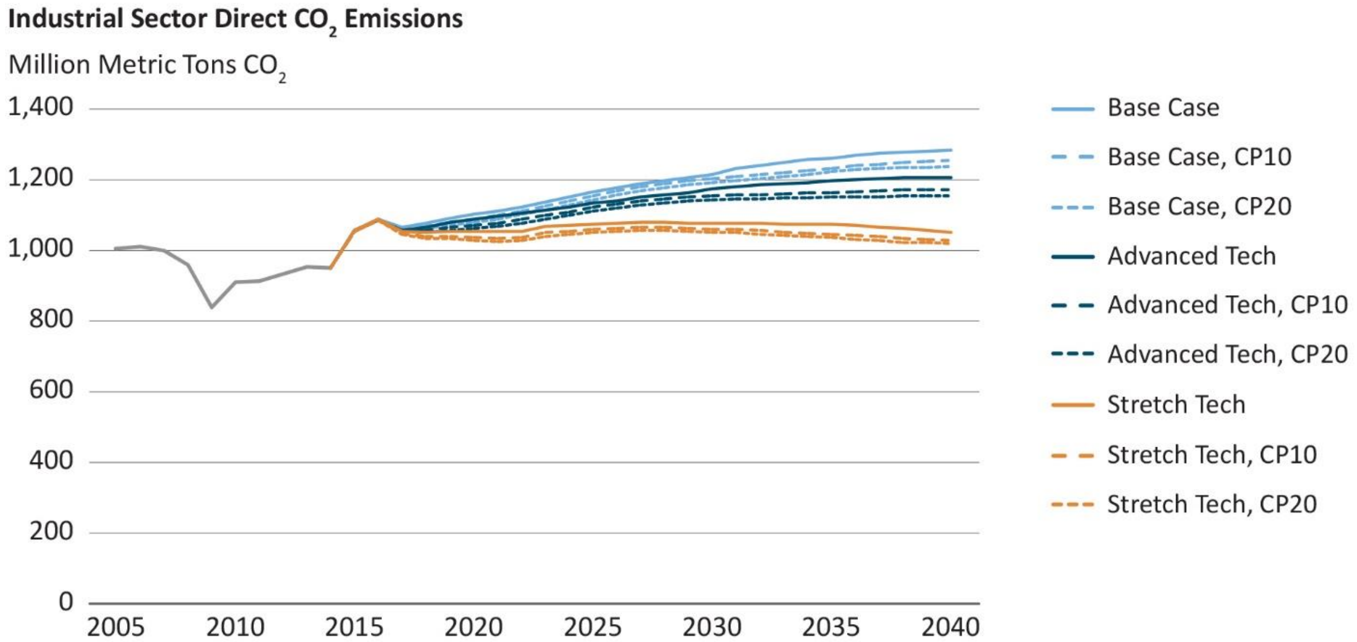


Figure 7. The projected impact of technology innovation and additional policies on direct CO_2 emissions from the industrial sector. Technology innovation is projected to have a larger impact on emissions from direct fuel combustion in the industrial sector (compared to additional policy, which has a greater impact on total industrial emissions; Figure 2c). Efficiency improvements (especially in energy-intensive industries), additional policy, and the combination of the two can reduce industrial CO_2 emissions. It is important to note that effects beyond efficiency improvements were not modeled for industrial processes, and some emissions reductions in other sectors are largely facilitated by industrial improvements (such as lightweighting of vehicles).

Improvements in only some of the industrial sub-sectors were represented in the Advanced Technology and Stretch Technology analyses, and of those sub-sectors, only improved energy efficiency was modeled. Major shifts in industrial processes are not captured in this analysis. For example, major changes in industrial processes to less energy intensive processes (e.g., the production of dramatically improved materials or chemicals) have the potential to reduce emissions in the industrial sector. EPSA-NEMS does not permit much switching to lower-carbon fuels (e.g., carbon beneficial forms of biomass and electricity, including hydrogen) in the industrial sector, which could further reduce industrial emissions. Finally, CCUS for industrial applications is another important opportunity for reductions in CO_2 emissions from the industrial sector; however, it was not included in this analysis due to modeling constraints. These examples represent additional opportunities, and further support the conclusion that additional clean energy RDD&D is essential for achieving significant reductions in CO_2 emissions from the industrial sector.

Electricity Generation Mix

Under business as usual assumptions and assuming no new policies beyond those that were final at the time of this analysis, it is projected that fossil fuels will provide 60% of electricity generation out to 2040, two-thirds of which will be fueled by natural gas. Of the remaining electricity generation that comes from low- or zero-carbon generation, approximately 60% is provided by nuclear and conventional hydropower (Figure 8: Base Case).[p]

A purely "policy pull" approach is projected to drive a significant shift in the U.S. electricity generation mix. In the "Base Case + CP10" scenario (representing a price of $10 per tonne of CO_2 in 2017, rising at a rate of 5% per year in real dollars), uncontrolled fossil fuels and low- and zero-carbon sources provide roughly equal shares of electricity generation by 2040, with natural gas providing the majority of fossil fuel based electricity generation. Nuclear and conventional hydropower provide roughly half of all low- and zero-carbon electricity generation, with the other half coming from wind, solar, and other renewable sources. Similar but more accentuated shifts in the electricity generation mix are projected when the initial carbon price is increased to $20 per tonne of CO_2 (Figure 8: Base Case+CP10 and CP20).

The clean energy technology innovation represented in the Advanced Technology Case is projected to drive a more pronounced transition towards low- and zero-carbon generation sources than the Base Case without additional policy. By 2040, fossil fuels will provide roughly half of U.S. electricity generation, split evenly between coal and natural gas. The other half is sourced from low- or zero-carbon generation technologies, which primarily replace natural gas-fired generation in the Advanced Technology Case (Figure 9: Advanced Technology). Low- and zero-carbon generation is split roughly evenly between (1) nuclear and conventional hydropower, and (2) wind, solar, and other renewable energy sources.[q] Despite the inclusion of current DOE goals, deployment of fossil fuel plants with CCUS is limited in the Advanced Technology Case, relative to other analyses.[45] [46] [47] Finally, select low- and zero-carbon electricity generation technologies (e.g., marine hydrokinetics and bioenergy with carbon capture and storage) are not represented in EPSA-NEMS.

Additional successful technology innovation could accelerate and enhance this shift in the electricity generation mix. In particular, the Stretch Technology Case is an ambitious case that represents how a portfolio approach to clean energy RDD&D can drive significant changes in the electricity sector. The relative competitiveness of generation from uncontrolled fossil fuels and a wide array of low- and zero-carbon electricity generating technologies shifts in the Stretch Technology Case. However, the uncertainty associated with how and where significant new investments might be made in the future makes the results of this case largely illustrative, so the specific electricity generation mix for the Stretch Technology Case is not shown.

---

[p] EPSA-NEMS assumes that all operating nuclear power plants can continue operations to an 80-year lifetime.

[q] EPSA-NEMS requires modeling simplifications, as is typical of many energy sector models. These simplifications may limit the ability of the model to fully resolve differences in wind and solar power deployment. Notably, under the conditions of the Advanced Technology Case, EPSA-NEMS appears to be more sensitive to cost reductions from solar technology relative to wind, more than as would be indicated in alternative analysis, such as analysis utilizing the NREL ReEDS model. See T. Mai, W. Cole, E. Lantz, C. Marcy, and B. Sigrin, *Impacts of Federal Tax Credit Extensions on Renewable Deployment and Power Sector Emissions* (Golden, CO: National Renewable Energy Laboratory), NREL/TP-6A20-65571, http://www.nrel.gov/docs/fy16osti/65571.pdf.

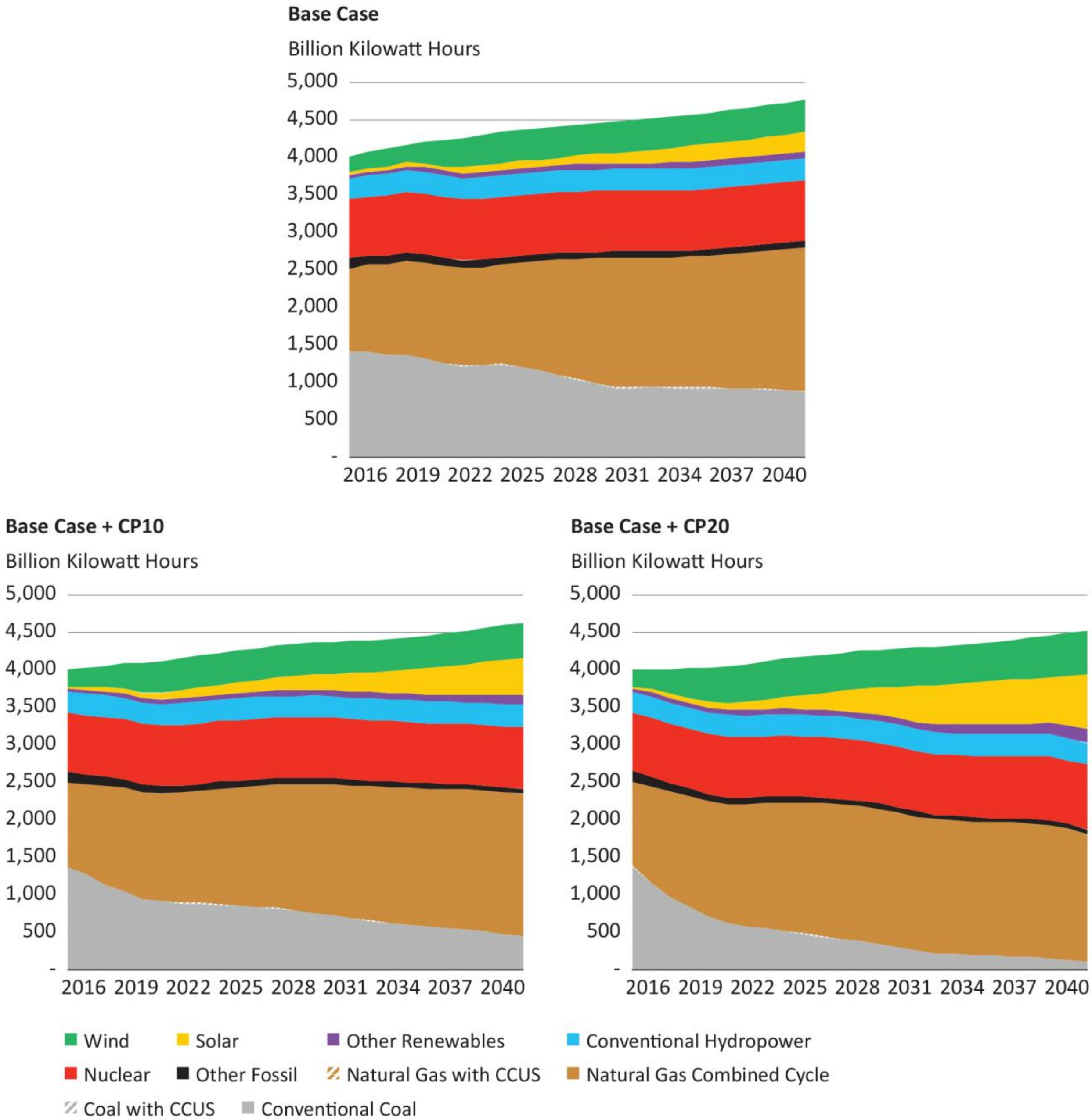


Figure 8. Electricity generation mixes for the Base Case with no additional policy (Base Case) and with the addition of initial carbon prices of $10 (Base Case + CP10) and $20 (Base Case + CP20) per tonne of CO_2, beginning in 2017 and increasing by 5% per year in real dollars. The purple wedge shows generation from Other Renewable sources, including geothermal, municipal waste, wood and other biomass, and pumped hydropower storage. The black wedge shows generation from Other Fossil fuel sources, including combustion turbines, fuel cells, and oil and gas steam. Comparison of the Base Case, Base Case + CP10, and Base Case + CP20 demonstrates the impact of a purely "policy pull" approach, which incentivizes the replacement of highly carbon-intensive generation (i.e., uncontrolled coal-fired generation) with low- and zero-carbon generation sources.

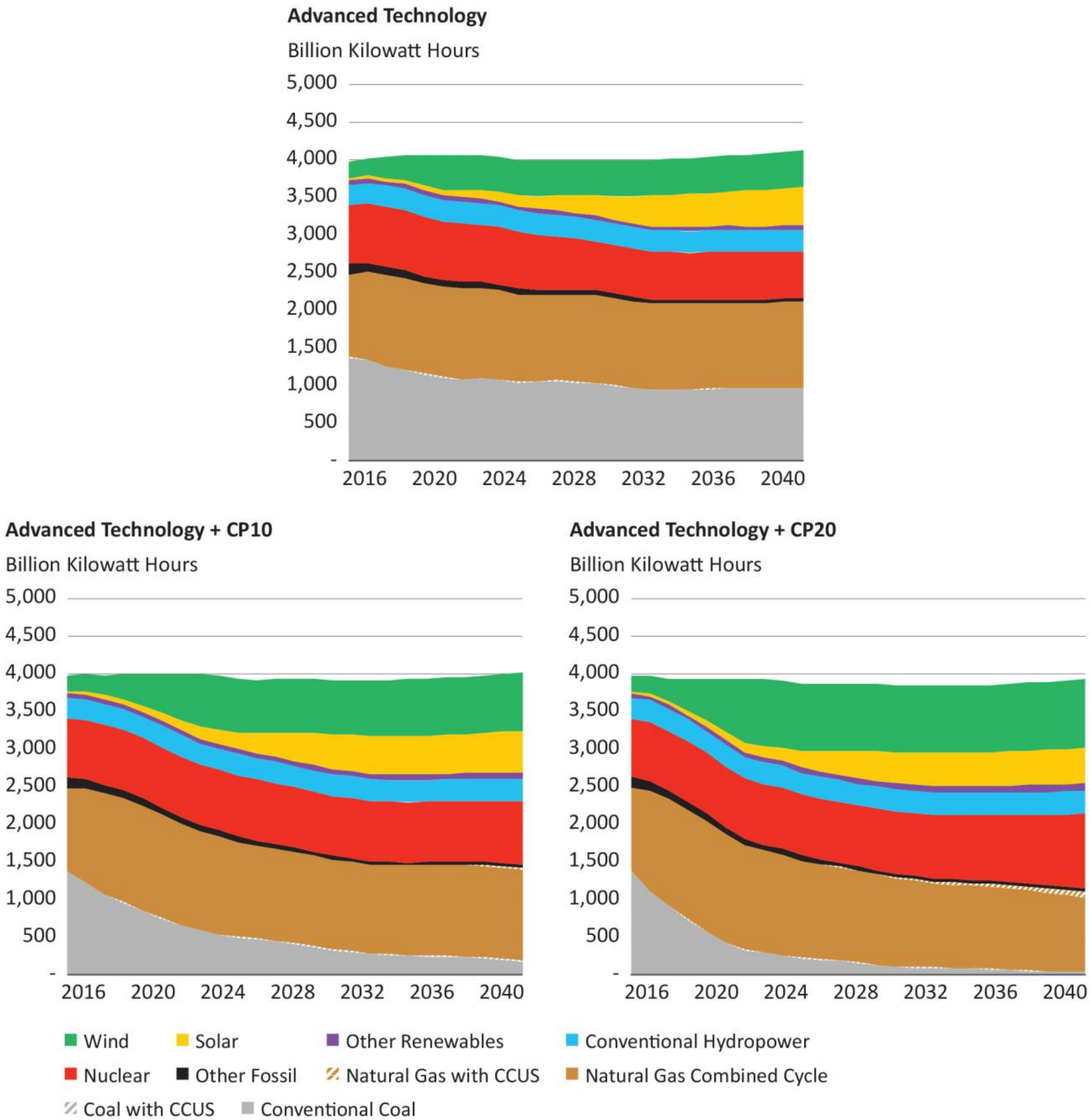


Figure 9. Electricity generation mix for the Advanced Technology Case assumptions with no additional policy (Advanced Tech) and with the addition of initial carbon prices of $10 ("Advanced Tech + CP10") and $20 ("Advanced Tech + CP20") per tonne of CO_2, beginning in 2017 and increasing by 5% per year in real dollars. A comparison of the Advanced Technology Case with the Base Case (Figure 8) demonstrates the impact of a purely "technology push" approach on the U.S. electricity generation mix. A comparison of the three charts in Figure 9 demonstrates the impact of a combined "technology push + policy pull" approach, which incentivizes replacement of highly carbon-intensive generation (i.e., uncontrolled coal-fired generation) with low- and zero-carbon generation sources, including renewables, nuclear power, and fossil fuel plants equipped with CCUS.

Similar to the purely "policy pull" scenarios (Figure 8), the "technology push + policy pull" approach (Figure 9, "Advanced Tech + CP10" and "Advanced Tech + CP20") incentivizes the replacement of highly carbon intensive electric generation (i.e., uncontrolled coal-fired generation). The future electricity generation mix is somewhat different when additional policy is layered on top of different technology input assumptions in that additional policy results in increased market share for wind, solar, and nuclear power under the Advanced Technology input assumptions (relative to the Base Case), with CCUS and natural gas's share of electricity generation increasing slightly. In the $10 initial carbon price scenario, low- and zero-carbon sources provide two-thirds of U.S. electricity generation by 2040, split roughly evenly between 1) nuclear and conventional hydropower, and 2) renewable sources excluding hydropower (Figure 9: Advanced Tech+CP10). A similar but more prominent shift is projected when layering an initial $20 carbon price onto the Advanced Technology Case: in this case, natural gas is the dominant remaining fossil fuel generation source in 2040, when it provides just 25% of total electricity generation in the United States, approximately 10% of which takes the form of natural gas with CCUS (Figure 9: Advanced Tech+CP20). It is worth noting that this result is fairly conservative in terms of the deployment of natural gas with CCUS, relative to other analyses.[48] [49] [50]

This analysis is one representation of a possible clean energy future, which is highly sensitive to the input assumptions (e.g., technology cost and performance, incentives, and the future prices of natural gas and oil). These input assumptions directly inform which generation sources are installed and dispatched, and slightly different assumptions could result in changes to the projected future electricity generation mix. One example of this lies in the competition between wind and solar photovoltaics (PV), where the actual market share of each technology is highly dependent on their relative costs. Therefore, the total share of renewable penetration is a more robust metric, and the specific electricity generation mix results for each analysis case should be interpreted with the technology and policy inputs in mind.

Another prominent example lies in how sensitive the future electricity generation mix is to the future prices of natural gas and oil, which are highly uncertain. Under Base Case technology assumptions, higher gas and oil prices (as modeled in the High Natural Gas and Oil Prices Side Case) result in natural gas's share of the electricity generation mix being less than half that projected in the Base Case by 2040. This lower generation from natural gas is replaced by generation from both coal and renewable energy sources (Appendix B). Under the technology assumptions of the Advanced Technology Case, higher natural gas and oil prices result in a smaller share of natural gas-fired generation and correspondingly larger generation from coal, wind, and nuclear power. Assuming established DOE program goals, CCUS on fossil fuel plants does not significantly deploy in the absence of additional policies in this analysis because costs are higher than those for other clean generation options (Appendix B).

Higher natural gas and oil prices also drive a significant shift in the electricity generation mix under the combined "technology push + policy pull" analysis cases. Most of the previously described shifts are accentuated when additional policy is layered on top of the Advanced Technology Case, with one important exception: in the presence of additional policy, fossil fuel plants with CCUS make up a larger share of the electricity generation mix in the later years when natural gas and oil prices are projected to be relatively high (Appendix B). This increased utilization of CCUS is largely driven by the improved economics of CO_2 capture that is used for enhanced oil recovery applications, which is more attractive when other resources are less abundant (as assumed in the High Natural Gas and Oil Prices Side Cases).

Finally, projections of the future electricity generation mix (Figures 8 and 9) can also be influenced by policy, and adding additional incentives could change deployment rates for any electricity generating technology. For example, a separate DOE analysis found that under Base Case technology assumptions, tax incentives for CCUS could drive additional deployment of coal and natural gas plants with CCUS. This result would likely be more pronounced in a case that combines tax incentives with the technology cost and performance assumptions for CCUS in the Advanced Technology and Stretch Technology analyses, particularly in the presence of a carbon price.[51]

Cumulative Electricity-Related CO_2 Emissions

The net result of the previously described changes to the electricity generation mix and end-use electricity demand (due to improved efficiency) is a reduction in electricity-related CO_2 emissions in all cases. Assuming only current policies and measures, the Base Case projects that power sector CO_2 emissions will largely be dictated by the CPP. The Advanced Technology Case projects that power sector CO_2 emissions fall below those projected in the Base Case (Table 4, Figure 10).

Table 4: Projected Electricity-Related CO_2 Emissions Reductions by 2040, Relative to 2005 Levels

Analysis Case	Low Natural Gas and Oil Prices	High Natural Gas and Oil Prices
Business as Usual		
Base Case	32%	33%
Impacts of Technology Innovation		
Advanced Technology	40%	40%
Stretch Technology	58%	--
Impacts of Additional Policy		
Base Case, CP10	54%	--
Base Case, CP20	69%	--
Impacts of Additional Policy + Technology Innovation		
Advanced Technology, CP10	73%	72%
Advanced Technology, CP20	81%	87%
Stretch Technology, CP10	88%	--
Stretch Technology, CP20	92%	--

Reductions occur over time in all analysis cases. Business as usual projections (the Base Case) are largely dictated by the CPP. Technology innovation can drive additional emissions reductions via a cleaner electricity generation mix and reduced electricity demand through improved efficiency. The combination of technology and additional policy achieves greater reductions (beyond the Base Case) than the sum of each approach on its own. Additional technology innovation can also reduce the cost of additional policy that is needed to achieve similar levels of emissions reductions.

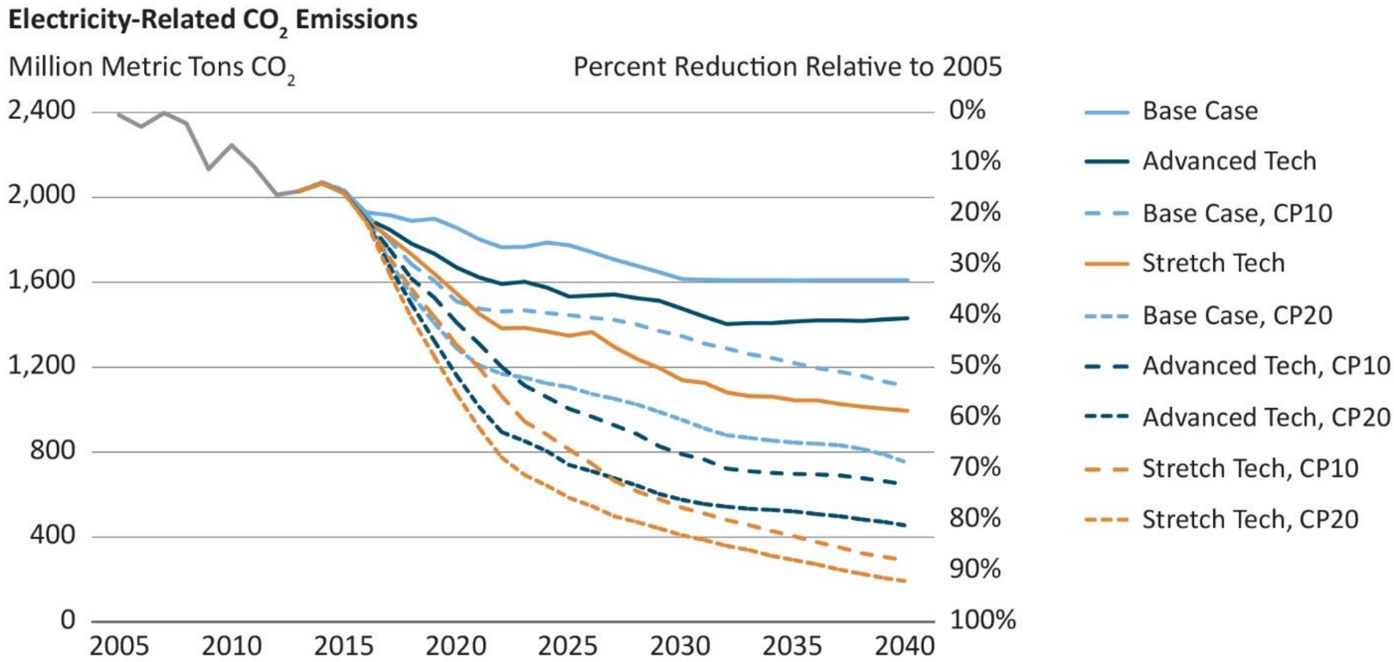


Figure 10. The projected impact of technology innovation and/or additional policy on U.S. electricity-related CO_2 emissions. Technology innovation is projected to reduce electricity-sector CO_2 emissions beyond those projected under current policies, measures, and projections for technology advancements. Additional policy (i.e., a price on carbon) drives significant decreases in CO_2 emissions, especially in the electricity sector where cost-effective solutions are available for rapid deployment. The combination of increased technology investments and a price on carbon is projected to drive even greater emissions reductions than the sum of each approach on its own.

In the near term, the majority of projected emissions reductions can be attributed to a corresponding decrease in the emissions intensity of electricity generation (Appendix A).[r] This is largely driven by the previously described replacement of coal-fired generation with lower-carbon generation sources, which is accelerated and enhanced by technology innovation, additional policy, and the combination of the two.[s] With respect to projected increases in natural gas fired generation, it is worth noting that this analysis does not consider upstream emissions of non-CO_2 gases (such as methane) emitted during the production, transport, and storage of natural gas. However, methane is a small enough share of total lifecycle emissions for natural gas fired generation that this omission is not expected to change the main conclusions of this report (Section 4).[52] [53]

[r] In this case, emissions intensity of electricity generation is defined as the amount of CO_2 emitted per unit of electricity generation (e.g., lb CO_2/kWh).

[s] For all cases, the necessary installation rates for this fairly rapid shift in the generation mix—particularly for natural gas combined cycle, wind, and utility-scale solar PV—are within the range of recent historical deployment rates and projections for technology learning in these industries. See, for example, U.S. Energy Information Administration (EIA), *Wind and Solar Data and Projections from the U.S. Energy Information Administration: Past Performance and Ongoing Enhancements* (Washington, DC: EIA, March 2016), http://www.eia.gov/outlooks/aeo/supplement/renewable/pdf/projections.pdf.

In the later years, the CO_2 emissions intensity of utility-scale electricity generation is projected to increase slightly on an annual basis (Appendix A) in certain years, for both the Base Case and Advanced Technology Case. Despite the fact that the market share of zero-carbon utility-scale solar PV and wind generation increases during this time period, the emissions intensity also increases due to either a slight rebound in coal generation or retirements of nuclear units, depending on the analysis case.

Under the purely "policy pull" approach, this analysis projects that the modeled carbon price proxies could drive reductions in electricity-related CO_2 emissions that are larger than those projected to be achieved under current investments in clean energy RDD&D (Table 4, Figure 10). These policy-driven reductions are largely due to the fact that the power sector has the most and lowest-cost options for reducing carbon intensity compared to end-use sectors with high percentages of liquid fuel use (e.g., transportation and industry).

This analysis further shows that the combined "technology push + policy pull" approach drives significant emissions reductions in the U.S. power sector. In particular, when combining additional successful clean energy RDD&D with additional policy (Stretch Tech, CP10 or Stretch Tech, CP20), this analysis finds that the U.S. power sector CO_2 emissions are reduced by approximately 90% in 2040 as compared to 2005 (Table 4). This level of emissions reductions is largely consistent with the level of reductions that would be needed from the electricity sector to achieve an overall economy-wide 80% reduction from 2005 levels by 2050 (Figure 10).

Finally, while future natural gas and oil prices have an important impact on the generation mix (as previously described), they have little effect on electricity-related CO_2 emissions in the analysis cases that assume no additional policy. For both the Base Case and Advanced Technology Case, higher natural gas and oil prices result in smaller near-term reductions in electricity-related CO_2 emissions until the CPP comes into effect (see Appendix B) and in slightly larger electricity-related CO_2 emissions over the longer term (Table 4).

Under a combined "technology push + policy pull" approach, the relationship between future natural gas and oil prices and projected CO_2 emissions reductions is complex (see Appendix B). When assuming the technology improvements modeled in the Advanced Technology scenarios, the addition of an initial carbon price of $10 per tonne of CO_2 drives a similar level of electricity-related emissions reductions beyond those projected from technology advancements alone in 2040, regardless of the assumed prices of natural gas and oil. However, when the modeled initial carbon price is increased to $20 per tonne of CO_2, this additional policy has a significantly larger impact on electricity-related CO_2 emissions reductions when natural gas and oil prices are higher (Table 4). This result indicates that the modeled initial carbon price of $20 per tonne of CO_2 is somewhat of a tipping point, such that low- and zero-carbon generation sources (e.g., solar PV, wind, and nuclear) become decidedly more cost-effective than uncontrolled natural gas-fired generation in the later years.

KEY FINDINGS AND CONCLUSIONS

This final section presents the key findings and conclusions based on the previously described analysis.

First, current levels of RDD&D investment in clean energy technologies, sustained over the next two decades and achieving stated goals, can facilitate significant reductions in energy CO_2 emissions beyond business as usual projections. In particular, successful RDD&D activities that drive advancements in clean energy technologies, supported by deployment activities that reduce or eliminate specific market barriers, can result in significant reductions in energy CO_2 emissions. This analysis indicates that clean energy RDD&D, including DOE's work, can contribute to significant progress toward current U.S. climate and energy goals. In addition, opportunities exist for greater energy CO_2 emissions reductions through more ambitious advancements in clean energy technology innovation and systems, such as what could be enabled by additional support for clean energy RDD&D (e.g., through Mission Innovation).

Next, the combination of additional policies and clean energy technology advances and penetration can drive deeper emissions reductions than the sum of what could be achieved under each individual approach. Put another way, this analysis demonstrates that "policy pull" and "technology push" are synergistic policies, which achieve deeper emissions reductions when they are implemented together.

This analysis further shows that technology innovation can reduce the cost of additional policies needed to achieve a level of carbon reductions that would mitigate the worst impacts of climate change. In particular, a more modest level of additional policy is able to achieve deeper emissions reductions when more cost-effective technologies are available due to successful clean energy RDD&D.

Finally, despite the progress described above, current policies and U.S. RDD&D clean energy technologies program goals, if they are met, are not projected to achieve the level of GHG emissions reductions from the energy sector that are needed to mitigate the worst impacts of climate change. Opportunities also exist for greater energy CO_2 emissions reductions through more ambitious advancements in clean energy technologies and systems (e.g., what could be enabled by additional support for clean energy RDD&D), and additional policies that incentivize reductions in energy CO_2 emissions. Ultimately, cost-effectively achieving an 80% economy-wide reduction by 2050 would require both increased innovation and new policy.

It is important to note that this analysis was performed from the bottom up, and it was not designed to achieve a specific level of energy CO_2 emissions. This is in contrast to other studies that explicitly set out to identify pathways for achieving specific levels of CO_2 emissions, consistent with mitigating the worst impacts of climate change.[54, 55, 56] These studies have demonstrated that with the right incentives, decarbonizing the U.S. economy at the pace that is required to mitigate the worst impacts of climate change is feasible but will require a significant transition from many current approaches and technologies. These studies also explored the costs, benefits, and savings to the economy associated with technology innovation and additional policies.

Within the context of these other studies, this analysis suggests that targeted technology innovation, additional policies, and/or market-based incentives will be needed to accelerate the transition towards clean energy technologies and practices. In particular, while additional policy and technology innovation can drive significant decarbonization of the electricity sector, the projected emissions reductions from end-use sectors fall short of the levels needed to mitigate the worst impacts of climate change. Especially in the industrial and transportation sectors, there is significant opportunity for additional emissions reductions through targeted technology innovation and/or additional policies.

APPENDIX A: EMISSIONS INTENSITY RESULTS

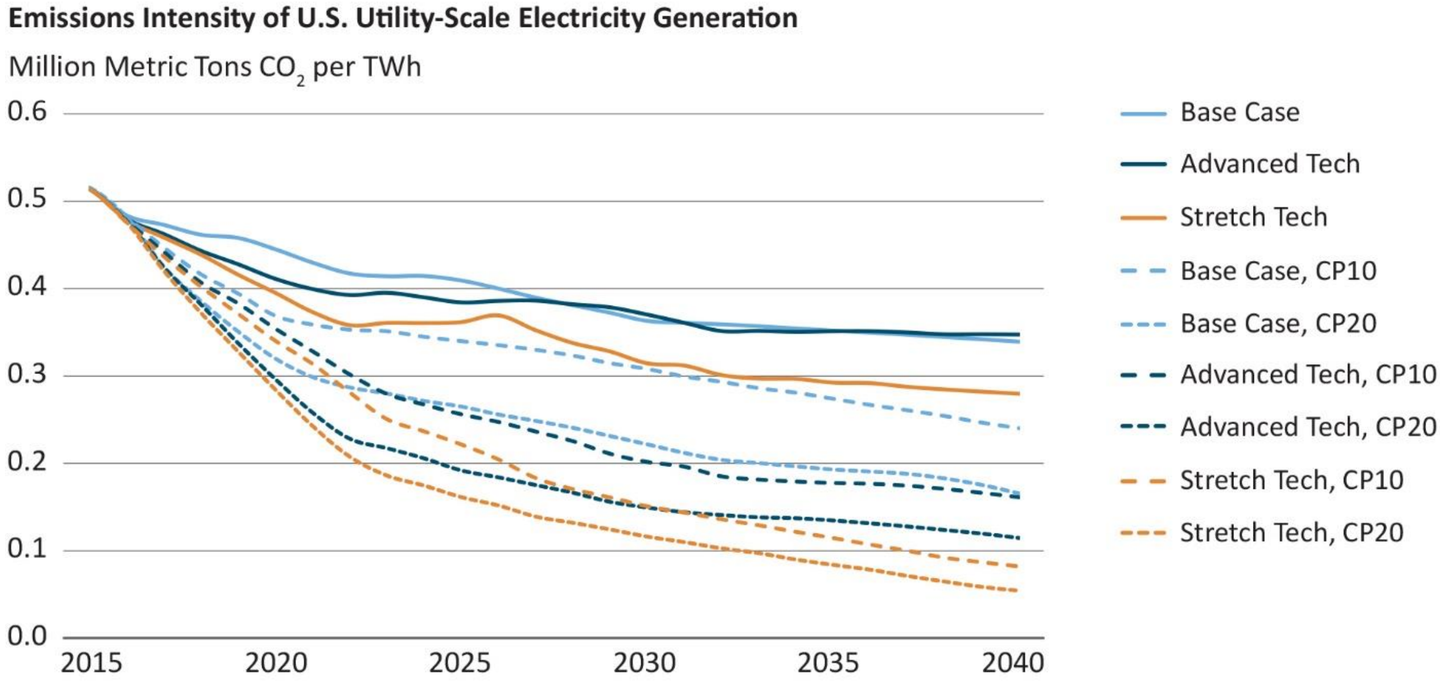


Figure A-1. Projected emissions intensity of utility-scale U.S. electricity generation under various technology (Base Case, Advanced Technology, and Stretch Technology) and policy (no additional policy, an initial carbon price of $10 per tonne of CO_2, and an initial price of $20 per ton of CO_2, starting in 2017 and increasing at a rate of 5% per year in real dollars) assumptions. Current DOE program goals (as modeled) are projected to drive a reduction in the emissions intensity of U.S. electricity generation in the near term; however, additional significant increases in successful clean energy RDD&D and a price on carbon will be needed to drive reductions that are consistent with long-term climate goals. In addition, the combination of the increased RDD&D and a carbon price drives even greater reductions in energy CO_2 emissions than the sum of each approach on its own.

APPENDIX B: THE INFLUENCE OF NATURAL GAS AND OIL PRICES ON ANALYSIS RESULTS

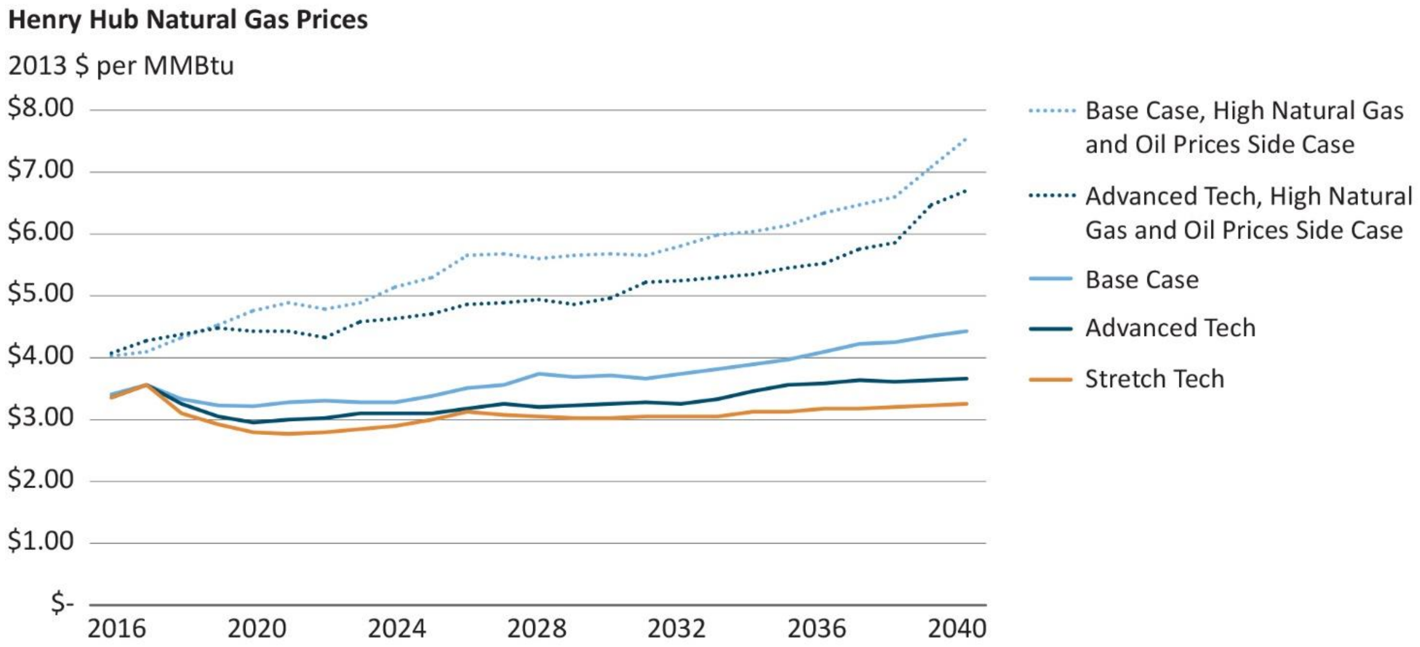


Figure B-1. Projected Natural Gas Prices in the Base Case (*blue solid line*), Side Case (*blue dotted line*), Advanced Technology Case (*black solid line*), Advanced Technology Side Case (*black dotted line*), and the Stretch Technology Case (*orange solid line*). A comparison of the similarly colored solid and dotted lines shows the impact that the assumed natural gas resource has on the projected price of natural gas, assuming similar assumptions regarding technology advances. In turn, the projected price of natural gas impacts the electricity generation mix, capacity mix, and demand. A comparison of the three solid lines demonstrates that technology assumptions impact the projected price of natural gas by changing demand for natural gas across the energy sectors.

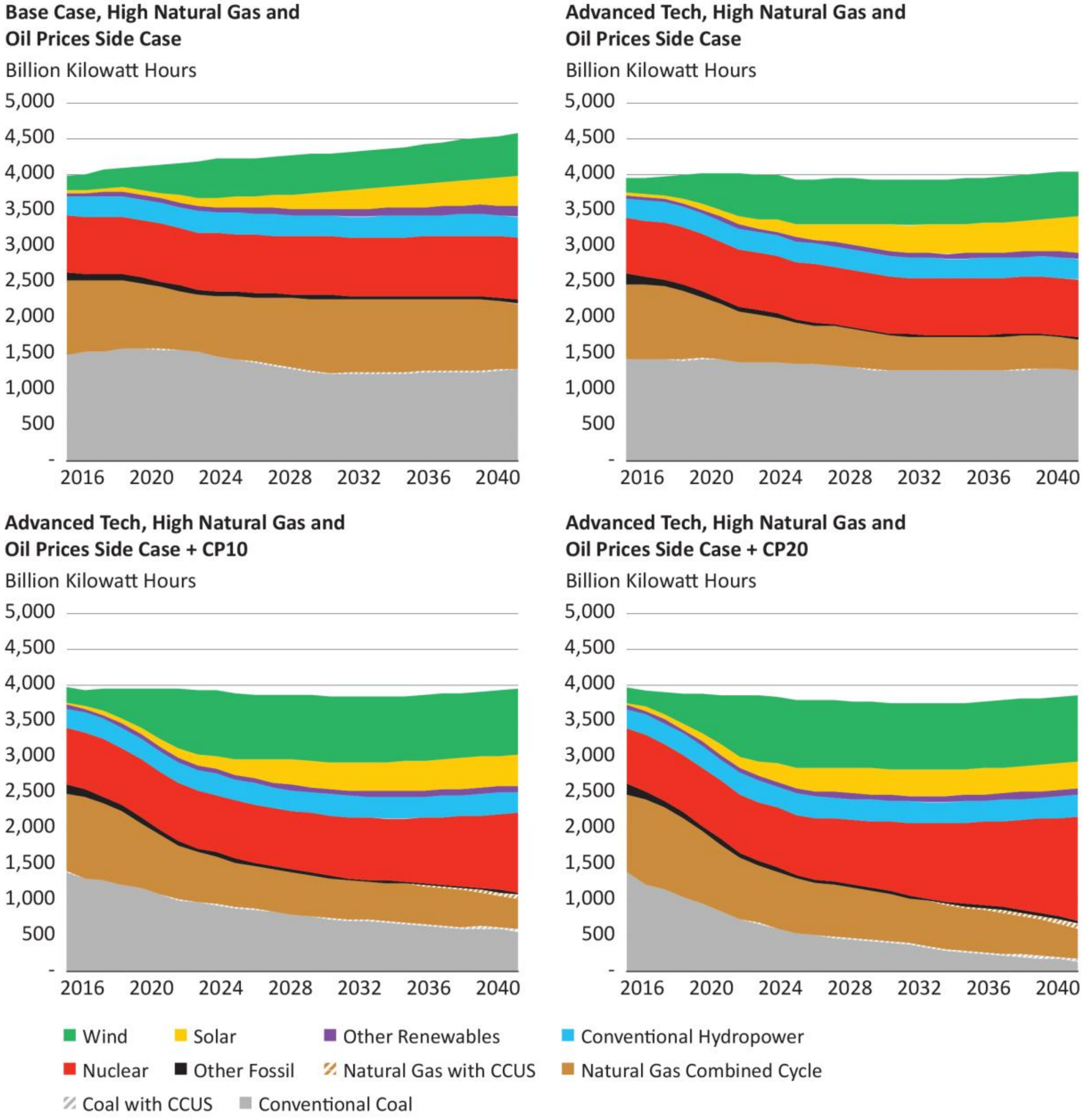


Figure B-2. Projected electricity generation mix assuming higher prices of natural gas and oil with input assumptions from the Base Case (*top left*), Advanced Technology Case (*top right*), Advanced Technology Case with an initial $10 (*bottom left*) or $20 (*bottom right*) carbon price, starting in 2017 and increasing at a rate of 5% per year in real dollars. The purple wedge shows generation from Other Renewable sources, including geothermal, municipal waste, wood and other biomass, and pumped hydropower storage. The black wedge shows generation from Other Fossil fuel sources, including combustion turbines, fuel cells, and oil and gas steam. Assuming higher natural gas and oil prices, a combination of coal and renewables gain increasing market share relative to the analysis cases with the same technology and policy input assumptions but with lower natural gas and oil prices. In the combined "technology push + policy pull" approach, higher natural gas and oil prices drive increased deployment of nuclear, coal with CCUS, and natural gas with CCUS.

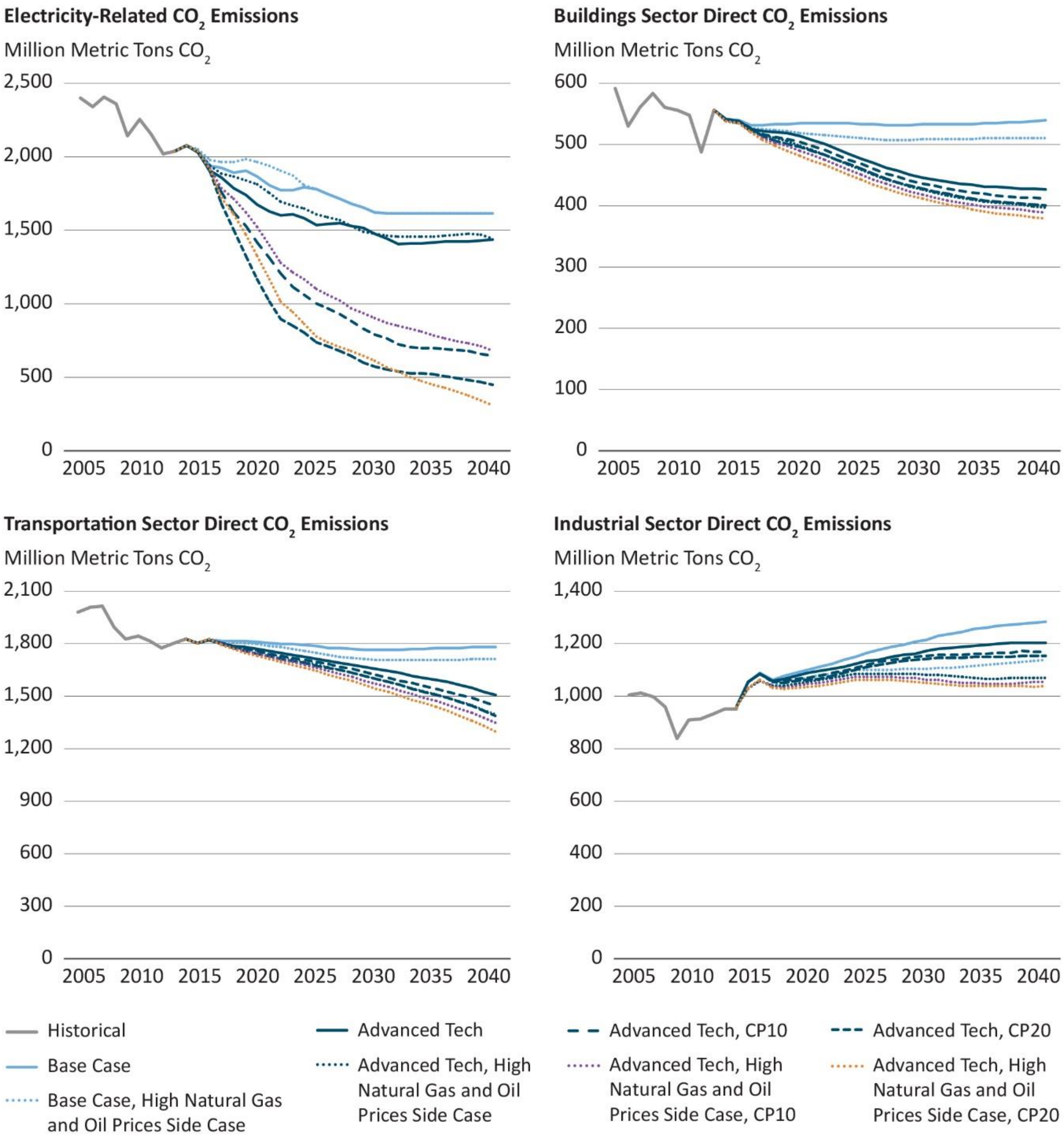


Figure B-3. The impact of natural gas and oil prices on CO_2 emissions from the energy sectors: electricity (*top left*), buildings (*top right*), transportation (*bottom left*), and industrial (*bottom right*). Note that emissions from the end-use energy sectors include only direct emissions from the on-site combustion of fossil fuels. Under the technology assumptions for both the Base Case and Advanced Technology Case, the impact of the higher assumed natural gas and oil prices on CO_2 emissions from direct fuel use in buildings and transportation is comparable to that of a $20 initial carbon price (see Figures 3 and 5 in the main text). The industrial sector is even more sensitive to higher natural gas and oil prices (see Figure 7).

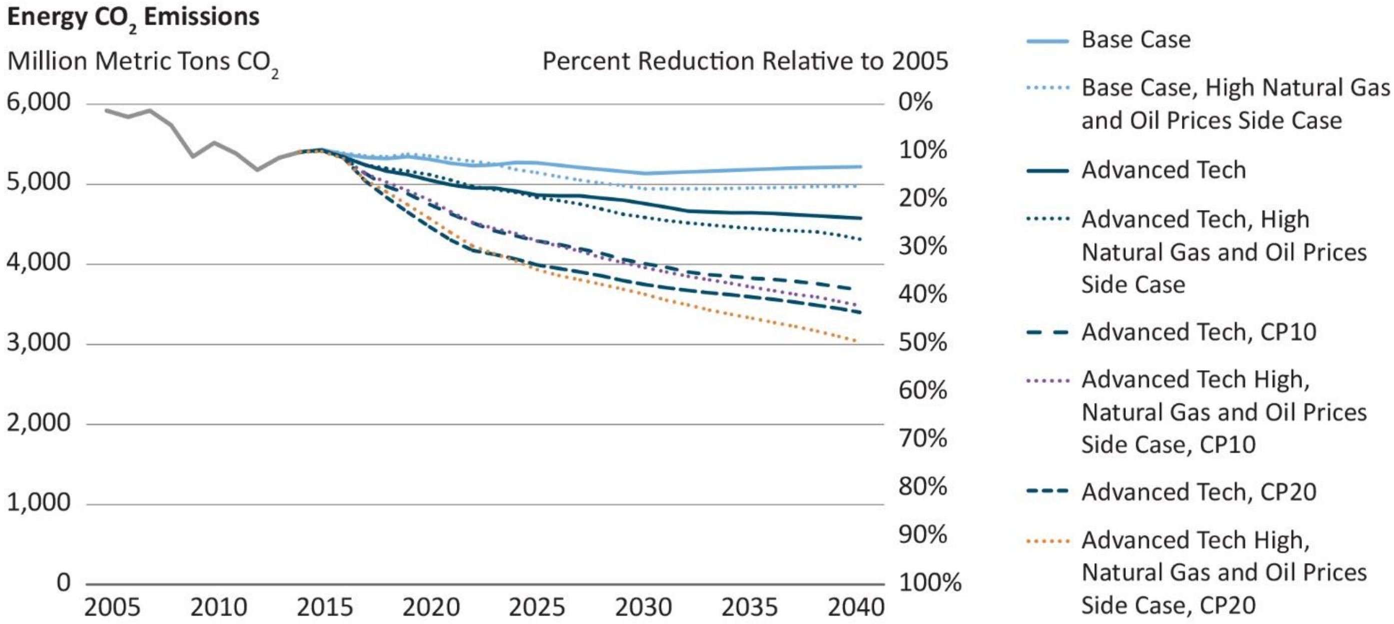


Figure B-4. The impact of natural gas and oil prices on total energy CO_2 emissions. Over the longer term, the analysis cases with higher natural gas and oil prices are projected to drive reductions in energy CO_2 emissions that are 10%–20% larger; thus, indicating that higher natural gas and oil prices drive greater reductions in economy-wide emissions intensity and overall energy consumption over the long term. Because emissions are reduced more when natural gas and oil prices are higher, the addition of a carbon policy has a smaller effect on reducing emissions in the High Natural Gas and Oil Prices Side Cases as compared to the Base Case or Advanced Technology Case.

APPENDIX C: TECHNOLOGY CASE INPUTS

This appendix presents detailed information about the technology input assumptions for the various analysis cases. The section begins with a series of tables and figures that compare the specific technology inputs for the Base Case and Advanced Technology Case, and goes on to present a detailed description of how technology input assumptions were changed in the Advanced Technology and Stretch Technology Cases, based on input from experts in the DOE program offices.

Table C-1. Levelized Cost of Energy (LCOE) for Electricity Generating Technologies[t] in 2025 and 2040, as Assumed in EPSA-NEMS in the Base Case and Advanced Technology Case[u, 57]

	2018[a]	2025		2040	
Technology	--	Base Case	Advanced Tech	Base Case	Advanced Tech
Coal with Partial CCUS	113.3[b]	107.8	88.8	103.8	81.4
Coal with Full CCUS	121.1[b]	111.9	111.3	103.2	90.1
Natural Gas Combined Cycle (NGCC)	48.9	53.0	45.3	56.8	48.2
NGCC with CCUS	75.1[c]	76.8	64.0	79.2	56.1
Nuclear Light Water Reactors	95.2[d]	93.9	81.6	90.2	64.8
Land-Based Wind	58.3	65.6	40.0	62.6	37.0
Offshore Wind	196.9[d]	196.1	103.6	183.8	88.0
Utility-Scale Solar PV	80.8	79.8	43.2	75.7	34.2
Concentrating Solar Power (CSP)	220.3	230.7	90.0	215.0	77.5

[a] Where available, the simple regional average of LCOEs for generating technologies entering service in 2018 is provided based on EIA's LCOE for AEO 2016.

[b] Denotes data sourced from NETL's Cost and Performance Baseline for Fossil Energy Plants Supplement: Sensitivity to CO_2 Capture Rate in Coal-Fired Power Plants.

[c] Denotes data sourced from NETL's Cost and Performance Baseline for Fossil Energy Plants Volume 1a: Bituminous Coal (PC) and Natural Gas to Electricity Revision 3.

[d] Denotes data sourced from EIA's LCOE for AEO 2015.

[t] LCOEs assume a 30-year lifetime and 6% real weighted average cost of capital. Costs do not reflect available tax credits, and they are simple averages across regions (despite the fact that renewable energy and other costs vary significantly by region). Hydropower and geothermal are not shown because they are site-specific in this analysis.

[u] Note LCOE is an imperfect metric for comparing technologies, as many factors are at play in deployment.

Figure C-1. End-Use energy use intensity changes from 2010 levels for residential (*top*) and commercial (*bottom*) buildings. Reductions in residential energy demand in the Advanced Technology Case (relative to the Base Case) are mainly due to new and existing shell improvements, better space heating technologies, accelerated consumer adoption of highly efficient lighting, and cost and performance improvements for fridge and freezer technologies. Reductions in commercial energy demand in the Advanced Technology Case (relative to the Base Case) are primarily driven by improved efficiency in lighting and space heating due to shell improvements, appliance standards, and accelerated consumer adoption of highly efficient technologies.

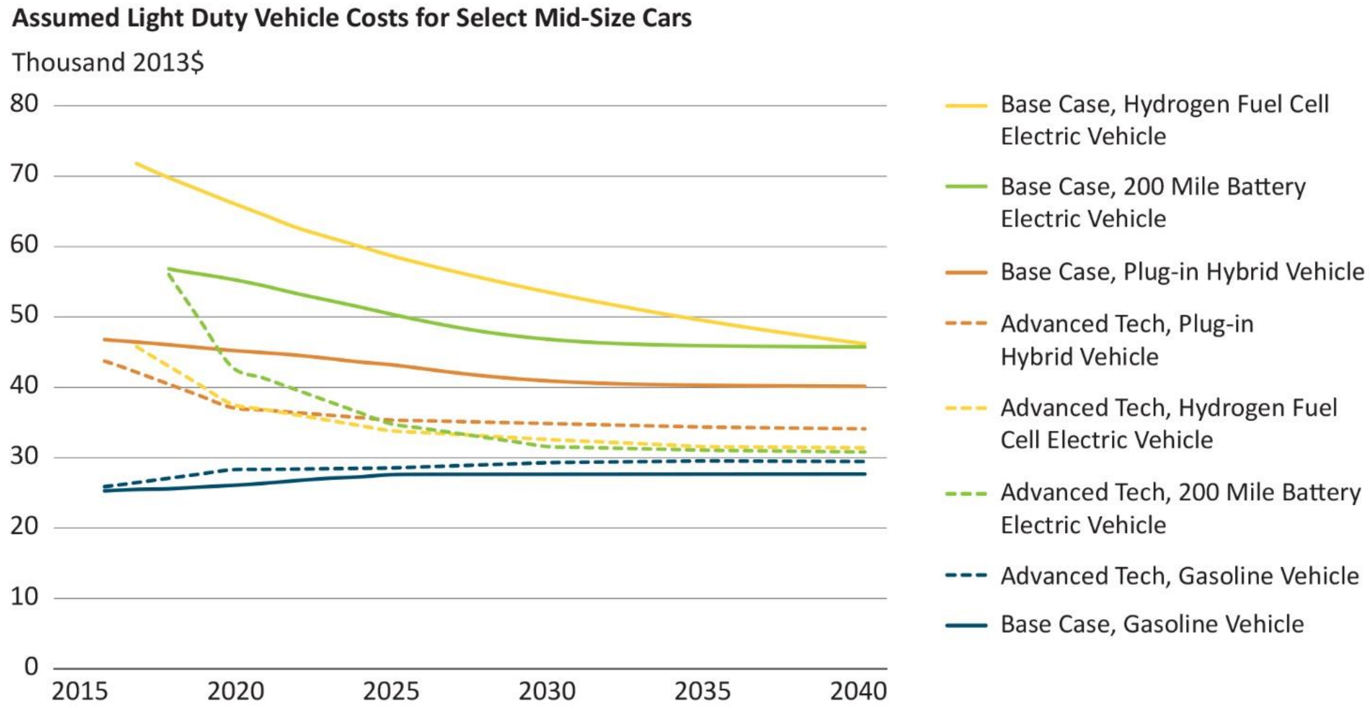


Figure C-2: Light-duty vehicle cost assumptions for select mid-size cars in the Base Case (*solid lines*) and Advanced Technology Case (*dashed lines*). Vehicle types shown include mid-size fuel cell EVs, battery EVs with a range of 200 miles per charge, PHEVs with a range of 40 miles per charge, and gasoline-powered internal combustion vehicles. Note that initial cost assumptions can vary due to differences in current cost estimates for select vehicle types.

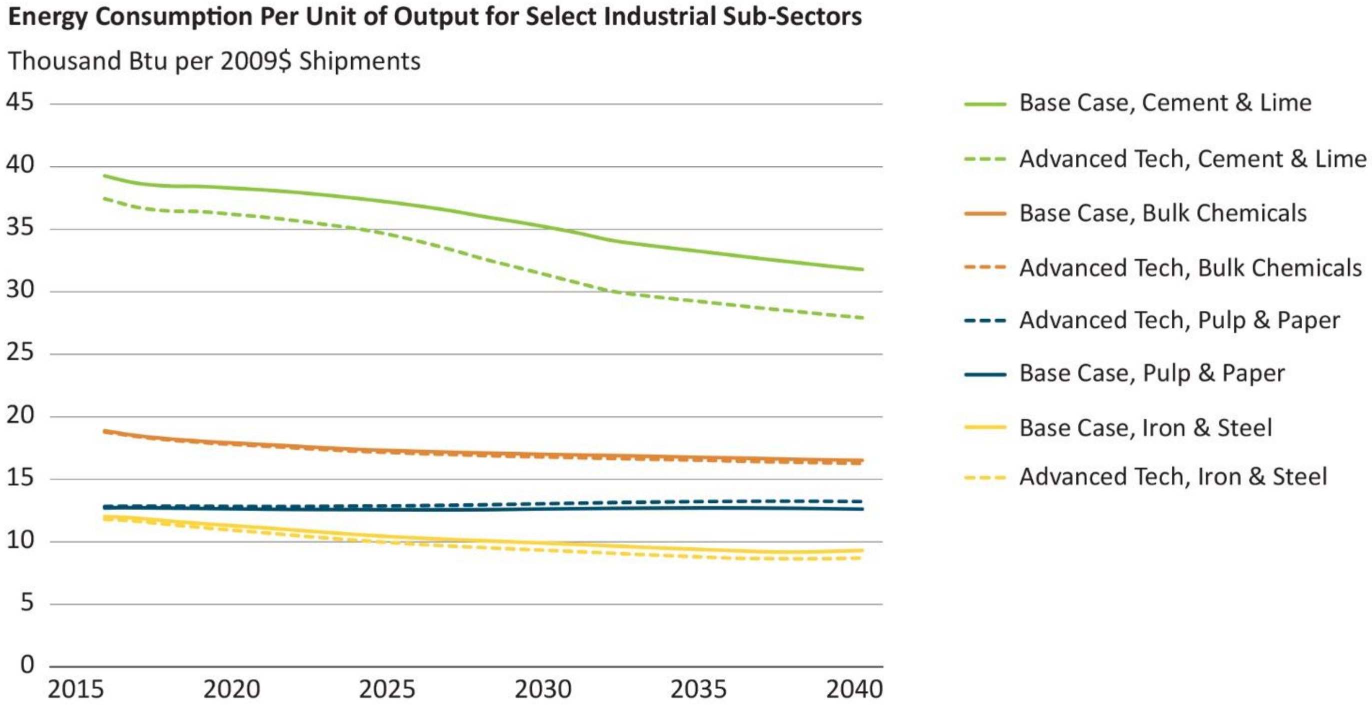


Figure C-3. Energy consumption per unit of output for select industrial sub-sectors in the Base Case (*solid lines*) and Advanced Technology Case (*dashed lines*). The Stretch Technology Case assumed industry-wide efficiency improvements and is thus not depicted here. Energy consumption per unit of output has only minor differences between the Base and Advanced Technology Cases for most of the industrial sub-sectors. Refining (not shown) and Cement & Lime are exceptions. Note that improvements in only some of the industrial sub-sectors were represented in the Advanced Technology and Stretch Technology analyses, and of those sub-sectors, only improved energy efficiency was modeled. Major shifts in industrial processes are not captured in this analysis.

The remainder of this section is a list of the input assumptions for the Advanced Technology and Stretch Technology Cases, as well as how those assumptions were translated for use in EPSA-NEMS. These assumptions were based on information provided by the DOE program offices. Note that these are short descriptions that attempt to summarize as best as possible how DOE program office goals were used in this analysis, but some input assumptions may be missing or oversimplified.

Advanced Technology Assumptions

EERE Bioenergy Technologies Office (BETO): Reductions in biofuel costs for cellulosic ethanol and biofuel liquids processed using Fischer-Tropsch or pyrolysis pathways to achieve goals of $2.65 and $3.00 per gallon with biomass feedstock cost of $84 per ton (BETO biomass cost assumption) ready for commercialization in 2020 and 2025; additional capital cost reductions from learning as more capacity is built after near-term goals are reached. Biomass-to-liquids processing conversion efficiency improved and planned new capacity of 50 million gallons/year of advanced biofuels by 2020 included (BETO goals and sponsored demonstration).

EERE Vehicle Technologies Office (VTO): Changes in vehicle costs and improved fuel economy for all vehicle types, and increase in availability of hybrid, EVs, and fuel cell EVs, leading to a 38% increase in average LDV fuel economy sold in 2040 and a 21% increase in the on-road fleet average (vehicle attributes by type from Argonne National Laboratory Autonomie study[58]) in 2040 relative to the Base Case.

EERE VTO: Modification of heavy duty-vehicle (HDV) types to better represent VTO HDV classifications and changes in HDV costs and projected fuel economy by vehicle class (following BaSCe analysis of VTO program[59]) leading to an average 20% improvement in new HDV fuel economy by 2040 and a 15% improvement in average HDV fuel economy by 2040 relative to the Base Case.

EERE Fuel Cell Technologies Office (FCTO): Short- and long-term cost reductions for the retail price of hydrogen, $7/kg-$H_2$ ramping down to $4/kg-$H_2$ by 2020 and held constant thereafter. For the fuel cell EVs, costs and fuel economies from the Argonne National Laboratory Autonomie outputs.[60]

EERE Building Technologies Office (BTO) (including the Federal Energy Management Program [FEMP] and Weatherization and Intergovernmental Programs Office [WIP]): For residential and commercial buildings, increased stringency of appliance standards and building codes, improved new building shell technology performance, introduced new cost effective energy efficient technologies, increased rate of building shell upgrades, and increased consumer acceptance of high efficiency products (represented by lowering hurdle rates to 7% by 2025 and removal of non-economic decision-making factors) leading to achievement of the BTO goal of reducing energy use per square foot in all U.S. buildings by 30% in 2030 from 2010 levels, with a longer term goal of achieving a 50% reduction.

EERE Advanced Manufacturing Office (AMO): AEO industrial high tech assumptions (earlier availability, lower costs, and higher efficiency industrial equipment and a more rapid rate of improvement in the recovery of biomass byproducts from industrial processes) combined with technology improvements, which yields more efficient energy use for pulp and paper, iron and steel, petroleum refining, chemicals, and cement (2007 and 2015 AMO Bandwidth studies[61]), and updated data on the use of recycled aluminum (2006–2014 U.S. Geological Survey Minerals Yearbook[v]).

[v] You can find the *Minerals Yearbook: Aluminum* for past years on the U.S. Geological Survey website: http://minerals.usgs.gov/minerals/pubs/commodity/aluminum/index.html#myb.

DOE Office of Fossil Energy (FE): Improvements to capital cost trajectories, heat rates, and fixed and variable operating and maintenance (O&M) costs for new full capture coal and NGCC CCUS plants, partial capture coal CCUS plants, and existing coal units that are retrofitted with CCUS (see Appendix C for LCOEs).

DOE Office of Nuclear Energy (NE): 9% reduction in projected overnight capital costs for state-of-the art nuclear technology in 2025 and 32% by 2040 relative to the Base Case. O&M costs reduced by approximately 9% and new nuclear plant build times reduced from 6 to 5 years. Assumes existing nuclear plants will receive license extensions to operate for 80 years, with no required early retirements. Note that recently announced retirements of nuclear generating units were not included in this analysis.

DOE Office of Electricity Delivery and Energy Reliability (OE) and Grid Modernization: Share of new transmission capacity applied to reserves increased from 75% to 85%, reflecting improved sensors and controls and enhanced regional coordination. Available capacity on existing transmission lines was increased from 75% to 85%. Spinning reserve requirements for variable renewables embedded as a model constraint in EPSA-NEMS decreased from 50% to 30% of generation, reflecting more use of energy storage and other demand side capabilities. Maximum use of load shifting technologies for reducing peak demand tripled from a national average of 3.5% to 11% by 2040, reflecting greater use of distributed energy resources and storage technologies. Improvement in utility grid interconnection limitation factors for new distributed generation in buildings was accelerated by 10 years.

EERE Solar: Cost reductions for utility-scale, commercial, and residential PV following the 2016 NREL Annual Technology Baseline (ATB) Low Case. Solar thermal/concentrated solar power was modified to reflect a technology with 6-hours of electricity storage, leading to improved capacity factors and capital costs that are higher in the near term than the Base Case assumptions. By 2040, capital costs are projected to be 22% below the Base Case and O&M costs are 41% below the Base Case.

EERE Wind:[w] For land-based and offshore wind power, capital costs were reduced from the Base by 20% and 32%, respectively, by 2020, and reduced by 19% and 44%, respectively, by 2040 for the best wind classes, with more modest reductions for lower wind classes based on the draft 2016 ATB Low Case.[62] Capacity factors were also improved, ranging from roughly a 13% to 28% increase for land-based wind by 2020 and a 24% to 44% increase by 2040, and a 15% to 19% increase for offshore wind by 2020 and a 28% to 34% increase by 2040 compared to the Base Case. Also lengthened the land-based wind production tax credit eligibility schedule by 1 year and increased the construction time from 3 to 4 years based on new Internal Revenue Service guidance.

EERE Hydropower: Improved the site-specific costs, performance and resource availability for some hydropower sites, including adding upgrade options for existing sites.

EERE Geothermal: Reduced site-specific costs for geothermal flash, binary, and enhanced geothermal sites by 12.5% by 2040 compared to current costs, following the Draft 2016 NREL ATB.[63]

[w] The ATB Low Case does not capture all of the projected cost reductions anticipated in the current Wind Program Goals.

Stretch Technology Assumptions

EERE BETO: Decreased cost of advanced biofuels (biomass-to-liquids and pyrolysis) from $3/gallon in the Advanced Technology assumptions to $2.50/gallon by 2040 (at $84/ton biomass). Increased number of initial biofuel plants from 3 to 30 before EPSA-NEMS growth limits start to apply. Same new planned capacity as for Advanced Technology assumptions included for Stretch Technology assumptions.

EERE VTO, LDVs: Modified vehicle choice model to allow all types of LDVs to compete on vehicle attributes only. Advanced Technology cost assumptions plus an additional 4% weight reduction due to vehicle light-weighting by reducing fuel consumption by 6% (conventional/hybrid) or 4% (EVs) for every 10% decrease in vehicle weight. Reduced the cost of energy storage for PHEVs and BEVs to $100/kilowatt-hour (kWh) by 2030, compared to $120/kWh in the Advanced Technology assumptions.

EERE VTO, HDVs: Advanced Technology cost assumptions plus increased maximum market penetration rate for hybrids and advanced conventional vehicles (following Super Truck definition); accelerated adoption of advanced conventional and hybrid vehicles by modifying S-shape diffusion curve 50% parameter from 14 to 10 years.

EERE FCTO: Reduced the modeled commercial scale cost of automotive fuel cells to $35/kilowatt (kW) by 2030, and $30/kW by 2040. Reduced the cost of hydrogen (dispensed and untaxed) to $4.00/gge[x] in 2020, to $3.00 in 2030 and to $2.50 in 2040 (on the path towards $2.00 in 2050). Assumed all hydrogen was produced from renewable sources and had no GHG emissions associated with production.

EERE BTO (including FEMP and WIP), Residential Buildings: Advanced technology assumptions with the following changes: Reduced energy consumption by 40% from 2009 to 2030 for MELs; removed the option for building shell packages that achieve less than 50% energy reduction from International Energy Conservation Code 2009 levels from 2030 onwards.

EERE BTO (including FEMP and WIP), Commercial Buildings: Advanced technology assumptions with the following changes: (for MELs other than office equipment), flat energy use intensity after 2010. Modified new building shells to represent 100% adoption of a 50% reduction relative to the ASHRAE 90.1-2007 standards, which is equivalent to a 29% improvement from the Base Case.

EERE Geothermal: Increased efficiency for the least efficient geothermal heat pumps for use in residential and commercial buildings.

EERE AMO: For all of the non-refining manufacturing processes except cement and lime, aluminum, and glass, improved process efficiency by 50% beyond the Base Case by 2040. Improved industrial motor-driven system efficiency for pumps, fans, and air compressors following AEO 2014 Low Electricity Demand[64] case. Net result is an approximately 20% reduction in non-refining industrial energy consumption by 2040 relative to the Base Case.

FE: Improvements in capital costs, O&M costs, and heat rates for CCUS technologies are accelerated in the Stretch Technology assumptions, reaching the same long-term goals as the Advanced Technology assumptions 8 years earlier (by 2030).

[x] Gallon gasoline equivalent

NE: 14% reduction in projected overnight capital costs for state-of-the art nuclear technology in 2025 and 30% by 2040 relative to the Advanced Technology assumptions (22% in 2025 and 53% from the Base Case). O&M costs reduced by 28% from Advanced Technology assumptions and new nuclear plant build times reduced from 5 years to 4 years.

OE and Grid Modernization: Advanced Technology assumptions plus increased maximum percentage of regional variable generation from 40% to 50%, enabled by grid advances.

EERE Solar:[y] Similar overnight capital cost trajectories for utility solar PV as for Advanced Technology assumptions with no change in 2020 and 2025, but ramping down to a 13% reduction from the Advanced Technology assumptions and 52% improvement in O&M costs by 2040. For CSP, approximately a 35% reduction in overnight capital costs from the Advanced Technology assumptions in 2020 and then approximately a 6% cost reduction compared to the Advanced Technology assumptions out to 2040. A 14% reduction in O&M costs for CSP from Advanced Technology assumptions. Reduced capital and O&M costs for rooftop solar PV in residential and commercial buildings by ~40% for capital and ~60% for O&M by 2040 compared to the Advanced Technology assumptions, and reduced degradation in PV panels.

EERE Wind: Same capacity factors, construction time, and similar fixed O&M costs as for the Advanced Technology assumptions. Includes 25% lower overnight capital costs in 2025, and 55% lower overnight capital costs from 2030 onwards for onshore wind as compared to Advanced Technology assumptions. For offshore wind, 14% lower overnight capital costs in 2025 and ~50% lower overnight capital costs from 2030 onwards as compared to Advanced Technology assumptions.

EERE Hydropower: Advanced Technology assumptions plus further reduced overnight capital costs for new stream reach development and non-powered dams by an additional 42% and 51%, respectively, beyond the Advanced Technology costs by 2040.

EERE Geothermal: Added undiscovered hydrothermal and deep Enhanced Geothermal System sites and reduced initial costs for existing sites by 40% relative to the Base Case; by 2040, overnight capital costs are further reduced by 35%.

[y] The Solar Energy Technologies Office has updated its technology cost and performance goals since this analysis was performed. The newly updated goal—to cut the LCOE from utility-scale solar by an additional 50% between 2020 and 2030 to $0.03 per kWh, while also addressing grid integration. Challenges and addressing key market barriers in order to enable greater solar adoption can be found at http://energy.gov/eere/sunshot/downloads/sunshot-initiative-2030-goals-paper-and-graphics.

ENDNOTES

[1] Intergovernmental Panel on Climate Change (IPCC), *Fifth Assessment Report* (IPCC, 2014), https://ipcc.ch/report/ar5/.

[2] Jerry M. Melillo, Terese Richmond, and Gary W. Yohe, eds., C*limate Change Impacts in the United States: The Third National Climate Assessment* (Washington, DC: U.S. National Climate Assessment, U.S. Global Change Research Program, 2014), http://nca2014.globalchange.gov/.

[3] U.S. Environmental Protection Agency (EPA), *U.S. Greenhouse Gas Inventory Report: 1990–2014* (Washington, DC: EPA, April 2016), https://www.epa.gov/ghgemissions/us-greenhouse-gas-inventory-report-1990-2014.

[4] "The Paris Agreement," United Nations Framework Convention on Climate Change, accessed December 21, 2016, http://unfccc.int/paris_agreement/items/9485.php.

[5] National Academies of Sciences, Engineering, and Medicine, *The Power of Change: Innovation for Development and Deployment of Increasingly Clean Electric Power Technologies* (Washington, DC: The National Academies Press, 2016), doi:10.17226/21712.

[6] U.S. Department of Energy (DOE), Office of Energy Policy and Systems Analysis, *Quadrennial Energy Review First Installment: Energy Transmission, Storage, And Distribution Infrastructure* (Washington, DC: DOE-EPSA, April 2015), https://energy.gov/epsa/downloads/quadrennial-energy-review-first-installment.

[7] National Research Council, *Energy Research at DOE: Was It Worth It? Energy Efficiency and Fossil Energy Research 1978 to 2000* (Washington, DC: The National Academies Press, 2001), https://www.nap.edu/read/10165/chapter/1.

[8] National Research Council, *Review of DOE's Nuclear Energy Research and Development Program* (Washington, DC: The National Academies Press, 2008), doi:10.17226/11998.

[9] National Academies of Sciences, Engineering, and Medicine, *The Power of Change: Innovation for Development and Deployment of Increasingly Clean Electric Power Technologies* (Washington, DC: The National Academies Press, 2016), doi:10.17226/21712.

[10] "Program Evaluation: EERE Planned and Completed Evaluations," U.S. Department of Energy, accessed December 21, 2016, http://energy.gov/eere/analysis/program-evaluation-eere-planned-and-completed-evaluations.

[11] "EERE Success Stories," U.S. Department of Energy, accessed December 20, 2016, https://energy.gov/eere/success-stories/eere-success-stories.

[12] "Mission Innovation at DOE," U.S. Department of Energy, accessed December 20, 2016, https://energy.gov/mission-innovation/mission-innovation-doe.

[13] *Mission Innovation: Accelerating the Clean Energy Revolution,* accessed December 20, 2016, www.mission-innovation.net.

[14] *Mission Innovation: Accelerating the Clean Energy Revolution,* accessed November 17, 2016, www.mission-innovation.net.

[15] "Table 12.1. Carbon Dioxide Emissions from Energy Consumption by Source," Energy Information Administration, *Monthly Energy Review*, December 2016, http://www.eia.gov/totalenergy/data/monthly/pdf/sec12_3.pdf.

[16] The White House, *United States Mid-Century Strategy for Deep Decarbonization* (Washington, DC: The White House, November 2016), https://www.whitehouse.gov/sites/default/files/docs/mid_century_strategy_report-final.pdf.

[17] James H. Williams, Benjamin Haley, Fredrich Kahrl, Jack Moore, Andrew D. Jones, Margaret S. Torn, Haewon McJeon, et al., *Pathways to Deep Decarbonization in the United States* (San Francisco, CA: Energy and Environmental Economics, 2014) http://deepdecarbonization.org/countries/#united-states.

[18] L. Diaz Anadon, M. Bunn, and V. Narayanamurti, eds., *Transforming US Energy Innovation* (Cambridge University Press, 2014), https://www.cambridge.org/core/books/transforming-us-energy-innovation/63F72CD59AD2EF2CCE241DF6A92FC3CF.

[19] U.S. Department of Energy (DOE), *Monthly Energy Review* (Washington, DC: DOE, October 2016), Tables 12.1–12.7, www.eia.gov/totalenergy/data/monthly/#environment.

[20] "Annual Energy Outlook 2016 Early Release: Annotated Summary of Two Cases," U.S. Energy Information Administration, May 17, 2016, Slide 24, http://www.eia.gov/forecasts/aeo/er/pdf/0383er(2016).pdf.

[21] U.S. Energy Information Administration (EIA), *U.S. Energy-Related Carbon Dioxide Emissions, 2014* (Washington, DC: EIA, November 2015), Figure 12, http://www.eia.gov/environment/emissions/carbon/.

[22] Tim Shear, "Scheduled 2015 Capacity Additions Mostly Wind and Natural Gas; Retirements Mostly Coal," U.S. Energy Information Administration, *Today in Energy,* March 10, 2015, www.eia.gov/todayinenergy/detail.cfm?id=20292.

[23] U.S. Department of Energy (DOE), *Monthly Energy Review* (Washington, DC: DOE, October 2016), Tables 12.1–12.7, www.eia.gov/totalenergy/data/monthly/#environment.

[24] U.S. Environmental Protection Agency, "By the Numbers: Cutting Carbon Pollution from Power Plants," Clean Power Plan Fact Sheet, accessed April 22, 2016, https://www.epa.gov/sites/production/files/2015-08/documents/fs-cpp-by-the-numbers.pdf.

[25] U.S. Department of Energy (DOE), *Monthly Energy Review* (Washington, DC: DOE, October 2016), Tables 12.1–12.7, www.eia.gov/totalenergy/data/monthly/#environment.

[26] Trieu Mai, Wesley Cole, Eric Lantz, Cara Marcy, and Benjamin Sigri, *Impacts of Federal Tax Credit Extensions on Renewable Deployment and Power Sector Emissions* (Golden, CO: National Renewable Energy Laboratory, February 2016), NREL/TP-6A20-65571, http://www.nrel.gov/docs/fy16osti/65571.pdf.

[27] *Mission Innovation: Accelerating the Clean Energy Revolution,* accessed November 17, 2016, www.mission-innovation.net.

[28] U.S. Energy Information Administration (EIA), *Cost and Performance Characteristics of New Generating Technologies, Annual Energy Outlook 2016* (Washington, DC: EIA, June 2016), http://www.eia.gov/outlooks/aeo/assumptions/pdf/table_8.2.pdf.

[29] Documentation found in Energy Information Administration (EIA), *Annual Energy Outlook 2015: With Projections to 2040* (Washington, DC: EIA, April 2015), table 1, http://www.eia.gov/forecasts/aeo/pdf/0383%282015%29.pdf.

[30] Government Performance and Results Act of 1993, Pub. L. No. 103-62 § 2.a.2, 2.b.3, 2.b.4 (1993).

[31] National Research Council, *Energy Research at DOE: Was It Worth It? Energy Efficiency and Fossil Energy Research 1978 to 2000* (Washington, DC: The National Academies Press, 2001), 48, https://www.nap.edu/read/10165/chapter/1.

[32] U.S. Department of Energy (DOE), *Report of the External Expert Peer Review Panel: DOE Benefits Forecasts* (Washington, DC: DOE, December 2006), 2, https://energy.gov/sites/prod/files/2015/05/f22/report_expert_peer_review_panel.pdf.

[33] Memorandum from Peter R. Orszag to the Heads of Executive Departments and Agencies, "Increased Emphasis on Program Evaluations," (Washington, DC: Executive Office of the President, Office of Management and Budget, October 7, 2009), M-10-01, 1, https://www.whitehouse.gov/sites/default/files/omb/assets/memoranda_2010/m10-01.pdf.

[34] Memorandum from Silvia M. Burwell, Cecilia Muñoz, John Holdren, and Alan Krueger to the Heads of Executive Departments and Agencies, "Next Steps in the Evidence and Innovation Agenda" (Washington, DC: Executive Office of the President, Office of Management and Budget, July 26, 2013), M-13-17, 2, https://www.whitehouse.gov/sites/default/files/omb/memoranda/2013/m-13-17.pdf.

[35] U.S. Energy Information Administration (EIA), *Assumptions to the Annual Energy Outlook 2016* (Washington, DC: EIA, December 2016), http://www.eia.gov/outlooks/aeo/assumptions/.

[36] Documentation found in Energy Information Administration (EIA), *Annual Energy Outlook 2015: With Projections to 2040* (Washington, DC: EIA, April 2015), table 1, http://www.eia.gov/forecasts/aeo/pdf/0383%282015%29.pdf.

[37] The Federal renewable tax credits were extended in the Consolidated Appropriations Act of 2016, which is available at https://www.congress.gov/114/bills/hr2029/BILLS-114hr2029enr.xml. Summaries of the current federal production and investment tax credits can be found at http://programs.dsireusa.org/system/program/detail/734 and http://programs.dsireusa.org/system/program/detail/658, respectively.

[38] Cost and performance characteristics are based on the National Energy Technology Laboratory (NETL) Baseline Studies (new units with CCS), which can be found at https://www.netl.doe.gov/research/energy-analysis/baseline-studies; as well as the NETL Quality Guidelines for Energy System Studies (retrofit of existing units with CCS), which can be found at http://www.netl.doe.gov/energy-analyses/temp/QGESSRetrofitDifficultyFactors_083013.pdf and http://www.netl.doe.gov/energy-analyses/temp/QGESSCapitalCostScalingMethodology_013113.pdf.

[39] "Table 12.1 Carbon Dioxide Emissions from Energy Consumption by Source," U.S. Energy Information Administration, *Monthly Energy Review,* November 2016, http://www.eia.gov/totalenergy/data/monthly/pdf/sec12_3.pdf.

[40] "Table 1-26: Average Age of Automobiles and Trucks in Operation in the United States," U.S. Department of Transportation, Bureau of Transportation Statistics, July 2016, accessed December 20, 2016, http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/html/table_01_26.html.

[41] David Green, *Why the Market for New Passenger Cars Generally Undervalues Fuel Economy* (Paris, France: OECD Joint Transport Research Centre, January 2010), 6, http://www.oecd-ilibrary.org/transport/why-the-new-market-for-new-passenger-cars-generally-undervalues-fuel-economy_5kmjp68qtm6f-en.

[42] Congressional Budget Office, *Effects of a Carbon Tax on the Economy and Environment* (Washington, DC: Congressional Budget Office, May 2013), 4, https://www.cbo.gov/publication/44223.

[43] A. A. Fawcett, L. E. Clarke, S. Rausch, and J. P. Weyant, "Overview of EMF 24 Policy Scenarios," *The Energy Journal* 35 (2014), http://dx.doi.org/10.5547/01956574.35.SI1.3.

[44] L. Clarke, K. Jiang, K. Akimoto, M. Babiker, G. Blanford, K. Fisher-Vanden, J.-C. Hourcade, V. Krey, E. Kriegler, A. Loschel, D. McCollum, S. Paltsev, S. Rose, P. R. Shukla, M. Tavoni, B. C. C. van der Zwaan, and D. P. van Vuuren, "Assessing Transformation Pathways," in: O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlomer, C. von Stechow, T. Zwickel, and J.C. Mix (eds), *Climate Change: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 2014).

[45] U.S. Department of Energy (DOE), *Carbon Capture, Utilization, and Storage: Climate Change, Economic Competitiveness, and Energy Security* (Washington, DC: DOE, 2015), http://energy.gov/fe/downloads/doe-white-paper-carbon-capture-utilization-and-storage.

[46] A. A. Fawcett, L. E. Clarke, and J. P. Weyant, "The EMF24 Study on U.S. Technology and Climate Policy Strategies," *The Energy Journal* 35 (2014), http://dx.doi.org/10.5547/01956574.35.SI1.7.

[47] James H. Williams, Benjamin Haley, Fredrich Kahrl, Jack Moore, Andrew D. Jones, Margaret S. Torn, Haewon McJeon, et al., *Pathways to Deep Decarbonization in the United States* (San Francisco, CA: Energy and Environmental Economics, 2014), http://deepdecarbonization.org/countries/#united-states.

[48] U.S. Department of Energy (DOE), *Carbon Capture, Utilization, and Storage: Climate Change, Economic Competitiveness, and Energy Security* (Washington, DC: DOE, 2015), http://energy.gov/fe/downloads/doe-white-paper-carbon-capture-utilization-and-storage.

[49] A. A. Fawcett, L. E. Clarke, and J. P. Weyant, "The EMF24 Study on U.S. Technology and Climate Policy Strategies," *The Energy Journal* 35 (2014), http://dx.doi.org/10.5547/01956574.35.SI1.7.

[50] James H. Williams, Benjamin Haley, Fredrich Kahrl, Jack Moore, Andrew D. Jones, Margaret S. Torn, Haewon McJeon, et al., *Pathways to Deep Decarbonization in the United States* (San Francisco, CA: Energy and Environmental Economics, 2014), http://deepdecarbonization.org/countries/#united-states.

[51] U.S. Department of Energy (DOE), *Carbon Capture, Utilization, and Storage: Climate Change, Economic Competitiveness, and Energy Security* (Washington, DC: DOE, 2015), http://energy.gov/fe/downloads/doe-white-paper-carbon-capture-utilization-and-storage.

[52] J. Bradbury, Z. Clement, and A. Down, *Greenhouse Gas Emissions and Fuel Use within the Natural Gas Supply Chain – Sankey Diagram Methodology* (Washington, DC: U.S. Department of Energy, Office of Energy Policy and Systems Analysis, 2015), https://energy.gov/sites/prod/files/2015/07/f24/QER%20Analysis%20-%20Fuel%20Use%20and%20GHG%20Emissions%20from%20the%20Natural%20Gas%20System%2C%20Sankey%20Diagram%20Methodology_0.pdf

[53] H. McJeon, J. Edmonds, N. Bauer, L. E. Clarke, B. Fischer, B. P. Flannery, J. Hilaire, V. Krey, G. Marangoni, R. Mi, K. Riahi, H. Rogner, and M. Tavoni, "Limited impact on decadal-scale climate change from increased use of natural gas," *Nature* 514 (2014), doi:10.1038/nature13837.

[54] The White House, *United States Mid-Century Strategy for Deep Decarbonization* (Washington, DC: The White House, November 2016), https://www.whitehouse.gov/sites/default/files/docs/mid_century_strategy_report-final.pdf.

[55] James H. Williams, Benjamin Haley, Fredrich Kahrl, Jack Moore, Andrew D. Jones, Margaret S. Torn, Haewon McJeon, et al., *Pathways to Deep Decarbonization in the United States* (San Francisco, CA: Energy and Environmental Economics, 2014), http://deepdecarbonization.org/countries/#united-states.

[56] L. Diaz Anadon, M. Bunn, and V. Narayanamurti, eds., *Transforming US Energy Innovation* (Cambridge University Press, 2014), https://www.cambridge.org/core/books/transforming-us-energy-innovation/63F72CD59AD2EF2CCE241DF6A92FC3CF.

[57] "Levelized Cost and Levelized Avoided Cost of New Generation Resources in the *Annual Energy Outlook 2016*," U.S. Energy Information Administration, August 2016, 2–3, http://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf.

[58] Argonne National Laboratory (ANL), *Assessment of Vehicle Sizing, Energy Consumption, and Cost through Large-Scale Simulation of Advanced Vehicle Technologies* (Argonne, IL: ANL, 2016), http://www.ipd.anl.gov/anlpubs/2016/04/126422.pdf.

[59] Argonne National Laboratory (ANL), *Vehicle Technologies and Fuel Cell Technologies Program: Prospective Benefits Assessment Report for Fiscal Year 2016* (Argonne, IL: ANL, 2016), https://www.anl.gov/energy-systems/publication/vehicle-technologies-and-fuel-cell-technologies-program-prospective.

[60] Argonne National Laboratory (ANL), *Assessment of Vehicle Sizing, Energy Consumption, and Cost through Large-Scale Simulation of Advanced Vehicle Technologies* (Argonne, IL: ANL, 2016), http://www.ipd.anl.gov/anlpubs/2016/04/126422.pdf.

[61] U.S. Department of Energy (DOE), *Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Chemical Manufacturing* (Washington, DC: DOE, June 2015), http://energy.gov/eere/amo/downloads/bandwidth-study-us-chemical-manufacturing; DOE, *Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Iron and Steel Manufacturing* (Washington, DC: DOE, June 2015), http://energy.gov/eere/amo/downloads/bandwidth-study-us-iron-and-steel-manufacturing; DOE, *Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Petroleum Refining* (Washington, DC: DOE, June 2015), http://energy.gov/eere/amo/downloads/bandwidth-study-us-petroleum-refining; DOE, *Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Pulp and Paper Manufacturing* (Washington, DC: DOE, June 2015), http://energy.gov/eere/amo/downloads/bandwidth-study-us-pulp-and-paper-manufacturing; DOE, *Mining Industry Energy Bandwidth Study* (Washington, DC: DOE, June 2007), http://www.energy.gov/eere/amo/downloads/us-mining-industry-energy-bandwidth-study.

[62] "Annual Technology Baseline and Standard Scenarios," National Renewable Energy Laboratory, last updated November 16, 2016, http://www.nrel.gov/analysis/data_tech_baseline.html.

[63] "Annual Technology Baseline and Standard Scenarios," National Renewable Energy Laboratory, last updated November 16, 2016, http://www.nrel.gov/analysis/data_tech_baseline.html.

[64] U.S. Energy Information Administration (EIA), *Annual Energy Outlook 2014* (Washington, DC: EIA, 2014), http://www.eia.gov/forecasts/archive/aeo14/.