EXPERT REPORT
OF
JAMES H. WILLIAMS, Ph.D.

Associate Professor, University of San Francisco
Director of Deep Decarbonization Pathways Project

Kelsey Cascadia Rose Juliana; Xiuhtezcatl Tonatiuh M.,
through his Guardian Tamara Roske-Martinez; et al.,
Plaintiffs,

v.

The United States of America; Donald Trump,
in his official capacity as President of the United States; et al.,
Defendants.

IN THE UNITED STATES DISTRICT COURT
DISTRICT OF OREGON

(Case No.: 6:15-cv-01517-TC)

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TABLE OF ACRONYMS AND ABBREVIATIONS

80 x 50:	80% reduction in greenhouse gas emissions by 2050
BAU:	business as usual
BEV:	battery electric vehicle
C:	Celsius
CCS:	carbon capture and storage
CH_4:	methane
CO_2:	carbon dioxide
CO_2e:	carbon dioxide equivalent
DDP-LAC:	Deep Decarbonization Pathways for Latin America and the Caribbean
DDPP:	Deep Decarbonization Pathways Project
Decarbonization:	deep reductions in greenhouse gas emissions from a system
EIA:	Energy Information Agency
FCV:	hydrogen fuel cell vehicle
GDP:	gross domestic product
GHG:	greenhouse gas
ICE:	internal combustion engine
IDDRI:	Institute for Sustainable Development and International Relations
IPPC:	Intergovernmental Panel on Climate Change
NEMS:	National Energy Modeling System
ppm:	parts per million
PV:	photovoltaic – a type of solar electric generating technology
SDSN:	Sustainable Development Solutions Network

INTRODUCTION

I, James H. Williams, have been retained by the Plaintiffs to provide expert testimony regarding the feasible pathways to achieve deep decarbonization of the U.S. energy system in line with best available science for stabilizing the climate system, and the policies that could be used to achieve this outcome. In this report, I examine how the federal government, including the agencies listed as Defendants in this case, can transform the U.S. energy system from one powered by fossil fuels to one powered by renewable energy and other low carbon forms of energy, if it plans for, and implements policies to achieve, that objective.

This expert report contains my opinions, conclusions, and the reasons for them. A copy of my full CV is attached as **Exhibit A**. A current and complete copy of a list of publications I authored or co-authored within the last ten years is attached as **Exhibit B**. In preparing this expert report, I have reviewed a number of documents. My expert report contains a list of citations to the documents that I have used or considered in forming my opinions, listed in **Exhibit C**.

In preparing my expert report and testifying at trial, I am deferring my expert witness fees to be charged to the Plaintiffs given the financial circumstances of these young Plaintiffs. If a party seeks discovery under Federal Rule 26(b), I will charge my reasonable fee of $300 per hour for the time spent in addressing that party’s discovery. I have not provided previous testimony within the preceding four years as an expert at trial or by deposition.

The opinions expressed in this expert report are my own and are based on the data and facts available to me at the time of writing, as well as based upon my own professional experience and expertise. All opinions expressed in it are to a reasonable degree of scientific certainty, unless otherwise specifically stated. Should additional relevant or pertinent information become available, I reserve the right to supplement the discussion and findings in this expert report in this action.

QUALIFICATIONS

I, James H. Williams, currently serve as Associate Professor in the graduate program in Energy Systems Management at the University of San Francisco. I also serve as Director of the Deep Decarbonization Pathways Project (DDPP) for the Sustainable Development Solutions Network (SDSN). The DDPP is an international consortium of research teams that was convened at the request of the United Nations Secretary General and is led by the SDSN and the Institute for Sustainable Development and International Relations (IDDRI). I also consult with Evolved Energy Research on energy planning.

I received my B.S. in Physics from Washington and Lee University, and my M.S. and Ph.D. in Energy and Resources from U.C. Berkeley. I have spent the past three decades studying various aspects of energy planning, energy technology applications, and energy policy and regulation, most recently as Chief Scientist at the San Francisco consulting firm Energy and Environmental Economics, Inc. (E3).

I was the Principal Investigator for two studies, *Pathways to Deep Decarbonization in the United States* (2014) and *Policy Implications of Deep Decarbonization in the United States* (2015), funded by the Earth Institute at Columbia University. As the Principal Investigator, I led a research team from E3, Lawrence Berkeley National Laboratory, and Pacific Northwest National Laboratory in the preparation of these studies.

In 2007, I led an analysis for the State of California on greenhouse gas (GHG) emission reduction strategies, which became a key input into implementation of Assembly Bill 32, the State's main law governing mitigation of climate change. I was lead author of a 2012 article in the journal *Science* that analyzed California's options for reducing GHGs 80% below 1990 levels by 2050, the target set by AB 32. In 2017, I was a contributing author of a study commissioned by the State of Washington Governor's office on options for reducing GHGs 80% below 1990 levels in that state by 2050.

As a scientist who also has a background in Asian studies, I previously served as Associate Professor of International Environmental Policy at the Middlebury Institute of International Studies, where my research addressed the technical and institutional challenges of reducing carbon emissions from China's power sector.

I have worked with numerous international forums and research teams. For example, I am the lead author of a 2018 technical report on expanding the coordination of deep decarbonization activities between the northeastern states of the U.S. and the Canadian province of Quebec. I am a technical advisor to the Inter-American Development Bank on their Deep Decarbonization Pathways for Latin America and the Caribbean (DDP-LAC) project, which expands on the work done by the DDPP under my leadership.

I served as the Program Director for the China-U.S. Climate Change Forum held at U.C. Berkeley in 2006, on the Steering Committee for the Asia Society's *Roadmap for California-China Collaboration on Climate Change* starting in 2013, and the U.S.-China Collaboration on Clean Air Technologies and Policies starting in 2015. I have co-authored several technical journal articles and policy analyses with colleagues at universities and research institutes in China.

Since 2004, I have served on the Board of Advisors of Palangthai, a Thailand-based NGO focused on clean and equitable energy development in southeast Asia. Since 2005, I have served on the Board of Advisors of EcoEquity, a U.S.-based NGO focused on improving international climate equity by producing analyses that highlight equity issues, and by developing practical proposals for equitable climate policies.

I have, in the past or currently, served as an advisor or invited member for numerous energy or climate change-related committees and task forces, including the California's Energy Future Policy Committee of the California Council for Science and Technology, the California Climate Policy Modeling Forum, and the American Geophysical Union Energy Engagement Task Force.

I have served as a reviewer for scholarly publications including *Nature Climate Change, Energy Policy, Environmental Science and Technology*, *Energy, Pacific Affairs, and China Quarterly.*

EXECUTIVE SUMMARY

Federal government policy can transform the U.S. energy system from one powered by fossil fuels to one powered by renewable and other low carbon energy sources, if the federal government takes that path. My past work has already demonstrated that it is technically feasible to develop and implement a plan to achieve an 80% greenhouse gas reduction below 1990 levels by 2050 in the United States. Multiple alternative pathways exist to achieve these reductions using existing commercial or near-commercial technologies; however, to be successful, each pathway requires the leadership of the federal government, including the agencies listed as Defendants in this case, and comprehensive systemic planning as well as periodic interim targets that must be met to achieve the long-term (such as mid-century and beyond) targets. We determined in our studies that reductions can be achieved through high levels of energy efficiency, decarbonization of electric generation, electrification of most end uses, and switching the remaining end uses to lower carbon fuels. The cost of achieving this level of reductions within this timeframe is affordable, estimated to have an incremental cost for supplying and using energy in the U.S. equivalent to 0.8% of a forecast 2050 GDP, with a range of -0.2% to +1.8% of GDP. These incremental costs do not include potential non-energy savings and benefits including, for example, avoided human and infrastructure costs of climate change and air pollution. Our 80 x 50 analysis demonstrated that the changes required to achieve this level of emissions reductions will support the same level of energy services and economic growth as a reference case based on the U.S. Department of Energy's *Annual Energy Outlook*. Starting immediately on the deep decarbonization path would allow infrastructure replacement to follow natural replacement rates, reducing costs and allowing gradual consumer adoption.

The target of 80% reductions below 1990 levels by 2050 is used by many countries. However, climate scientists have shown that this level of reductions is not sufficient to avoid dangerous anthropogenic interference with the climate system over the long term, and the negative impacts on human, ecological, and economic health that would result from that. My research team is therefore currently modeling the requirements to meet a more stringent target in which fossil fuel CO_2 emissions in 2050 are reduced by as much as 96% below current levels, consistent with achieving an atmospheric CO_2 concentration of 350 ppm by 2100. In my expert opinion, based upon our 80 x 50 work and our early modeling results, I believe that this level of reductions is technologically feasible using current and emerging technologies; that it will likely have a higher per-unit cost for the remaining reductions beyond 80% by 2050; that it will likely require some early retirements of fossil fuel infrastructure; and that it could be aided by changes in consumption of energy services and/or rates of consumption growth, but will not diminish basic quality of life and standards of living.

EXPERT OPINION

Scientific evidence makes it increasingly clear that human-caused climate change requires rapid, aggressive mitigation action if humanity is going to avoid the most catastrophic climate change outcomes. Government policy, and the environment it creates for business and individual actions and investments, drives the shape and future of the U.S. energy system. These same influences can move the U.S. energy system decisively away from fossil fuels to an economy powered by renewable and other low carbon energy sources, if the federal government, including the agencies listed as Defendants in this case, takes that path.

I coined the term "deep decarbonization" and have studied it extensively. As the Principal Investigator for the U.S. Deep Decarbonization Pathways Project modeling and scenarios research conducted from 2013 to 2015, I led a team of researchers from Energy and Environmental Economics, Inc., Lawrence Berkeley National Laboratory, and Pacific Northwest National Laboratory. This research was focused on achieving reductions in GHG emissions 80% below 1990 levels by 2050, a target that many governments around the world have adopted.

Based on the lessons from this research, we now know it is entirely possible to rapidly remove greenhouse gas emissions from the U.S. economy while maintaining a healthy economy and modern standard of living. We also know that even deeper emission cuts beyond 80%, which science indicates is necessary to avoid dangerous anthropogenic interference with the climate system, are feasible with greater costs. We also know that there are multiple pathways to achieve deep decarbonization in the U.S., but each of them requires federal government leadership and comprehensive systemic planning as well as periodic interim targets that must be met to achieve the long-term targets (such as mid-century and beyond).

United States Deep Decarbonization Research and Conclusions

The U.S. Deep Decarbonization Pathways Project modeling and scenarios research conducted from 2013 to 2015 demonstrated the feasibility and affordability of rapidly transitioning away from fossil fuels. The research focused on achieving reductions in GHG emissions 80% below 1990 levels by 2050 (referred to hereafter as "80 x 50").

Our research asked the following questions:

a) Is achieving this target technically feasible, given realistic constraints?

b) What changes in physical infrastructure and technology are required?

c) What is the expected cost of these changes?

d) What are the policy and political economy implications of these changes?

We made the following assumptions:

a) Future U.S. population, gross domestic product, and energy service demand are consistent with the U.S. Department of Energy's *Annual Energy Outlook* Reference Case, a transparent, conservative, and well-vetted long-term forecast produced using the U.S. Energy Information Agency's National Energy Modeling System (NEMS).

b) Only commercially-demonstrated or near-commercial technologies are used. Their modeled costs and performance are based on those in the *Annual Energy Outlook* and other conservative and well-vetted public sources, such as studies by the National Academies of Science and Engineering. Changes in forecast technology and fuel prices are addressed through sensitivity analyses.

c) The time required to change the emissions characteristics of the U.S. energy system – sometimes referred to as its technological inertia – is well-represented in the analysis by the rate at which energy-related infrastructure and equipment is retired and replaced by new equipment, using an annual stock-rollover model and following conventional turnover times based on well-vetted public sources. Equipment and infrastructure that is retired before the conventionally accepted end of its economic life is subject to full cost recovery and appears as a cost in the economic modeling.

d) Electricity system operability and reliability is well-represented in the analysis using a regionally-specific hourly dispatch model of the electricity system. All future scenarios contain realistic costs of balancing supply and demand, including in scenarios with high levels of inflexible generation, such as intermittent renewable energy.

e) Environmental limits are adhered to as constraints on low-carbon resources. For example, future use of biomass resources and hydroelectric resources are constrained by transparent and well-vetted analysis conducted by the U.S. Department of Energy and its associated national laboratories. The terrestrial carbon sink on managed lands is held constant at 2012 levels in the Environmental Protection Agency's U.S. GHG inventory (the most recent available at the time of analysis).

f) All emissions reductions are the result of physical measures within the U.S., not "offsets" related to emission reductions in other countries. All emissions reductions involve the replacement of one kind of infrastructure or equipment with a higher-efficiency and/or lower carbon alternative, and this change entails a net cost that includes all conventionally assumed factors such as overnight cost, operating and maintenance cost, and finance cost over the lifetimes of the equipment involved.

Below are the key conclusions of our 80 x 50 study:

a) It is technically feasible to reduce total U.S. GHG emissions (in CO_2e) to 80% below 1990 levels by 2050. This includes reducing energy CO_2 emissions below 750 Mt, which is 84% less than the 1990 level.

b) Incremental changes in energy use and policy will not be sufficient to drive this level of change (and in some cases, may prove counter-productive). Rather, a complete transformation of the energy system is required.

c) Achieving the targets relies on three principal strategies:

(1) *Highly efficient end use of energy in buildings, transportation, and industry.* Energy intensity of GDP (energy consumed per dollar of GDP) must decline by 70% from now to 2050, with final energy use reduced by 20% despite

forecast increases of 40% in population and 166% in GDP. Relative to the reference case, 2050 energy intensity and final energy use are 33% lower.

(2) *Nearly complete decarbonization of electricity, and reduced carbon in other kinds of fuels.* The carbon intensity of electricity must be reduced by at least 97%, from more than 500 g CO_2/kWh today to 15 g CO_2/kWh or less in 2050.

(3) *Electrification where possible and switching to lower-carbon fuels otherwise.* The share of end-use energy coming directly from electricity or fuels produced from electricity, such as hydrogen, must increase from less than 20% in 2010 to over 50% in 2050. Deeply decarbonized electricity and other fuels must displace most direct fossil fuel combustion in the absence of carbon capture and storage.

d) We examined four different scenarios with different technology mixes – referred to as "High Renewable," "High Nuclear," "High Carbon Capture and Storage (CCS)," and "Mixed" –scenarios - that met the 80 x 50 target. This demonstrates that multiple pathways exist to achieve these reductions using existing commercial or near-commercial technologies, and that the results are robust in the absence of any given technology or technologies. Many more scenarios that meet the target are possible.

e) Deep decarbonization requires ongoing replacement of conventional fossil fuel-based energy supply and end use infrastructure and equipment with efficient, low emissions technologies. In all four scenarios, the 80 x 50 target could be achieved through natural replacement at the end of the existing infrastructure's economic life, and early retirement was not required. However, making any new investments in fossil fuel infrastructure *today* risks the creation of stranded assets.

f) The 80 x 50 target was demonstrated to be affordable. In the year 2050, the net energy system cost—the net change in capital, fuel, and operating costs of supplying and using energy — across the four deep decarbonization scenarios has an average median value of $300 billion, equivalent to 0.8% of a forecast 2050 GDP of $40 trillion. Uncertainty analysis shows a range across scenarios of -0.2% to +1.8% of GDP (negative $90 billion to $730 billion).[1]

g) The 80 x 50 reduction targets could be met without requiring changes in people's behaviors or consumption patterns. That means that the physical energy system will need to change but the use of "energy services" in the U.S. economy would not have to in order to meet an 80 x 50 target. Deep decarbonization will profoundly transform the physical energy system of the U.S. On average across the four scenarios, fossil fuel use decreases by two-thirds from today while decarbonized energy supplies expand by a

[1] This represents the interquartile range of a Monte Carlo simulation of key cost parameters, primarily technology costs and fossil fuel prices.

factor of five.[2] However, this can be achieved while supporting all anticipated demand for energy services – for example, current or higher levels of driving, home heating and cooling, and use of appliances.

h) Deep decarbonization would profoundly transform the U.S. energy economy, in terms of what money is spent on and where investment will flow. In contrast to today's system in which more than 80% of energy costs go to fossil fuel purchases, in a deeply decarbonized system more than 80% of energy costs will go to fixed investments in low-carbon infrastructure such as wind generation and electric vehicles. However, the net change in consumer costs for energy services is shown to be relatively small because of savings from avoiding conventional energy costs.

i) Deep decarbonization would have a small net cost relative to U.S. GDP, as increased spending on low-carbon infrastructure and equipment is offset by reduced spending on fossil fuels. In all deep decarbonization scenarios, U.S. energy costs actually decrease as a share of GDP over time, from about 7% in 2015 to about 6% in 2050.

j) While the overall impact on energy costs is modest, the transition to deep decarbonization nonetheless offers significant benefits for the U.S. macro-economy, such as insulation from oil price shocks, even without counting the potential economic benefits of avoiding severe climate change and avoiding the public health costs of fossil fuel-related air pollution.

k) Though not a part of our initial research, a third party conducted an analysis of impacts of the deep decarbonization scenarios we modeled on the U.S. macro-economy in terms of jobs, household income, and GDP (ICF International, 2015). The study found that, compared to business as usual, deep decarbonization scenarios would result in net gains in U.S.-wide employment (1 million more jobs by 2030, up to 2 million more jobs by 2050), gains in GDP (0.6% by 2030, up to 0.9% by 2050), and increased disposable household income ($300 by 2030, up to $600 by 2050).

l) As part of our research, we discovered a number of important policy implications of deep decarbonization in the U.S. Some of the key policy challenges indicated by our analysis include:

- *Sustained transformation*. Deep decarbonization requires the economic intensity of GHG emissions to decrease 8% per year, and per capita emissions to decrease 5.5% per year.[3] These rates of change can be achieved technically and at an

[2] Fossil fuel use is reduced by approximately 80% from today in the high renewables scenario, 70% in the mixed and high nuclear scenarios, and 40% in the high CCS scenario.
[3] For comparison, from 2014 to 2015, economic intensity of energy-related CO_2 emissions fell by 5.2% per year and per capita emissions fell by 3.3% per year. Over the prior decade, the average rate of economic intensity decline was 2.4% per year, and per capita decline was 1.9%

affordable cost, but *require a sustained commitment to infrastructure transformation over decades*. Incremental improvements that do not facilitate complete transformation are likely to result in technology lock-in and emissions dead ends (**Figure 1**). Pathway A, the dotted black line, represents a linear trajectory from 2010 emissions of energy-related CO_2 to the 80 x 50 target level. Pathway B, the dotted red line, represents policies that reduce emissions in the short-term but do not lead to deep decarbonization in the long-term. Some examples of potential dead-ends include a pathway focused solely on energy efficiency in buildings that does not also include end-use electrification; a transition from coal to natural gas power generation without a further transition to zero carbon generation; or improvement in the fuel economy of gasoline internal combustion engine vehicles without widespread deployment of electric or fuel cell light duty vehicles.

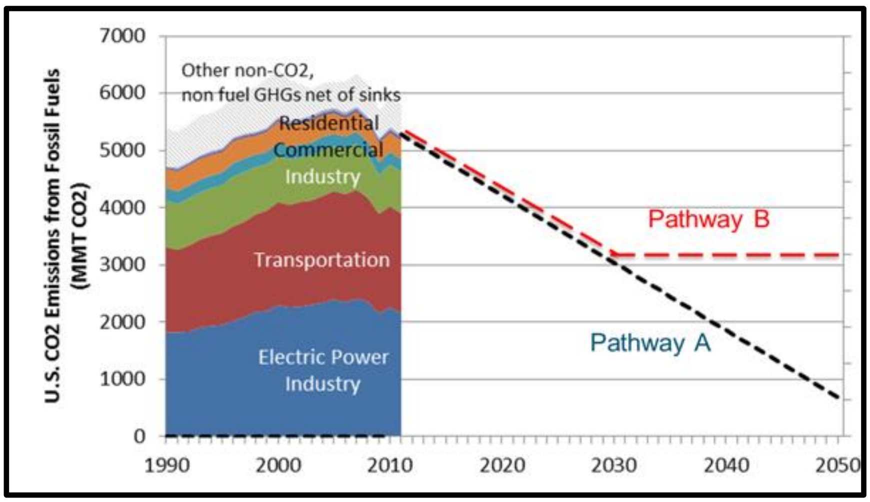

***Figure 1**: Illustrative Deep Decarbonization 80 x 50 Trajectory (Pathway A) and "Dead End" Trajectory (Pathway B).*

A sustained transformation requires stable policy and a predictable investment environment, and it also requires *planning*. Deferring responsibility to a carbon market, *ad hoc* decisions, and inconsistent incentives are not likely to produce a sustained or sufficiently rapid transition to full decarbonization.

- *Timely replacement*. 80 x 50 could be achieved in the U.S. without retiring existing equipment before the end of its economic lifetime, defined as the time required to recoup initial capital investment including financing costs.[4] However,

per year. See EIA, *US Energy-Related Carbon Dioxide Emissions 2015*, available at https://www.eia.gov/environment/emissions/carbon/.

[4] While this indicates that it is possible to deeply decarbonize the economy without creating the problem of stranded investments, the question of what to do with fully depreciated coal plants

because these lifetimes are long, there is only one natural replacement cycle before mid-century for some of the most important infrastructure, such as electric power plants, buildings, and industrial boilers. Failure to replace retiring infrastructure with efficient and low-carbon successors would lead either to failure to meet emissions goals or to potentially costly early retirement of the replacement equipment.

- *Cross-sector coordination*. As deep decarbonization proceeds, interactions between mitigation measures in different sectors (for example, electricity and transportation) become dominant in determining overall emissions. Purely sectoral policies that do not recognize the importance of these interactions will produce sub-optimal outcomes, yet there is currently little institutional coordination across sectors. Anticipatory development of shared institutional structures, both market and regulatory, will be required for efficient coordination of operations, planning, investment, and research.

- *Integration of supply- and demand-side planning and procurement*. Related to the cross-sector coordination challenge is the supply-demand side challenge within the electricity sector. Maintaining reliability in an electricity system with high levels of wind and solar, or baseload nuclear, will require corresponding levels of flexible demand, such as EV charging and hydrogen production. Currently these are seen as outside the purview of electricity planning. To build a low-carbon system that matches supply and demand resources at the required spatial and time scales, however, will require integrated planning and procurement well beyond the scope of what is currently thought of as "integrated resource planning."

- *Suitable investment environment*. The annual investment requirement for low carbon and efficient technologies rises from under $100 billion today to over $1 trillion in a span of about 20 years. This is a large increase from the standpoint of energy sector capital investment, *but not from the standpoint of the share of investment in U.S. GDP as a whole*. Financial markets can supply this level of capital *if investment needs are anticipated and a policy framework is constructed that limits risk and ensures adequate returns*.

- *The right kinds of competition*. Competition is potentially an important tool for driving innovation and reducing costs, but poorly informed policies can lead to unproductive competition. An example of this is current policies that have biofuels competing with gasoline; in the long run, this will be a poor use of scarce biomass resources, because gasoline ICE vehicles have preferred substitutes such as BEVs and FCVs, while the biomass will be needed for production of low

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and other highly emitting equipment continuing to operate after their financial lifetimes are complete is a separate policy challenge.

carbon fuels used in applications that are difficult to electrify. Long-term pathways analysis will help policy makers and investors understand what types of competition have value. Federal policy will play an important role in driving market response.

- *High rates of consumer adoption*. Achieving necessary rates of consumer adoption of equipment ranging from heat pumps to alternative vehicles will require a combination of incentives, financing, market strategies, and supporting infrastructure. This requires a high level of public-private cooperation among, for example, government agencies, auto manufacturers, and utilities in rapidly expanding alternative vehicle markets in tandem with the expansion of fueling or charging infrastructure, not unlike the public-private cooperation that originally created the fossil-fuel based energy system and infrastructure supporting ICEs.

- *Cost reductions in key technologies*. Policy makers can drive cost reductions in key technologies by helping to create large markets. High production volumes drive technological learning, efficient manufacturing, and lower prices. This effect is already visible in battery storage and wind and solar PV generation. Large markets can be built through government procurement, technology standards, consumer incentives, coordinated research and demonstration, trade, and long-term policy certainty.

- *Cost increases faced by consumers*. Businesses, utilities, and policy makers have a mutual interest in limiting the level and rate of consumer cost increases during a low-carbon transition. Coordinating energy efficiency improvements with decarbonization of energy supplies limits increases in total consumer bills even if per unit energy prices increase.

- *Distributional effects*. A low-carbon transition policy can also minimize regressive cost impacts. Distributional effects across regions, sectors, and industries are largely a function of technology strategies, which can be tailored to mitigate these effects.

Going Beyond 80% Reductions by 2050

While most analyses of deep decarbonization, including our own, have focused on 80% reductions in greenhouse gas emissions by 2050, recent studies in climate science indicate that even this level of reductions will not be steep enough to prevent dangerous climate impacts. Hansen (2008, 2013, 2017) shows that returning atmospheric CO_2 concentrations to 350 parts per million (ppm) by 2100 will be required to restore the energy balance of the planet and lower the risk of dangerous anthropogenic interference with the climate system. This objective implies reductions in fossil fuel combustion CO_2 emissions as deep as 96% below present by 2050, in addition to enhanced negative emissions. Many other researchers have also proposed steeper reduction trajectories (e.g. Rogelj, 2017) to avoid the worst impacts of climate change. This is the subject of a forthcoming IPCC special report on limiting global warming above preindustrial temperatures to 1.5 degrees Celsius or less.

For these reasons, I, along with my deep decarbonization team and in collaboration with colleagues at Evolved Energy Research, have set out to describe the pathways needed to reach an emissions target consistent with these scientific analyses.

In my expert opinion, deep decarbonization beyond 80% by 2050 is feasible, and we are now undertaking the research and analysis to illustrate the possible technical and policy pathways. Based on my extensive experience with these and other decarbonization analyses, in my expert opinion, meeting a target as deep as 96% below 2018 levels by 2050 for fossil fuel CO_2 emissions:

- Is technologically feasible given current and emerging technologies
- Will require immediate and decisive action to develop and implement a plan to cut emissions in the near term in order to meet the target and not overspend a 350 ppm carbon budget
- Will have a higher unit cost for the remaining reductions beyond 80% by 2050
- Will likely require some early retirements of fossil fuel-based infrastructure and equipment
- Will require an unprecedentedly rapid build out of renewable generation capacity – potentially building out more renewable generation capacity on an annual basis for several years than the U.S. has in operation right now.
- Will require overproduction of renewable electricity generation in many hours due to the variable nature of their output – excess power that can be stored or used in other applications that reduce CO_2
- Will require rapidly minimizing coal-fired power generation in the near term
- May require a temporary expansion of natural gas generation as coal-fired generators are phased out, at the same time that rapid electrification of the transportation and building sectors cause demand for electricity to increase more rapidly than renewables can be deployed
- Will likely require an increasing share of new appliances, heaters, and other electricity-consuming devices to be more flexible in order to be responsive to changes in electricity generation from variable renewable sources
- May require extensive use of autonomous vehicle technology in combination with electric vehicle technology to facilitate the rapid electrification of the transportation sector
- May require the use of technology to capture carbon and store it geologically or biologically, or reuse it in the synthesis of fuels
- Could be aided by changes in consumption of energy services and/or rates of consumption growth, but will not diminish basic quality of life and standards of living

CONCLUSION

My previous work demonstrates that it is technically feasible to achieve an 80% reduction in greenhouse gas emissions below 1990 levels by 2050 in the United States, while maintaining current levels of energy services without requiring any conservation measures, consistent with on the U.S. Department of Energy's *Annual Energy Outlook*. Multiple alternative pathways exist to achieve these reductions using existing commercial or near-commercial technologies. The net cost of changing the way energy is supplied and used to achieve this target is small compared to GDP and to what is currently spent on energy, even without including such benefits as avoided human and infrastructure costs of climate change and air pollution. Starting immediately on the deep decarbonization path would allow infrastructure replacement to follow natural replacement rates, reducing costs and allowing gradual consumer adoption. That is why it is important for the federal government, including the agencies listed as Defendants in this case, to promptly develop and implement a plan to reduce U.S. greenhouse gas emissions.

The target of 80% reductions below 1990 levels by 2050 is used by many countries. However, recent work by climate scientists indicates that this level of reductions is not sufficient to avoid dangerous anthropogenic interference with the climate system over the long term, and the negative impacts on human, ecological, and economic health that would result from that. My research team is therefore currently modeling the requirements to meet a more stringent target in which fossil fuel CO_2 emissions in 2050 are reduced as much as 96% below current levels, consistent with achieving an atmospheric CO_2 concentration of 350 ppm by 2100.

In my expert opinion, I believe that a reduction in national emissions as deep as 96% below present levels is technologically feasible given current and emerging technologies; that it will likely have a higher unit cost for the remaining reductions beyond 80% by 2050; that it will likely require some early retirements of fossil fuel infrastructure; and that it could be aided by changes in the consumption of energy services and/or rates of consumption growth, but will not diminish basic quality of life and standards of living.

Signed this 13th day of April, 2018 in Berkeley, California.

James H. Williams

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James H. Williams

EXHIBIT A: CURRICULUM VITAE

JAMES H. WILLIAMS
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Education

Ph.D. Energy and Resources, University of California, Berkeley, 1994

M.S. Energy and Resources, University of California, Berkeley, 1986

B.S. Physics, Washington & Lee University, Lexington, VA, 1980

Professional Positions

Associate Professor, University of San Francisco, 2017 - present

Director, Deep Decarbonization Pathways Project, New York/Paris, 2015 - present

Chief Scientist, Energy & Environmental Economics, San Francisco, 2005 - 2017

Associate Professor, Monterey Institute of International Studies, 2008-2013

Lecturer, U.C. Berkeley, 2002, 2003, 2006

Project Manager/Senior Associate, Nautilus Institute, 1997-2000

Post-Doctoral Fellow, U.C. Berkeley and Lawrence Berkeley National Laboratory, 1995-97

Graduate Student Research Assistant, Rocky Mountain Biological Laboratory, 1985

Engineer, MOS Analog Group, National Semiconductor Corp., Santa Clara, CA, 1982-84

Oil and Gas Exploration Field Engineer, Schlumberger Well Services, 1981

Peer-Reviewed Journal Articles

Iyer, G., C. Ledna, L. Clarke, J. Edmonds, H. McJeon, P. Kyle, J.H. Williams (2017). Measuring progress from nationally determined contributions to mid-century strategies. *Nature Climate Change*, 7(12), 871. http://dx.doi:10.1038/s41558-017-0005-9

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Selected Invited Presentations

"Introduction to *2050 Pathways: A Handbook*," 2050 Pathways Platform, Building Momentum During Climate Week Conference, New York, September 2017

"Scale Challenges of Deep Decarbonization," Low Emissions Solutions Conference, Columbia University, September 2017

"Introduction to the *2050 Pathways Handbook*," 2050 Pathways Platform Partners Meeting, Pocantico, NY, April 2017

"Global Lessons Learned by the Deep Decarbonization Pathways Project," American Geophysical Union Fall Meeting, San Francisco, December 2016

"Pathways to a Low-Carbon Energy System in the United States," Plenary Lecture, *Ensuring Energy Security Through a Low Carbon Energy Economy*, National Renewable Energy Laboratory, Golden, CA December 2016

"Deep Decarbonization Pathways for Washington State: Final Results" (with Ben Haley and Gabe Kwok), Governor's Office, Olympia, WA, December 2016

"Global Lessons Learned by the Deep Decarbonization Pathways Project," *Mid-Century Strategies for Deep Decarbonization at Continental, National, and Subnational Scales*, Low Emissions Solutions Conference, COP-22, Marrakesh, Morocco, November, 2016

"Pathways to Deep Decarbonization in the United States," panel on *U.S. Climate Regulation, Beyond First Steps*, Earth Now: Earth 2050 Symposium, UCLA Law School, October 2016

"Global Lessons from the Deep Decarbonization Pathways Project," Joint Global Change Research Institute, College Park, MD, October 2016

"Deep Decarbonization Pathways Analysis for Washington State," (with Ben Haley and Gabe Kwok), Governor's Office, Olympia, WA, October 2016

"Pathways to Deep Decarbonization in the United States," (with Ben Haley and Ryan Jones), U.S. EPA, July 2016

"Pathways to Deep Decarbonization in the United States," (with Ryan Jones and Gabe Kwok), Keynote Talk, RE-AMP Annual Meeting, Chicago, June 2016

"Pathways to Deep Decarbonization in the United States," Keynote Talk, Renewables-Nuclear Synergies Workshop, National Renewable Energy Laboratory, June 2016

"Pathways to Deep Decarbonization," Deep Decarbonization Workshop for Signatories of the Under 2 MOU, Clean Energy Ministerial, San Francisco, June 2016

"Pathways to Deep Decarbonization in the United States," (with Margaret Torn and Ryan Jones), U.S. Department of Energy, May 2016

"Global Lessons Learned by the Deep Decarbonization Pathways Project," Major Economies Forum, April 2016

"Pathways to Deep Decarbonization in the United States," (with Ben Haley), Union of Concerned Scientists, February 2016

"Prospecting for a Low Carbon Future," Keynote Talk, Philomathia Forum, Berkeley Energy and Climate Initiative, U.C. Berkeley, February 2016

"Pathways to a Sustainable Energy Future," (with Margaret Torn and Ben Haley), Environmental Defense Fund Climate Committee/Board of Trustees, Sausalito, CA, February 2016

"Deep Decarbonization of the U.S. Energy System by 2050," (with Ben Haley, Ryan Jones, and Margaret Torn), Poster, American Geophysical Union Fall Meeting, San Francisco, December 2015

"Integrating Land Conservation and Renewable Energy Goals in California," (with Grace Wu, Nick Schlag, Dick Cameron, Erica Brand, Laura Crane, Snuller Price, Rebecca Hernandez, and Margaret Torn), Poster, American Geophysical Union Fall Meeting, San Francisco, December 2015

"Policy Implications of Deep Decarbonization in the United States," DDPP-MAPS Technical Workshop, Paris, December 2015

"Challenges for Low Carbon Electricity Systems: Observations from California," EDF Climate and Energy Symposium, Electricite de France, Paris, September 2015

"The Power of the Pathway: Key Results from the DDPP," Deep Decarbonization Pathways Project Media Workshop, Paris, September 2015

"Deep Decarbonization Pathways: Taking 2°C Seriously," Energy and Resources Group Colloquium, U.C. Berkeley, September 2015

"Deep Decarbonization Pathways in CA, US, World: Main Findings and Research Directions," Integrated Energy Policy Report Workshop, California Energy Commission, July 2015

"Pathways to Deep Decarbonization in the United States," Chair's Lecture, California Air Resources Board, Sacramento, May 2015 http://www.arb.ca.gov/research/lectures/speakers/williams/williams.htm

"2030 Greenhouse Gas Reduction Scenarios," (with Amber Mahone, Elaine Hart, Nancy Ryan, Snuller Price, Ben Haley, and Sam Borgeson), California Air Resources Board webinar, April 2015

"Pathways to Deep Decarbonization in the United States," Commonwealth Club, San Francisco, March 2015 http://www.commonwealthclub.org/events/archive/podcast/deep-decarbonization-united-states

"California Pathways: GHG Scenario Results," (with Amber Mahone, Elaine Hart, Nancy Ryan, Snuller Price, Ben Haley, and Sam Borgeson), California Climate Policy Modeling Forum, U.C. Davis, February 2015 https://ethree.com/public_projects/energy_principals_study.php

"The Implications of Deep Reductions in Greenhouse Gas Emissions for Carbon Cycle Science," (with Margaret Torn and Andrew Jones), LBNL, Februry 2015

"Investment Analysis for DDPP Phase 2 Synthesis Report," (with Ben Haley), Deep Decarbonization Pathways Project Country Team Meeting, Paris, France, January 2015

"The Implications of Deep Reductions in Greenhouse Gas Emissions for Carbon Cycle Science," (with Margaret Torn, Andrew Jones, Ben Haley, and Jack Moore, North American Carbon Program of the U.S. Global Change Research Program, Washington, D.C., January 2015

"Deep Decarbonization in the U.S.: Can We Get There From Here?" (with Ben Haley), U.S. Department of Energy, Washington, D.C., January 2015

"Deep Decarbonization in the U.S.: Can We Get There From Here?" (with Ben Haley), State Department, Washington, D.C., January 2015

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"Ecological Limits to Terrestrial Biological Carbon Dioxide Removal" (with Margaret Torn, Daniel Sanchez, Lydia Smith, and Umakant Mishra), American Geophysical Union, San Francisco, December 2014

"China's Electricity System: A Primer on Planning, Pricing, and Operations" (with Fritz Kahrl and Trevor Houser), California Energy Commission, Sacramento, October 2014

"Deep Decarbonization in the U.S.: Can We Get There From Here?" (with Snuller Price and Jack Moore), Fahr Group LLC and NextGen America, San Francisco, September 2014

"U.S. Low Carbon Scenario Dashboard Exercise," Deep Decarbonization Pathways Project County Team Meeting, Reid Hall, Paris, April 2014

"California's Transition to a Low Carbon Economy," Bay Area Air Quality Management District, San Francisco, February 2014

"Pathways to a Low Carbon World," International Honors Program, San Francisco, February 2014

"Low Carbon Pathways Model: California and the U.S.," Deep Decarbonization Pathways Project County Team Meeting, International Energy Agency, Paris, January 2014

"The Importance of Regulation in Potential California-China Collaboration in Energy," Inaugural Meeting of California-China Climate Change Collaboration Advisory Committee, Asia Society, December 2013

"Backcasting: A Case Study of Low Carbon Pathways Modeling in California" (with Margaret Torn), Sustainable Agriculture and Food Systems Thematic Group, Sustainable Development Solutions Network, December 2013

"Low Carbon Pathways Modeling: Methods and Results," California Climate Policy Modeling Forum, U.C. Davis, December 2013

"Priorities for Energy Policy Analysis in California," Forum on California's Electricity Policy Future: Beyond 2020, Shultz-Stephenson Task Force on Energy Policy, Hoover Institution, Stanford University, December 2013

"The Implications of Adopting the Soviet Model of Technological Development," Conference on The Historical Influence of Chinese Grand Strategy on Science and Technology," Institute for Global Conflict and Cooperation, UCSD, San Diego, October 2013

"U.S. and California Deep Decarbonization Pathway Analysis," DDPP Inception Meeting, U.N. Sustainable Development Solutions Network, Seoul, October 2013

"Modeling Principles for Deep Decarbonization Pathways," DDPP Inception Meeting, U.N. Sustainable Development Solutions Network, Seoul, October 2013

"Pathways to 2050: Modeling a Low Carbon Future," IDDRI (Institute for Sustainable Development and International Relations," Paris, July 2013

"Discussion of a Societal Cost Test in California" (with Brian Horii, Fritz Kahrl, Ben Haley, and Priya Shreedharan), Workshop on Societal Cost Test, California Public Utilities Commision, June 2013

"Pathways to 2050: Modeling a Low Carbon Future," U.N. Sustainable Development Solutions Network, New York, April 2013

"The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050," Yale University, Climate and Energy Institute, New Haven, April 2013

"Water-Energy Avoided Cost Framework" (with Ben Haley and Eric Cutter), California Public Utilities Commission, March 2013

"The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050," Pacific Energy Center, Pacific Gas & Electric, San Francisco, December 2012

"The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050," Environmental Defense Fund, San Francisco, October 2012

"The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050," U.C. Berkeley, Environmental Engineering Seminar, October 2012

"The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050," UK Office of Energy and Climate Change, London, March 2012

"The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050," California's Energy Future Policy Committee, Berkeley, March 2012

"The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050," East Bay Environmental Network, Berkeley, March 2012

"The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050," CALHEAT (California Hybrid, Efficient, and Advanced Truck Program) Forum, Stockton, February 2012

"The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050," Long-Term Energy Research and Development Working Group (LERDWG), U. S. Department of Energy, Washington, D.C., February 2012

"Climate Mitigation in California: The Path to 2050," Environmental Leadership Program, U.C. Berkeley, July 2011

"The Fukushima Accident and the Status of Nuclear Power in Japan," U.C. Berkeley and Monterey Institute of International Studies, April 2011

"Transforming the Energy Economy: Lessons from 2050 We Can Use Today," Institute for the Future, (with Rebecca Ghanadan,) Palo Alto, January 2011

"After Cap and Trade: US Climate Policy Options." Briefing to U.S. Senator Jeff Bingaman, (with Ren Orans and Frank Pearl), June 2010.

"Electricity With Chinese Characteristics: The Complexities of Decarbonizing China's Power Sector," China Environment Forum, Woodrow Wilson Center, Washington, D.C., (with FERC Chairman Jon Wellinghof, Fritz Kahrl, and Ding Jianhua), June 2010. http://www.wilsoncenter.org/index.cfm?fuseaction=events.event_summary&event_id=622580

"The World in 2050: Technology Pathways to a Low-Carbon Future," Institute for Urban and Environmental Studies, Chinese Academy of Social Sciences, Beijing, June 2010

"The World in 2050: Technology Pathways to a Low-Carbon Future," Climate Policy Institute, Tsinghua University, Beijing, June 2010

"Introduction to the Energy Efficiency Power Plant Calculator," Energy Efficiency Power Plant Workshop, Beijing, June 2010

"Radiation Hazards of Nuclear Energy and Nuclear Weapons," Guest Lectures, ER102 Quantitative Analysis of Global Environmental Problems, U.C. Berkeley, April 2010

"The World in 2050: Technology Pathways to a Low-Carbon Future," Monterey Institute of International Studies, Environmental Speaker Series, December 2009

"Meeting California's Greenhouse Gas Reduction Goals in 2050," European Community, Brussels, Belgium, September 2009.

"Meeting California's Greenhouse Gas Reduction Goals in 2050," California Air Resources Board, (with Snuller Price and Bill Morrow), September 2009.

"Transforming the Global Energy System: The View from California," Sonoma State University, Environmental Forum, May 2009.

"Transforming the Global Energy System: The View from California," (with Snuller Price), World Affairs Council, March 2009.

"Modeling AB32 in California's Electricity Sector: Impacts and Implications," (with Snuller Price), Energy and Resources Group Colloquium, U.C. Berkeley, November 2008.

"Reducing Greenhouse Gas Emisions from Electricity Generation in California," Guest Lecture, ER254 Electric Power Systems, U.C. Berkeley, April 2008.

"Climate Change Mitigation and Adaptation: Markets vs. Regulation," U.C. Hastings School of Law, San Francisco, April 2008

"China's Energy and Climate Policy," Guest Lecture, ER291 Climate Policy, U.C. Berkeley, March 2007.

"The Berkeley Consensus: U.S. and Chinese Perspectives on Global Climate Change," China-U.S. Climate Change Forum, U.C. Berkeley, May 2006

"North Korean Energy and Regional Conflict," School of Journalism, U.C. Berkeley, November 2005

"Demand Response Pathways," Workshop on Demand Response Valuation, Title 24 Building Energy Standards Update, California Energy Commission, July 2005.

"Bad Energy in North Korea: Is Northeast Asian Grid Interconnection a Solution?" School of Advanced International Studies, Johns Hopkins University, February 2005

"Institutional Dimensions of Electricity Demand Response," Panelist, Demand Response Research Design Workshop, California Energy Commision/PIER/CIEE, February 2004

"Energy and Conflict on the Korean Peninsula," Environmental Studies Seminar, Sonoma State University, May 2003

"The Social Contract of Electricity," Political Economy of Power Sector Reform Conference, Stanford University, February 2003

"Fuel and Famine: North Korea's Rural Energy Crisis," World Affairs Council, San Francisco, November 2000

"Environmental Security on the Korean Peninsula," Panelist, Director of Central Intelligence Environmental Center, Arlington, VA, April 2000

"Solving North Korea's Rural Energy Crisis," briefing to South Korean Unification Minster Lim Dong Wan, September 1999

"Rural Energy and North Korean Stability," Roundtable Symposium on Korea, IGCC/Korean Economic Institute, U.C. San Diego, May 1999

"An NGO Co-Operative Engagement Project in the DPRK," Conference on Northeast Asian Cooperation, Montery Institute of International Studies, February 1999.

"A US NGO Project in Rural North Korea," Emerging from Conflict Conference, Stanley Foundation, Virginia, October 1998.

"A Chinese Physicist in the Post-War Political Arena," U.C. Berkeley, January 1998.

"Energy in Native America," Energy and Resources Group Colloquium, U.C. Berkeley, September 1997

"Sustainable Energy: Benefits for Tribes," Mni-Sose Intertribal Water Rights Coalition, Rapid City, SD, November 1996

"The Yurok Solar PV Electrification Project," invited expert testimony to Yurok Tribal Council, Eureka, CA, September 1995

Courses Taught

Energy Technologies, Resources, and Systems (ENGY 612), Spring 2018, University of San Francisco

Climate Change Science and Policy (ENVS 392), Spring 2018, University of San Francisco

Quantitative Methods for Energy in the Environment (ENGY 610), Fall 2017, University of San Francisco

Masters Project in Environmental Management (ENVM 698), Fall 2017, University of San Francisco

Climate Action: Solutions for a Changing Planet, SDG Academy Online Course (MOOC), Summer 2017, Sustainable Development Solutions Network (co-taught with others)

Electric Utility Planning (CEE221A), Winter 2013, Stanford University (co-taught with Joel Swisher and Ren Orans)

Climate Change Mitigation (IP626), Winter 2012, Monterey Institute of International Studies

Quantitative Methods in Environmental Science and Policy (IP512), Fall 2008, Spring 2009, Fall 2009, Fall 2010, Fall 2011 Monterey Institute of International Studies

After Copenhagen and Fukushima: The Nuclear Future in a Climate and Security Constrained World (IP621), Fall 2011 Monterey Institute of International Studies (co-taught with Patricia Lewis and Ferenc Dalnoki-Veress)

Electric Power System Analysis (IP659), Fall 2009, Fall 2011, Monterey Institute of International Studies

Advanced Energy Research Seminar (IP624), Spring 2010, Spring 2011, Monterey Institute of International Studies

Quantitative Analysis of Global Environmental Problems (ER102), U.C. Berkeley, 2002, 2003 (co-taught with John Harte), 2006, 2011 (co-taught with Margaret Torn)

Interdisciplinary Energy Analysis (IP548), Spring 2009, Fall 2010, Monterey Institute of International Studies

Renewable Energy Workshop (WKSH8580), Fall 2010, Monterey Institute of International Studies

Energy Efficiency Power Plant Calculator Training, June 2010, Workshop on Energy Efficiency Power Plants, Beijing

Energy and Development Workshop (WKSH8583), Spring 2010, Monterey Institute of International Studies

Climate Change Policy (IP643), Spring 2008 and Fall 2008, Monterey Institute of International Studies

Directed Study (IP698), Spring 2008, Fall 2008, Fall 2009, Spring 2010, Monterey Institute of International Studies

Energy and Environmental Journalism in China (J234), U.C. Berkeley, Spring 2007 (co-taught with Orville Schell, Sandy Tolan, Mark Dowie, Rone Tempest)

Biogeochemistry: Carbon and Nitrogen Cycles (ES320), Colorado College, Spring 1996 (co-taught with Margaret Torn)

Renewable Energy and Native American Communities, NAREEP Tribal College Instructor Workshops, 1995-1996

The Political Economy of Energy in Native America (ER290), U.C. Berkeley, 1995-1996 (co-taught with Rachel Schurmann)

Advising

Internship Mentor, Lucy McKenzie (U.C. Berkeley, E3 Summer Internship) 2014 (topic: Improving Clean Air Act 111.d.)

Internship Mentor, Andy Hultgren (U.C. Berkeley, E3 Summer Internship) 2014 (topic: Distributional Impacts of Deep Decarbonization in the United States.)

Masters Project Research Advisor, Grace Wu (U.C. Berkeley, Energy and Resources Group, M.S.) 2012-2013 (Title: Assessing Environmental Impacts of Low-Carbon Electricity Pathways)

Dissertation Committee, Fredrich Kahrl (U.C. Berkeley, Energy and Resources Group, Ph.D.) 2010-2011 (Title: Socioeconomic Transition and China's Energy and Climate Policy)

Internship Mentor, Ryan Jones (Stanford University, E3 Summer Internship) 2011 (topics: Wind Net Qualifying Capacity and Solar PV Deliverability Rules)

Internship Mentor, Michaelangelo Tabone (U.C. Berkeley, E3 Summer Internship) 2011 (topic: Value of Smart Grid Applications)

Research Advisor, Student Group Project (U.C. Berkeley, ER/MSE 226, Photovoltaic Technology and Markets) 2011 (topic: Community Solar Project on Lopez Island, Washington)

Internship Mentor, Eric Stoutenberg (Stanford University, Ph.D., E3 Summer Internship) 2010 (topic: Wind Integration in Europe and the U.S.)

Internship Mentor, Ben Haley (Monterey Institute of International Studies, M.A., E3 Summer Internship) 2010 (topic: The Nexus Between Water, Energy, and Greenhouse Gas Emissions in California)

Research Advisor, Ding Jianhua (Monterey Institute of International Studies, M.A., E3 Research Intern) 2010 (topic: China's Electric Power System)

Faculty Advisor for Directed Study, Ben Haley (Monterey Institute of International Studies, M.A.) 2010 (topic: Energy and Development)

Faculty Advisor for Directed Study, Claudine Desiree (Monterey Institute of International Studies, M.A.) 2010 (topic: Energy and Development)

Faculty Advisor for Directed Study, Ding Jianhua (Monterey Institute of International Studies, M.A.) 2009 (topic: Environmental Regulation in the U.S.: Lessons for China)

Faculty Advisor for Directed Study, Bridget Nuxoll (Monterey Institute of International Studies, M.A.) 2009 (topic: History of Energy Resources: Coal, Petroleum, and Nuclear Power)

Research Advisor, Anna Monders (Monterey Institute of International Studies, M.A.) 2008 (topic: Arctic Climate Change and International Security)

Faculty Advisor for Directed Study, Neal Reardon (Monterey Institute of International Studies, M.A.) 2008 (topic: Solar Thermal and Wind Power Systems and Site Assessment)

Internship Mentor, Jessica Shipley (U.C. Berkeley, Goldman School M.P.A., E3 Summer Internship) 2008 (topic: Achieving Agresssive Emissions Reductions by 2050: Changes and Strategies for the U.S.)

Masters Project Research Advisor, Zack Subin (U.C. Berkeley, ERG M.S. Project) 2008 (topic: Greenhouse Gas Abatement Supply Curves for California's Transportation Sector)

Internship Mentor, Zack Subin (U.C. Berkeley, E3 Summer Internship) 2007 (topic: Greenhouse Gas Abatement Supply Curves for California's Transportation Sector)

Switzer Foundation Mentor, Chris Greacen (U.C. Berkeley, ERG Ph.D. Dissertation) 1998-2002 (topic: Renewable Energy, Common Property, and Rural Electricity Provision in Thailand)

Service and Professional Activities

Technical Advisor to Inter-American Development Bank, Deep Decarbonization in Latin America and the Carribean Project, 2018

Reviewer for California Energy Commission, Deep Decarbonization in a High Renewables, Biofuel-Constrained Future study, 2018

Technical Advisor to New York State Energy Research and Development Agency, 100% Renewables Study, 2018

Techical Advisor to Tempus Analitica for MILES project on Renewables-Natural Gas Tradeoffs in Mexico for Energy Security and Paris Agreement Compliance

Panel Chair and Organizer, "Deep Decarbonization at Scale," Low Emission Solutions Conference II, Columbia University, 2017

Reviewer, *Nature Climate Change*, *Energy Policy*, *Environmental Science and Technology*, *Energy*, *Pacific Affairs*, *China Quarterly*, and others.

Invited Member, AGU Energy Engagement Task Force, American Geophysical Union, starting in 2016

Invited Member, Natural Gas Working Group for University of California Carbon Neutrality Goal, starting in 2016

Organizer, Session on Mid-Century Strategies for Deep Decarbonization at Continental, National, and Subnational Scale, Low Emissions Solutions Conference, COP-22, 2016

Invited Member, MILES Project, US Intended Nationally Defined Contribution Consistentency with Mid-Century Strategy Team, IDDRI, 2016

Co-Leader, Deep Decarbonization Workshop for Signatories of the Under 2 MOU, Clean Energy Ministerial, San Francisco, 2016

Invited Panelist, U.S. Department of Energy, Low Carbon Energy Futures Workshop, Washington, D.C., 2016

Project Advisory Committee, U.S.-China Collaboration on Clean Air Technologies and Policies, Asia Society, 2016

Invited Reviewer, U.S. Department of Energy, *Quadrennial Technology Review*, 2015

Steering Committee, Roadmap for California-China Collaboration on Climate Change, Asia Society, starting in 2013

Steering Committee, California Climate Policy Modeling Forum, starting in 2013

Coordinating Committee, Deep Decarbonization Pathways Project of the U.N. Sustainable Development Solutions Network, starting in 2013

Invited Panelist, After the 2020 Renewables Portfolio Standard: Next Steps for California, U.C. Berkeley, 2013

California's Energy Future Policy Committee, California Council on Science and Technology, starting in 2012

Chair, Energy-Business Faculty Hiring Committee, Graduate School of International Policy and Management, Monterey Institute of International Studies, 2011

Adjunct Faculty Hiring Lead, International Environmental Policy Program, Monterey Institute of International Studies, 2011

Invited Panelist/Reviewer, Dams and Sustainability in China, China Environment Forum, Woodrow Wilson Center, Washington, DC, 2011

Member, Faculty Promotion Committee, Graduate School of International Policy and Management, Monterey Institute of International Studies, 2011

Textbook Reviewer for Richard Wolfson, *Energy, Environment, and Climate,* published by W.W. Norton, 2011

Chair, Science Working Group, Graduate School of International Policy and Management, Monterey Institute of International Studies, 2010

Member, Faculty Contract Renewal Committee, Graduate School of International Policy and Management, Monterey Institute of International Studies, 2010

Research Proposal Reviewer, Netherlands Organization for Scientific Research (NWO), March 2010

Program Director and Convenor, China-US Climate Change Forum, U.C. Berkeley, Spring 2006

Board of Advisors, EcoEquity (US NGO focused on international climate equity issues), starting in 2005

Board of Advisors, Palang Thai (Bangkok-based energy and sustainable development NGO), starting in 2004

Program Director and Convenor, Workshop on the Political Economy of Asian Electricity Reform, Thailand Environment Institute, Bangkok, Thailand, December 2003

Board of Directors, Institute of Sustainable Power, 2001-2002

Organizer and Curriculum Designer, Second Study Tour of DPRK Energy Experts to the U.S. (including first visits by North Koreans to World Bank and U.S. Department of Energy), April 1999

Conference Organizer, Sustainable Energy in North Korea, U.C. Berkeley, April 1999

Conference Organizer, Clean Coal Technologies in China, Nautilus Institute, Berkeley, CA, January 1999

Conference Convenor and Organizer, Physicists in the Cold War Political Arena, Office of History of Science and Technology, U.C. Berkeley, January 1998

Organizer and Curriculum Designer, First Study Tour of DPRK Energy Experts to the U.S., December 1997

Program Director and Convenor, Berkeley-Princeton Conference on Renewable Energy and Development, May 1997

Organizer and Curriculum Designer, Tribal College Instructor Workshop, Native American Renewable Energy Education Project, Carbondale, CO, August 1996

Scientific Advisor, Citizens for a Better Environment, Oakland, CA 1995-2004

Editorial Advisory Board, *Chinese Studies in Philosophy*, 1993-1997

Honors/Fellowships

Energy and Resources Group Post-Doctoral Fellowship, 1995-97

MacArthur International and Strategic Studies Dissertation Fellowship, 1990-92

Institute on Global Conflict and Cooperation Dissertation Fellowship, 1988-90

Selected Grants and Contracts

Sustainable Development Solutions Network, *Deep Decarbonization Pathways Project*, Director, 2015-17

Earth Institute, Columbia University, *U.S. Deep Decarbonization Pathways Model and Scenarios*, Principal Investigator, 2014

Asia Society, Energy Foundation, Sunnylands Foundation, *California-China Collaboration on Climate Change*, Project Manager, 2013

Regulatory Assistance Project, *Water-Energy Nexus Phase 2*, Project Manager, 2013

China Environment Forum, *Policy Brief on U.S.-China Energy Cooperation*, Project Manager, 2011

Regulatory Assistance Project, *Technical Support for State Electricity Regulatory Commission and Development of Utility Energy Efficiency Planning Tool*, Project Manager, 2011

Regulatory Assistance Project, *Technical Support for State Electricity Regulatory Commission Analysis of Greenhouse Gas Reduction Policy Options in China's Electricity Sector*, Project Manager, 2009-2010

Regulatory Assistance Project, *Energy Efficiency Power Plant Calculator for China, Tool Development and Training*, Project Manager, 2009-2010

Mark Faculty Grant, *Current Developments in U.S. and International Climate Change Policy*, Monterey Institute of International Studies, 2009

Lundeen Faculty Grant, *Arctic Climate Change and International Security,* Monterey Institute of International Studies, 2008

California Public Utilities Commission, *Modeling of Implementation of AB32 (California's Global Warming Solutions Act) in California's Electricity Sector,* P.I. Energy and Environmental Economics, Inc., 2007-2008

California Energy Commission, Public Interest Energy Research Program, *Demand Response Valuation*, P.I. Energy and Environmental Economics, Inc., 2005-2006

California Energy Commission, Public Interest Energy Research Program, *Demand Response Rate Design*, P.I. Energy and Environmental Economics, Inc., 2005-2006

California Energy Commission, *UC/CSU Peak Load Reduction Project*, 2000-2001, P.I. University of California Office of the President/Gruenich Resource Advocates

Department of Energy, *North Korean Energy Study*, 1998-1999, P.I. Peter Hayes

W. Alton Jones Foundation, *North Korean Village Wind Energy Project*, 1997-1999, P.I. Peter Hayes (grant renewed once)

Department of Energy, *Native American Renewable Energy Education Project*, 1995-97, P.I. Neville Cook (grant renewed twice)

Institute on Global Conflict and Cooperation Research Grant, 1986-87, P.I. John Holdren

Certifications

EIT Certificate, California Board for Professional Engineers and Land Surveyors
Photovoltaic Design and Installation, Solar Energy International
Wind Electric System Design and Installation, Solar Energy International

Memberships

American Geophysical Union
IEEE Power and Energy Society

Dissertation Committee

Prof. John Holdren (chair), Prof. Kenneth Jowitt, Prof. Thomas Gold

EXHIBIT B: LIST OF PUBLICATIONS (LAST 10 YEARS)

James H. Williams

Publications Since 2007

Peer-Reviewed Journal Articles

Iyer, G., C. Ledna, L. Clarke, J. Edmonds, H. McJeon, P. Kyle, J.H. Williams (2017). Measuring progress from nationally determined contributions to mid-century strategies. *Nature Climate Change*, 7(12), 871. http://dx.doi:10.1038/s41558-017-0005-9

Sachs, J., Schmidt-Traub, G., and J.H. Williams (2016). Pathways to zero emissions. *Nature Geoscience*, 9, 799–801. http://dx.doi.org:10.1038/ngeo2826

Yeh, S., C. Yang, M. Gibbs, D. Roland-Holst, J. Greenblatt, A. Mahone, D. Wei, G. Brinkman, J. Cunningham, A. Eggert, B. Haley, E. Hart, J.H. Williams (2016). A modeling comparison of deep greenhouse gas emission reductions scenarios by 2030 in California. *Energy Strategy Reviews*, 13:14, 169-180. http://dx.doi.org/10.1016/j.esr.2016.10.001

Bataille, C., H. Waisman, M. Colombier, L. Segafredo, J.H. Williams, and F. Jotzo (2016). The need for national deep decarbonization pathways for effective climate policy. *Climate Policy*, 16:1, 1-20. http://dx.doi.org/10.1080/14693062.2016.1173005

Bataille, C., H. Waisman, M. Colombier, L. Segafredo, J.H. Williams (2016). The Deep Decarbonization Pathways Project (DDPP): insights and emerging issues. *Climate Policy*, 16:1, S1-S6. http://dx.doi/10.1080/14693062.2016.1179620

Morrison, G., S. Yeh, A. Eggert, C. Yang, J. Nelson, J. Greenblatt, R. Isaac, M. Jacobson, J. Johnston, D. Kammen, A. Mileva, J. Moore, D. Roland-Holst, M. Wei, J. Weyant, J.H. Williams, R. Williams, C. Zapata (2015). Comparison of low-carbon pathways for California. *Climatic Change*. http://dx.doi/10.1007/s10584-015-1403-5

Wu, G.C., M.S. Torn, and J.H. Williams (2015). Incorporating land-use requirements and environmental constraints in low-carbon electricity planning for California. *Environmental Science & Technology*, *49 (4)*, 2013-2021. http://dx.doi/10.1021/es502979v

McKenzie, L., R. Orans, J.H. Williams, A. Mahone (2014). Strengthening the Clean Power Plan: three key opportunities for the EPA. *The Electricity Journal*, *27 (10)*. http://dx.doi.org/10.1016/j.tej.2014.11.001

Cutter, E., B. Haley, J.H. Williams, C.K. Woo, (2014). Cost-effective water-energy nexus: a California case study. *The Electricity Journal*, *27 (5)*, 61–68. http://dx.doi.org/10.1016/j.tej.2014.06.009

Cutter, E., B. Haley, J. Hargreaves, J.H. Williams, (2014). Utility scale energy storage and the need for flexible capacity metrics. *Applied Energy*, *124*, 274–282. http://dx.doi.org/10.1016/j.apenergy.2014.03.011

Hu, J., G. Kwok, X. Wang, J.H. Williams, F. Kahrl, (2013). Using natural gas generation to improve power system efficiency in China. *Energy Policy, 60, 116-121.* http://dx.doi.org/10.1016/j.enpol.2013.04.066

Kahrl, F., J. Hu, G. Kwok, J. H. Williams (2013). Strategies for expanding natural gas-fired electricity generation in China: economics and policy. *Energy Strategy Review*, *1,* 1-8. http://dx.doi.org/10.1016/j.esr.2013.04.006

Kahrl, F., J.H. Williams, J. Hu (2013). The political economy of electricity dispatch reform in China. *Energy Policy*, *53*, 361-369. http://dx.doi.org/10.1016/j.enpol.2012.10.062

Haley, B., J.B. Gallo, A. Kehr, M. Perry, D. Siao, W. Smallen, M.S. Torn, J.H. Williams (2012). The 2020 emissions reduction impact of urban water conservation in California. *Journal of Water and Climate Change, 3, 151-162.* http://doi:10.2166/wcc.2012.047

Williams, J.H., A. DeBenedictis, R. Ghanadan, A. Mahone, J. Moore, W. Morrow, S. Price, M.S. Torn (2012). The technology path to deep greenhouse gas emissions cuts by 2050: the pivotal role of electricity. *Science*, *335*, 53-59. http://dx.doi.org/10.1126/science.1208365

Kahrl, F., J.H. Williams, J. Hu, J. Ding (2011). Challenges to China's transition to a low carbon electricity system (in Renewable Energy Special Issue). *Energy Policy, 39*, 4032-4041. http://dx.doi.org/10.1016/j.enpol.2011.01.031

Von Hippel, D., T. Suzuki, J.H.Williams, T. Savage, and P. Hayes (2011). Energy security and sustainability in Northeast Asia, in Asian Energy Security Special Issue. *Energy Policy*, *39*, 6719-6730. http://dx.doi.org/10.1016/j.enpol.2009.07.001

Mahone, A., C.K. Woo, J.H. Williams, I. Horowitz (2009). Renewable portfolio standards and cost-effective energy-efficiency investment. *Energy Policy*, *37*, 774-777. http://dx.doi.org/10.1016/j.enpol.2008.11.033

Williams, J.H. and F. Kahrl (2008). Electricity reform and sustainable development in China. *Environmental Research Letters*, *3*, 044009 1-14. http://iopscience.iop.org/1748-9326/3/4/044009

Von Hippel, D., P. Hayes, J.H.Williams, C. Greacen, M. Sagrillo, and T. Savage (2008). International energy assistance needs and options for the Democratic People's Republic of Korea (DPRK). *Energy Policy*, *36*, 541–552. http://dx.doi.org/10.1016/j.enpol.2007.09.027

Orans, R., S. Price, J.H. Williams, and C.K. Woo (2007). A Northern California-British Columbia partnership for renewable energy. *Energy Policy*, *35*, 3979-3983. http://dx.doi.org/10.1016/j.enpol.2007.03.013

Book Chapters

Kahrl, F., R. Bharvirkar, C. Greacen, C. Sangarasri Greacen, M. Patankar, P. Shreedharan, J.H. Williams (2012), Utilities regulation and sustainability, *The Encyclopedia of Sustainability, Volume 7: China, India, and East and Southeast Asia: Assessing Sustainability,* Great Barrington, MA: Berkshire.

Von Hippel, D., J.H. Williams, P. Hayes, Energy security – East Asia (2012), *The Encyclopedia of Sustainability, Volume 7: China, India, and East and Southeast Asia: Assessing Sustainability,* Great Barrington, MA: Berkshire.

Von Hippel. D., T. Suzuki, J. H. Williams, T. Savage, and P. Hayes (2011) Evaluating the energy security impacts of energy policies, in Benjamin Sovacool, ed., *The Routledge Handbook of Energy Security*, London: Routledge.

Reports, Manuals, Working Papers, Magazine Articles, and Book Reviews

Williams, J.H. *The Electric Economy.* IEEE Power & Energy Special Issue on Electrification (accepted, publication expected June 2018).

Jones, R., B. Haley, G. Kwok, J. Hargreaves, J. H. Williams, *Electrification and the Future of Electricity Markets.* IEEE Power & Energy Special Issue on Electrification (accepted, publication expected June 2018).

Williams, J.H., R. Jones, G. Kwok, B. Haley (2018), *Deep Decarbonization in the Northeast United States and Expanded Coordination with Hydro-Quebec*, http://unsdsn.org/resources/publications/deep-decarbonization-in-thenortheast-united-states-and-expanded-coordination-with-hydro-quebec/

Meier, A., et al. (2018), *University of California Strategies for Replacing Natural Gas*, TomKat Natural Gas Exit Strategies Working Group.

Williams, J.H. and H. Waisman (2017), *2050 Pathways: A Handbook*, for 2050 Pathways Platform. https://www.2050pathways.org/resources/

Haley, B., G. Kwok, R. Jones, J.H. Williams (2016), *Deep Decarbonization Pathways for Washington State*, prepared for the Governor's Office for Energy and Environment. http://www.governor.wa.gov/issues/issues/energy-environment/deep-decarbonization

Williams, J.H., B. Haley, R. Jones, (2015), *Policy Implications of Deep Decarbonization in the United States*, A report of the Deep Decarbonization Pathways Project of the Sustainable Development Solutions Network and the Institute for Sustainable Development and International Relations. http://usddpp.org/usddpp-reports/

Schmidt-Traub, G., J. Sachs, J.H. Williams, T. Ribera, M. Colombier, H. Waisman (2015), *Why Climate Policy Needs Long-Term Deep Decarbonization Pathways*, Sustainable Development Solutions Network and Institute for Sustainable Development and International Relations Working Paper. http://unsdsn.org/wp-content/uploads/2015/11/151130-Why-Climate-Policy-requires-long-term-Deep-Decarbonization-Pathways_rev.pdf

Waisman, H., L. Segafredo, C. Bataille, G. Schmidt-Traub, M. Colombier, J.H. Williams, (2015), *Pathways to Deep Decarbonization: 2015 Report.* Sustainable Development

Solutions Network and Institute for International Relations and Sustainable Development. http://deepdecarbonization.org/ddpp-reports/

Williams, J.H., and Teng Fei, (2015), *What Would New Breakthroughs on Climate Change Mean for the U.S.-China Relationship?* A ChinaFile Conversation, Asia Society. http://www.chinafile.com/conversation/what-would-new-breakthroughs-climate-change-mean-us-china-relationship

Williams, J.H., and H. Waisman, G. Schmidt-Traub, M. Colombier, L. Segafredo, (2015), *Pathways to Deep Decarbonization: 2015 Report Executive Summary*. Sustainable Development Solutions Network and Institute for International Relations and Sustainable Development. http://deepdecarbonization.org/wp-content/uploads/2015/06/DDPP_EXESUM.pdf

Wu, G., N. Schlag, D. Cameron, E. Brand, L. Crane, J. Williams, S. Price, (2015). *Integrating Land Conservation and Renewable Energy Goals in California: A Study of Costs and Impacts Using the Optimal Renewable Energy Build-Out (ORB) Model.* Technical report for The Nature Conservancy. http://scienceforconservation.org/dl/TNC_ORB_Report_Final_2015.pdf

Schell, O., J.H. Williams, G. He, R. Hsu (2015), *California and China: A Vital Partnership in Developing Clean Energy and Combating Climate Change*, a special report of the Asia Society. http://asiasociety.org/center-us-china-relations/vital-partnership-california-and-china-collaborating-clean-energy-and-comb

Mahone, A., E. Hart, B. Haley, J.H. Williams, S. Borgeson, N. Ryan, S. Price (2015), *California PATHWAYS: GHG Scenario Results*, analysis conducted for California Air Resources Board, Public Utilities Commission, Energy Commission, and Independent System Operator. https://ethree.com/documents/E3_PATHWAYS_GHG_Scenarios_Updated_April2015.pdf

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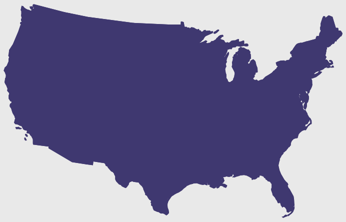
EXHIBIT D. RESEARCH REPORT: PATHWAYS TO DEEP DECARBONIZATION IN THE UNITED STATES

US 2050 Vol. 1
Technical Report

pathways to deep decarbonization *in the United States*



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Energy and Environmental Economics, Inc. (E3)
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Preface

Deep Decarbonization Pathways Project

The Deep Decarbonization Pathways Project (DDPP) is a collaborative global initiative to explore how individual countries can reduce greenhouse gas (GHG) emissions to levels consistent with limiting the anthropogenic increase in global mean surface temperature to less than 2 degrees Celsius (°C). Limiting warming to 2°C or less, an objective agreed upon by the international community, will require that global net GHG emissions approach zero by the second half of the 21st century.[1] This, in turn, will require steep reductions in energy-related CO_2 emissions through a transformation of energy systems, a transition referred to by the DDPP as "deep decarbonization."

The DDPP is led by the Sustainable Development Solutions Network (SDSN) and the Institute for Sustainable Development and International Relations (IDDRI). Currently, the DDPP includes 15 research teams from countries representing more than 70% of global GHG emissions: Australia, Brazil, Canada, China, France, Germany, India, Indonesia, Japan, Mexico, Russia, South Africa, South Korea, the United Kingdom, and the United States. The research teams are independent and do not necessarily reflect the positions of their national governments. Starting in the fall of 2013, the research teams have been developing potential high-level roadmaps, or "pathways," for deep decarbonization in their respective countries.

The initial results of this effort were published in September 2014 and officially presented as part of the *Economic Case for Action* session at the Climate Summit convened by UN Secretary General Ban Ki Moon in New York. That study, "Pathways to Deep Decarbonization: 2014 Report," included a chapter on deep decarbonization pathways in the U.S.[2] The present report represents a continuation of the analysis in the DDPP Report, providing expanded results and greater detail on methods and data sources.

Research Team

The research for this report was conducted by Energy and Environmental Economics, Inc. (E3), a San Francisco-based consulting firm, in collaboration with Lawrence Berkeley National Laboratory (LBNL) and Pacific Northwest National Laboratory (PNNL). The overall project director was Dr. Jim Williams (E3), with Dr. Andrew Jones (LBNL) and Dr. Haewon McJeon (PNNL) responsible for GCAM modeling. PATHWAYS analysis and report writing were conducted primarily by Ben Haley, Jack Moore, and Dr. Fredrich Kahrl of E3. Senior supervisors included Dr. Margaret Torn (LBNL) and Snuller Price (E3).

Advisory Committee

This report was reviewed by a distinguished advisory committee consisting of Prof. John Weyant of Stanford University and Director of the Energy Modeling Forum, and Dr. Jae Edmonds, a Laboratory Fellow at PNNL's Joint Global Change Research Institute.

[1] Intergovernmental Panel on Climate Change, *5th Assessment Report*, http://www.ipcc.ch/report/ar5/
[2] SDSN and IDDRI, *Pathways to Deep Decarbonization: 2014 Report*, www.deepdecarbonization.org/

Addendum to November 2015 Revision

This report includes a new technical supplement contained in Appendix D. It was prepared in order to show additional detail from the PATHWAYS analysis by case, sector, and geographic region for cost, GHG emissions, final energy demand, primary energy flows, and investment. The analysis was performed by Ben Haley and directed by Dr. Jim Williams.

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Abstract

Limiting the anthropogenic increase in global mean surface temperature to less than 2 degrees Celsius (°C), an objective agreed upon by the international community, will require that global net GHG emissions approach zero by the second half of the 21st century. The principal finding of this study, conducted using the PATHWAYS and GCAM models, is that it is technically feasible to achieve an 80% greenhouse gas reduction below 1990 levels by 2050 in the United States (U.S.), and that multiple alternative pathways exist to achieve these reductions using existing commercial or near-commercial technologies. Reductions are achieved through high levels of energy efficiency, decarbonization of electric generation, electrification of most end uses, and switching the remaining end uses to lower carbon fuels. The cost of achieving these reductions does not appear prohibitive, with an incremental cost to the energy system equivalent to less than 1% of gross domestic product (GDP) in the base case. These incremental energy system costs did not include potential non-energy benefits, for example, avoided human and infrastructure costs of climate change and air pollution. The changes required to deeply decarbonize the economy over the next 35 years would constitute an ambitious transformation of the energy system. However, this study indicates that these changes would not necessarily entail major changes in lifestyle, since the low carbon pathways were designed to support the same level of energy services and economic growth as the reference case based on the U.S. Department of Energy's *Annual Energy Outlook*. Starting now on the deep decarbonization path would allow infrastructure replacement to follow natural replacement rates, which reduces costs, eases demand on manufacturing, and allows gradual consumer adoption.

Executive Summary

Decision makers in government and business increasingly need to understand the practical implications of deep reductions in global greenhouse gas (GHG) emissions. This report examines the technical and economic feasibility of such a transition in the United States, evaluating the infrastructure and technology changes required to reduce U.S. GHG emissions in the year 2050 by 80% below 1990 levels, consistent with a global emissions trajectory that limits the anthropogenic increase in earth's mean surface temperature to less than 2°C.

The analysis was conducted using PATHWAYS, a detailed, bottom-up energy model that draws on the architecture and inputs of the U.S. National Energy Modeling System (NEMS). For each year out to 2050, PATHWAYS evaluates annual changes in infrastructure stocks by sector and region in each of the nine U.S. census divisions, and includes an hourly electricity system simulation in each of the three major electric grid interconnections. Scenarios using different portfolios of measures were developed to represent a range of decarbonization strategies across energy supply and demand sectors including electricity, fuels, residential and commercial buildings, passenger and freight transportation, and industry. The resulting incremental energy system emissions and costs were calculated in comparison to a reference case based on the U.S. Department of Energy's *Annual Energy Outlook (AEO)*. Uncertainty was addressed through sensitivity analysis. Complementary analyses were performed using GCAM, a global integrated assessment model, to examine land-use emissions associated with bioenergy production and the mitigation potential of non-CO_2 GHGs. The study addresses four main research questions:

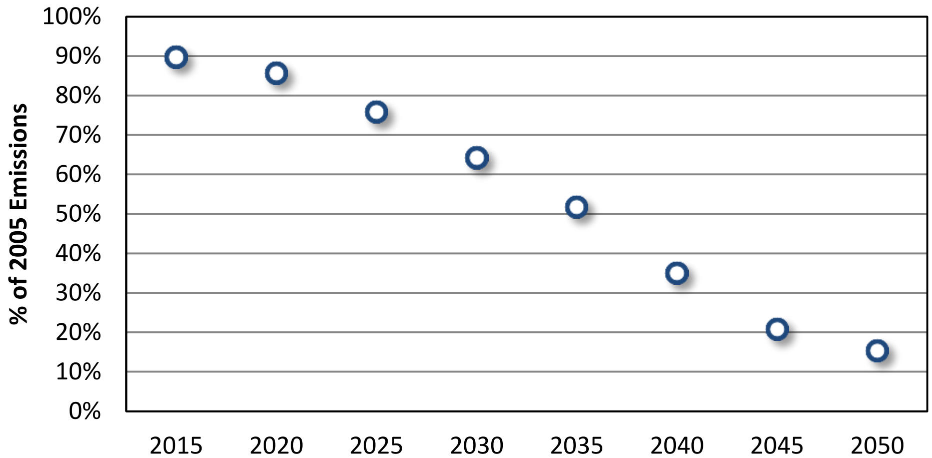
1. Is it technically feasible to reduce U.S. GHG emissions to 80% below 1990 levels by 2050, subject to realistic constraints?

This study finds that it is technically feasible for the U.S. to reduce GHG emissions 80% below 1990 levels by 2050 with overall net GHG emissions of no more than 1,080 $MtCO_2e$, and fossil fuel combustion emissions of no more than 750 $MtCO_2$. Meeting a 750 $MtCO_2$ target requires a transformation of the U.S. energy system, which was analyzed using PATHWAYS. The analysis employed conservative assumptions regarding technology availability and performance, infrastructure turnover, and resource limits. Four distinct scenarios employing substantially different decarbonization strategies —High Renewable, High Nuclear, High CCS, and Mixed Cases, which were named according to the different principal form of primary energy used in electricity generation, and also differed in other aspects of energy supply and demand—all met the target, demonstrating robustness by showing that redundant technology pathways to deep decarbonization exist.

Analysis using the GCAM model supports the technical feasibility of reducing net non-energy and non-CO_2 GHG emissions to no more than 330 Mt CO_2e by 2050, including land use carbon cycle impacts from biomass use and potential changes in the forest carbon sink.

The U.S. total emissions trajectory for the Mixed Case, assuming a constant terrestrial CO_2 sink, is shown in Figure ES-1.

Figure ES-1. U.S. Total GHG Emissions for the Years 2015-2050, as a Percentage of 2005 Emissions



2. What is the expected cost of achieving this level of reductions in GHG emissions?

Achieving this level of emissions reductions is expected to have an incremental cost to the energy system on the order of 1% of GDP, with a wide uncertainty range. This study uses incremental energy system costs—the cost of producing, distributing, and consuming energy in a decarbonized energy system relative to that of a reference case system based on the *AEO*—as a metric to assess the cost of deep reductions in energy-related CO_2 emissions. Based on an uncertainty analysis of key cost parameters in the four analyzed cases, the interquartile (25th to 75th percentile) range of these costs extends from negative $90 billion to $730 billion (2012 $) in 2050, with a median value of just over $300 billion. To put these estimates in context, levels of energy service demand in this analysis are consistent with a U.S. GDP of $40 trillion in 2050. By this metric, the median estimate of net energy system costs is 0.8% of GDP in 2050, with 50% probability of falling between -0.2% to +1.8%. GCAM analysis indicates that the complementary reductions in non-energy and non-CO_2 GHGs needed to meet the 80% target are achievable at low additional cost.

These cost estimates are uncertain because they depend on assumptions about consumption levels, technology costs, and fossil fuel prices nearly 40 years into the future. To be conservative, energy service demands in this analysis were based on an economy and lifestyles that resemble the present day and on technology cost assumptions that reflect near-term expectations, with relatively flat cost trajectories for many technologies out to 2050. Even at the higher end of the probability distribution (the 75th percentile estimate of $730 billion), which assumes little to no technology innovation over the next four decades, the incremental energy system cost of a transition needed to meet the 750 $MtCO_2$ target is small relative to national income.

These incremental energy system costs did not include non-energy benefits, for example, the avoided human health and infrastructure costs of climate change and air pollution. Additionally, the majority of energy system costs in this analysis were incurred after 2030, as deployment of new low-carbon infrastructure expands. Technology improvements and market transformation over the next decade could significantly reduce expected costs in subsequent years.

3. What changes in energy system infrastructure and technology are required to meet this level of GHG reduction?

Deep decarbonization requires three fundamental changes in the U.S. energy system: (1) highly efficient end use of energy in buildings, transportation, and industry; (2) decarbonization of electricity and other fuels; and (3) fuel switching of end uses to electricity and other low-carbon supplies. All of these changes are needed, across all sectors of the economy, to meet the target of an 80% GHG reduction below 1990 levels by 2050.

The transformation of the U.S. energy system, while gradual, entails major changes in energy supply and end use technology and infrastructure. With commercial or near-commercial technologies and limits on biomass availability and carbon capture and storage (CCS) deployment, it is difficult to decarbonize both gas and liquid fuel supplies. For this reason, meeting the 2050 target requires almost fully decarbonizing electricity supply and switching a large share of end uses from direct combustion of fossil fuels to electricity (e.g., electric vehicles), or fuels produced from electricity (e.g., hydrogen from electrolysis). In our four decarbonization cases, the use of electricity and fuels produced from electricity increases from around 20% at present to more than 50% by 2050.

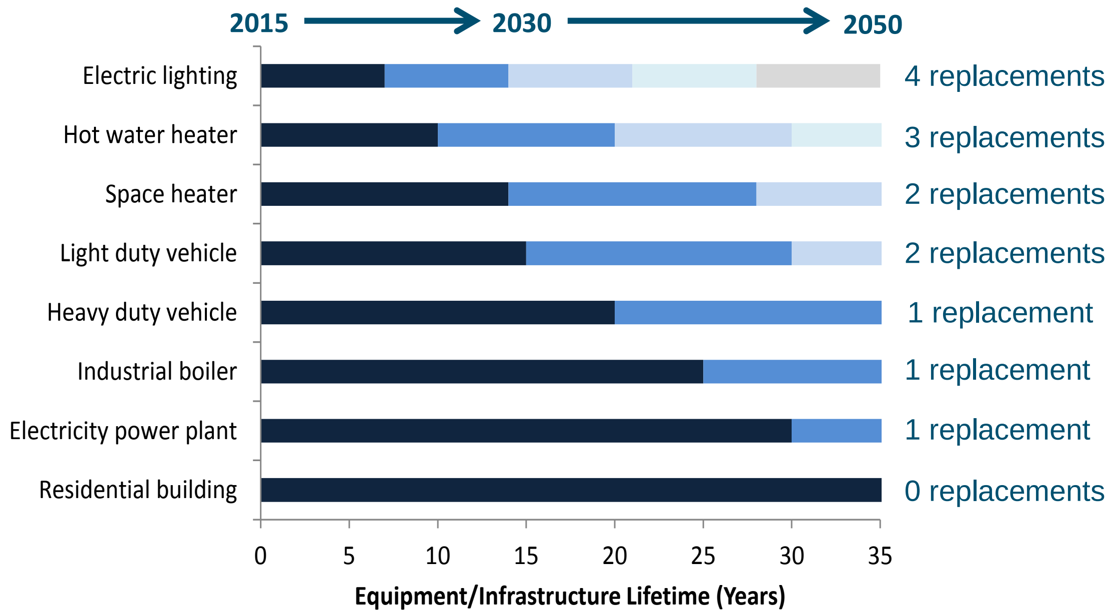
As a result, electricity generation would need to approximately double (an increase of 60-110% across scenarios) by 2050 while its carbon intensity is reduced to 3-10% of its current level. Concretely, this would require the deployment of roughly 2,500 gigawatts (GW) of wind and solar generation (30 times present capacity) in a high renewables scenario, 700 GW of fossil generation with CCS (nearly the present capacity of non-CCS fossil generation) in a high CCS scenario, or more than 400 GW of nuclear (4 times present capacity) in a high nuclear scenario.

Similar levels of transformation would be required in other sectors. For example, light duty vehicles (LDVs) would need to become more efficient and switch to low carbon fuels. The average fleet fuel economy of LDVs would need to exceed 100 miles per gallon gasoline equivalent in 2050, while shifting 80-95% of miles driven from gasoline to alternative fuels such as electricity and hydrogen. This would require the deployment of roughly 300 million alternative fuel vehicles by 2050.

4. What are the implications of these technology and infrastructure changes for the energy economy and policy?

There is still sufficient time for the U.S. to achieve 80% GHG reductions by 2050 relying on natural infrastructure turnover. However, to achieve emissions goals and avoid the costs of early retirement, it is critical to account for economic and operating lifetimes in investment decisions. The figure below illustrates the limited number of opportunities between now and 2050 for replacement or addition of infrastructure based on natural stock rollover for different types of equipment.

Figure ES 2. Stock Lifetimes and Replacement Opportunities



For some important kinds of long-lived infrastructure—for instance, power plants—there is likely to be only one opportunity for replacement in this time period. Adding new high carbon generation (e.g., coal plants) creates infrastructure inertia that either makes the 2050 target more difficult to reach, requires expensive retrofits, or puts investments at risk. Reflecting full lifecycle carbon costs up-front in investment decisions for long-lived infrastructure would reduce these risks. Transitions that involve shorter-lived equipment—for example, LDVs—raise other considerations. This analysis shows that adoption rates for alternative LDVs can initially ramp up slowly, constituting only a small share of the LDV fleet by 2030, but that they must comprise the bulk of new sales shortly thereafter in order to ensure that only a small share of conventional gasoline vehicles remain in the stock by 2050. This suggests that current barriers to adoption of low carbon LDV technologies need to be addressed well before 2030. One key barrier is upfront costs, which can be reduced by timely R&D, market transformation programs, and financial innovation. Anticipating and addressing such barriers in advance is essential to meeting emissions targets at low overall cost.

A deeply decarbonized energy economy would be dominated by fixed cost investments in power generation and in efficient and low-carbon end-use equipment and infrastructure, while fossil fuel prices would play a smaller role. Petroleum consumption is reduced by 76–91% by 2050 across all scenarios in this study, declining both in absolute terms and as a share of final energy. Meanwhile, incremental investment requirements in electricity generation alone rise to $30–70 billion per year above the reference case by the 2040s. The overall cost of deeply decarbonizing the energy system is dominated by the incremental capital cost of low carbon technologies in power generation, light and heavy duty vehicles, building energy systems, and industrial equipment. This change in the energy economy places a premium on reducing capital and financing costs through R&D, market transformation, and creative financing mechanisms. The new cost structure of the energy system reduces the exposure to volatile energy commodity prices set on global markets, while also suggesting a critical role for investment in domestic energy infrastructure.

The recent U.S. government commitment to reduce U.S. total GHG emissions by 26–28% below 2005 levels by 2025 is consistent with the results of this report. Figure ES-1 shows the reduction in total GHG emissions over time relative to 2005 for the Mixed Case in this study, assuming a constant terrestrial carbon sink. In this scenario, U.S. total GHG emissions (net CO_2e) were reduced by 25% in 2025 relative to 2005.

In its announcement, the U.S. government also reaffirmed the goal of "economy-wide reductions on the order of 80% by 2050." Since the U.S. commitment level for 2025 lies on the same trajectory as the deep decarbonization pathways in this analysis, this suggests that successfully achieving the 2025 target would put the U.S. on the road to 80% reductions by 2050. From the perspective of this study, there are different ways that the U.S. can achieve the 2025 target, some of which would lay the necessary groundwork for deeper reductions to follow, and others that might meet the target but tend to produce flat, rather than declining, emissions in the long term. This indicates the importance of evaluating near-term approaches in the light of deep decarbonization analysis. For example, proposals to prevent the construction of new coal power generation unless it is equipped with CCS are consistent with this report's finding that long-lived infrastructure additions must be low-carbon if the 2050 target is to be met while avoiding stranded assets. Other measures, such as increasing the stringency of vehicle fuel economy and appliance efficiency standards, are effective low-cost measures for reaching the 2025 goal, but to continue along the deep decarbonization trajectory after 2025 will require complementary efforts in policy, technology development, and market transformation to enable deeper decarbonization measures (e.g. deeper generation decarbonization, extensive switching of end uses to electricity and low carbon fuels) later on.

This study did not find any major technical or economic barriers to maintaining the U.S. long-term commitment to reducing GHG emissions consistent with limiting global warming to less than 2°C. In terms of technical feasibility and cost, this study finds no evidence to suggest that relaxing the 80% by 2050 emissions target or abandoning the 2°C limit is justified. In addition, the 2°C goal plays a critical role as a guide for near-term mitigation efforts, providing a benchmark for the necessary scale and speed of infrastructure change, technical innovation, and coordination across sectors that must be achieved in order to stay on an efficient path to climate stabilization.

Energy system changes on the scale described in this analysis imply significant opportunities for technology innovation and investment in all areas of the U.S. energy economy. Establishing regulatory and market institutions that can support this innovation and investment is critical. Both areas—technology innovation and institutional development—are U.S. strengths, and place the U.S. in a strong leadership and competitive position in a low carbon world.

1. Introduction

1.1. Background

The Deep Decarbonization Pathways Project (DDPP) is a collaborative global initiative to explore how individual countries can reduce greenhouse gas (GHG) emissions to levels consistent with limiting the anthropogenic increase in global mean surface temperature to less than 2 degrees Celsius (°C). Limiting warming to 2°C or less, an objective agreed upon by the international community, will require that global net GHG emissions approach zero by the second half of the 21st century. This, in turn, will require steep reductions in energy-related CO_2 emissions through a transformation of energy systems, a transition referred to by the DDPP as "deep decarbonization."

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The initial results of this effort were published in September 2014 and officially presented as part of the *Economic Case for Action* session at the Climate Summit convened by UN Secretary General Ban Ki Moon in New York. That study, "Pathways to Deep Decarbonization: 2014 Report," included a chapter on deep decarbonization pathways in the U.S. The present report represents a continuation of the analysis in the DDPP Report, providing expanded results and greater detail on methods and data sources.

1.2. Objectives

Decision makers in government and business need to understand the practical implications of deep reductions in greenhouse gas (GHG) emissions consistent with limiting the anthropogenic increase in global mean surface temperatures to 2°C or less. To that end, this report has four principal objectives:

1. To assess the technical and economic feasibility of reducing U.S. GHG emissions 80% below 1990 levels by 2050, a level consistent with the 2°C limit
2. To understand what this goal implies for the magnitude, scope, and timing of required changes in the U.S. energy system, at a relatively concrete and granular level
3. To provide a benchmark for evaluating the consistency of current and proposed climate policies with what is required to meet the 2050 target
4. To demonstrate the need for granular, long-term deep decarbonization analysis in both domestic and international climate policy processes

1.3. Research Questions

This study addresses four main research questions. First, is it technically feasible to reduce U.S. GHG emissions to 80% below 1990 levels by 2050, subject to realistic constraints? Second, what is the expected cost of achieving this level of reductions in GHG emissions? Third, what changes in energy system infrastructure and technology are required to meet this level of GHG reduction? Fourth, what are the implications of these technology and infrastructure changes for the energy economy and policy? The study focuses primarily on energy-related CO_2 emissions. Reductions in non-energy and non-CO_2 GHGs required to meet the 80% net CO_2e target are also considered, but in less detail.

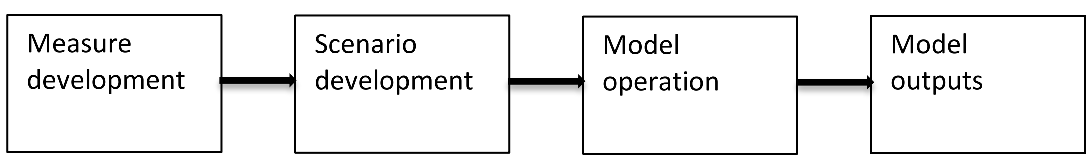
Technical feasibility is defined here as a robust analytical demonstration that multiple technology pathways exist for achieving the 2050 emissions target that satisfy a broad set of reasonableness criteria, including reliance on commercial or near-commercial technologies, natural infrastructure turnover, power system operability, and sustainability limits on natural resources. The cost of achieving the target is assessed in terms of incremental energy system costs—that is, the net cost of producing, distributing, and consuming energy in a decarbonized energy system relative to a reference case—using sensitivity analysis to address the high uncertainty in technology costs and fuel prices over a multi-decade time frame.

1.4. Research Approach

The research in this study was conducted using two models, PATHWAYS and GCAM. These models and their roles in the study are described in Chapter 2, along with other details on methods and data sources. The approach used in this study involves four main steps (see Figure 1):

1. Measure development. Model inputs used to represent energy supply and end use infrastructure and equipment, including current and projected cost and performance for incumbent technologies and a wide range of low carbon measures, were developed from a broad survey of the literature and expert opinion. The GCAM model was used to develop measures for non-energy and non-CO_2 GHG mitigation.
2. Scenario development. Cases were developed to represent a reference (current policy) scenario and four low carbon scenarios. To generate the latter, reference case infrastructure and equipment were replaced by the low carbon measures developed in step 1 at the scale and rate necessary as to meet the 2050 target while obeying a set of reasonableness constraints.
3. Model operation. The PATHWAYS model developed for this analysis produces changes in the annual stock of energy infrastructure and equipment based on the scenarios developed. It balances energy supply and demand by fuel type and end use, and employs an hourly dispatch to ensure that sufficient energy and capacity is available in a given scenario for the reliable operation of the electricity system. Complementary analyses were performed with GCAM to examine land-use emissions associated with bioenergy production and the mitigation potential of non-CO_2 GHGs.
4. Model outputs. Based on the scenarios and input values developed, the PATHWAYS model outputs annual results for primary and final energy, CO_2 emissions, the net cost of low carbon scenarios relative to the reference case, and stocks of specific infrastructure and equipment.

Figure 1. Research Approach



1.5. Current GHG Emissions and the 2050 Target

1.5.1. Current U.S. GHG Emissions

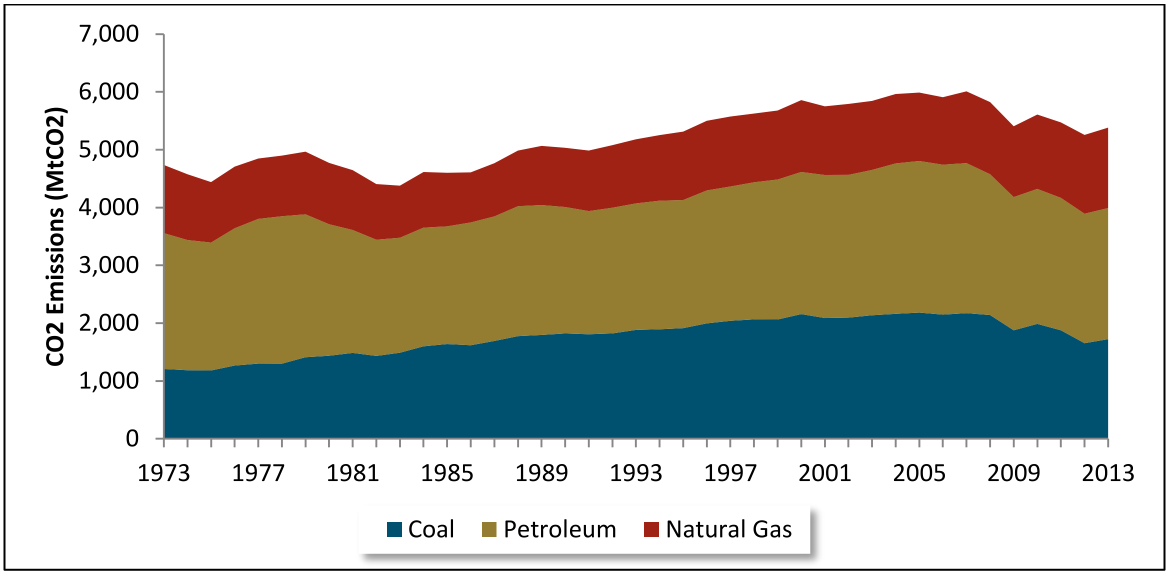
U.S. GHG emissions are dominated by CO_2 emissions from fossil fuel combustion. These have accounted for more than three-quarters of total gross GHG emissions over the last two decades (Table 1). Methane (CH_4) and nitrous oxide (N_2O) are also important GHGs in the U.S., accounting for around 15% of gross emissions. The U.S. has a net CO_2 sink (negative CO_2 flux) from land use, land-use change, and forestry (LULUCF), which the EPA estimates has grown since the 1990s. This sink represents CO_2 that is removed from the atmosphere each year and stored in terrestrial ecosystems, primarily forests. Net GHG emissions, which are the ultimate concern for climate policy, are calculated as gross GHG emissions minus the CO_2 sink.

Table 1. U.S. Gross and Net GHG Emissions, 1990, 2005, and 2012 (Source: U.S. EPA 2014)

	1990		2005		2012	
	$MtCO_2e$	% Gross	$MtCO_2e$	% Gross	$MtCO_2e$	% Gross
Fossil fuel combustion CO_2	4,745	76%	5,753	79%	5,066	78%
Total CO_2	5,109	82%	6,112	84%	5,377	83%
CH_4	632	10%	586	8%	564	9%
N_2O	399	6%	416	6%	410	6%
Hydrofluorocarbons (HFCs)	37	1%	120	2%	137	2%
Perfluorocarbons (PFCs)	21	0%	6	0%	5	0%
Sulfur hexafluoride (SF_6)	33	1%	15	0%	8	0%
Gross GHG emissions	**6,230**	**100%**	**7,254**	**100%**	**6,502**	**100%**
Net CO_2 flux from LULUCF	**-831**		**-1,031**		**-979**	
Net GHG emissions	**5,399**		**6,223**		**5,522**	

Figure 2 shows the contributions of the three fossil fuels—coal, natural gas, petroleum—to CO_2 emissions in the U.S. over the last four decades. Owing to a number of different factors—the global financial crisis, natural gas displacement of coal, and the accumulated effects of energy efficiency policies—emissions from fossil fuel combustion declined sharply beginning in 2008, and were only 14% above 1973 levels in 2013 (Figure 2).

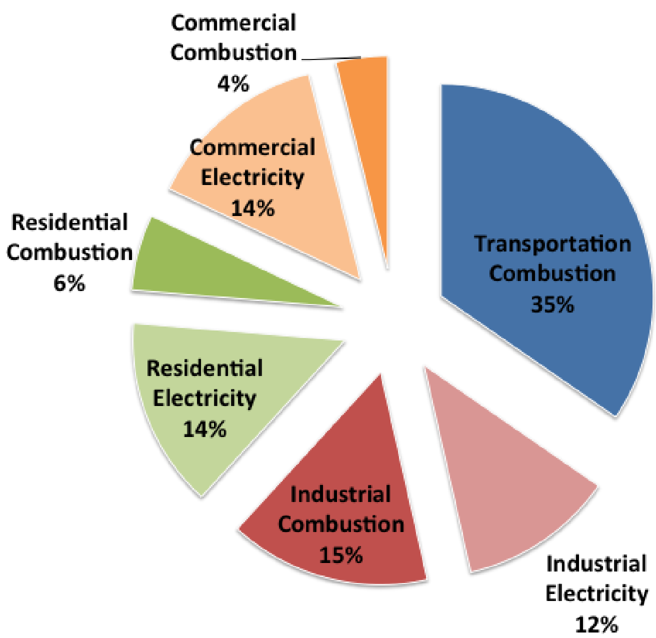
Figure 2. U.S. CO_2 Emissions from Fossil Fuel Combustion by Fuel Source, 1973–2013



Source: EIA , March, 2014 Monthly Energy Review

Fossil fuel combustion CO_2 emissions are spread across all major sectors, with the transportation and industrial sectors accounting for a higher share of emissions (62%) than the residential and commercial sectors (38%). Transportation sector CO_2 emissions arise largely from direct fuel combustion, whereas industrial sector CO_2 emissions are split between direct fuel combustion and electricity consumption, and residential and commercial emissions are primarily from electricity consumption (Figure 3).

Figure 3. U.S. CO_2 Emissions from Fossil Fuel Combustion, with Electricity Emissions Allocated to End Use, 2012



Source: U.S. EPA 2014

1.5.2. 2050 GHG Target

The target for CO_2 emissions from fossil fuel combustion used in this analysis is consistent with the DDPP *Pathways to Deep Decarbonization* report principle of convergence in global per capita energy-related CO_2 emissions to 1.7 tonnes CO_2 per person in 2050.[3] For the U.S., the target derived through this process is 750 $MtCO_2$ based on a population forecast of 440 million in 2050. This study also evaluates what additional non-energy and non-CO_2 reduction measures are required in order to meet the overall GHG emissions target for all emission sources and fuel types of 80% below 1990 by 2050, a level the scientific community has judged consistent with limiting anthropogenic warming to 2°C. Chapter 9 shows how the two targets—energy-CO_2 only and net CO_2e—are reconciled in this report using GCAM.

EPA's estimate for net GHG emissions in 1990 is 5,399 $MtCO_2e$ (Table 1). An 80% reduction below this level yields an upper limit of 1,080 $MtCO_2e$ for the 2050 target. If fossil fuel combustion results in emissions of 750 $MtCO_2e$, this implies that the total budget for all other emissions net of the LULUCF sink would be 330 $MtCO_2e$ in 2050 (Table 2). If EPA's estimated net terrestrial carbon sink for 2012 (979 $MtCO_2$ per year) were maintained out to 2050, the budget for gross emissions of all types other than fossil fuel CO_2 would be 1,309 $MtCO_2e$. Meeting this would require a 9% reduction below 2012 levels (1,436 $MtCO_2e$), or 12% below 1990 levels (1,485 $MtCO_2e$), of these non-energy and non CO_2 emissions. If the sink were to reduce sufficiently in size by 2050, deeper reductions would be required, either from energy CO_2 emissions or from these other emissions. We explore this sensitivity in Chapter 9.

Table 2. Budget for Allowable 2050 GHG Emissions Other than Fossil Fuel Combustion CO_2

Net GHG emissions target in 2050 (80% below 1990)	1,080 $MtCO_2e$	–
Budget for CO_2 emissions from fossil fuel combustion in 2050	750 $MtCO_2e$	=
Allowable other GHG emissions net of LULUCF sink in 2050	**330 $MtCO_2e$**	

At the 2009 Climate Change Summit in Copenhagen, the U.S. announced a target of reducing GHG emissions by 83% below 2005 levels by 2050. This target is consistent with legislation passed by the House of Representatives earlier in 2009, but never approved by the U.S. Senate. It is, nevertheless, an important reference point. At the EPA's current estimate of 6,223 $MtCO_2e$ of net GHG emissions in 2005, this target equates to an upper limit of 1,056 $MtCO_2e$ in net GHG emissions in 2050. In this case, assuming a constant sink at 2012 levels, allowable non-fossil fuel combustion GHGs in 2050 would be 306 $MtCO_2e$, and the required reduction in these gases below 2012 levels would be 11%.

1.6. Report Overview

The remainder of this report is organized as follows. Chapter 2 describes the methods used, including an overview of the PATHWAYS and GCAM models. Chapter 3 describes the scenarios developed and the principles underlying their design. Chapters 4-10 present detailed results for emissions, energy, and costs. Chapter 11 provides a synoptic view of the low carbon transition in the U.S. energy system. Chapter 12 provides summary observations and conclusions.

[3] SDSN and IDDRI, *Pathways to Deep Decarbonization: 2014 Report*, www.deepdecarbonization.org/

2. Methods

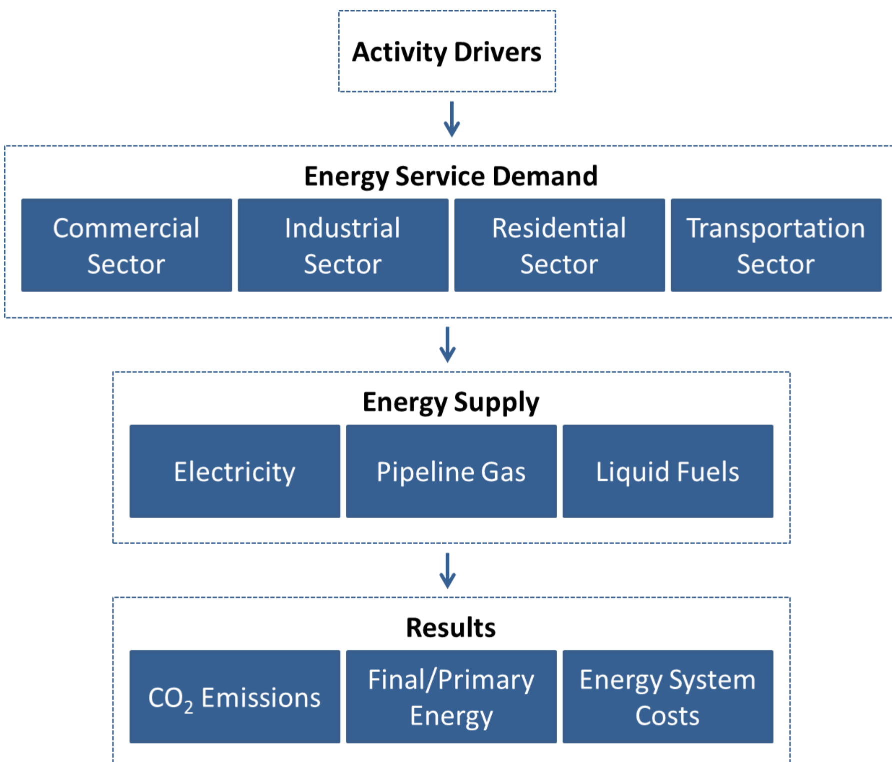
2.1. PATHWAYS Model

PATHWAYS is a bottom-up, stock rollover model of the U.S. energy system. It shares a common architecture with and uses many of the same inputs as NEMS,[4] but includes a more detailed representation of the electricity sector and is more flexible and transparent. PATHWAYS's combination of bottom-up detail and flexibility allows for examination of a broad range of technology pathways to deep decarbonization at different levels of resolution—from energy system-wide trends to, for instance, changes in the stock of light duty vehicles in the South Atlantic census region.

PATHWAYS tracks final and primary energy use, CO_2 emissions, and energy system costs across four end use sector modules: commercial, industrial, residential, and transportation (Figure 4). Energy demand in these four sectors is provided through electricity, pipeline gas, and liquid fuel modules. The electricity module includes an hourly dispatch of regional power systems for each model year, to ensure that electricity reliability requirements are met and that the costs of balancing wind, solar, and nuclear output with demand are accurately accounted for.

Energy service demand in each PATHWAYS end use sector module is driven by exogenously-specified activities. In the commercial and residential sectors, these include building floorspace, population, households, and residential square footage. In the transportation sector, activities are based primarily

Figure 4. PATHWAYS Model Architecture



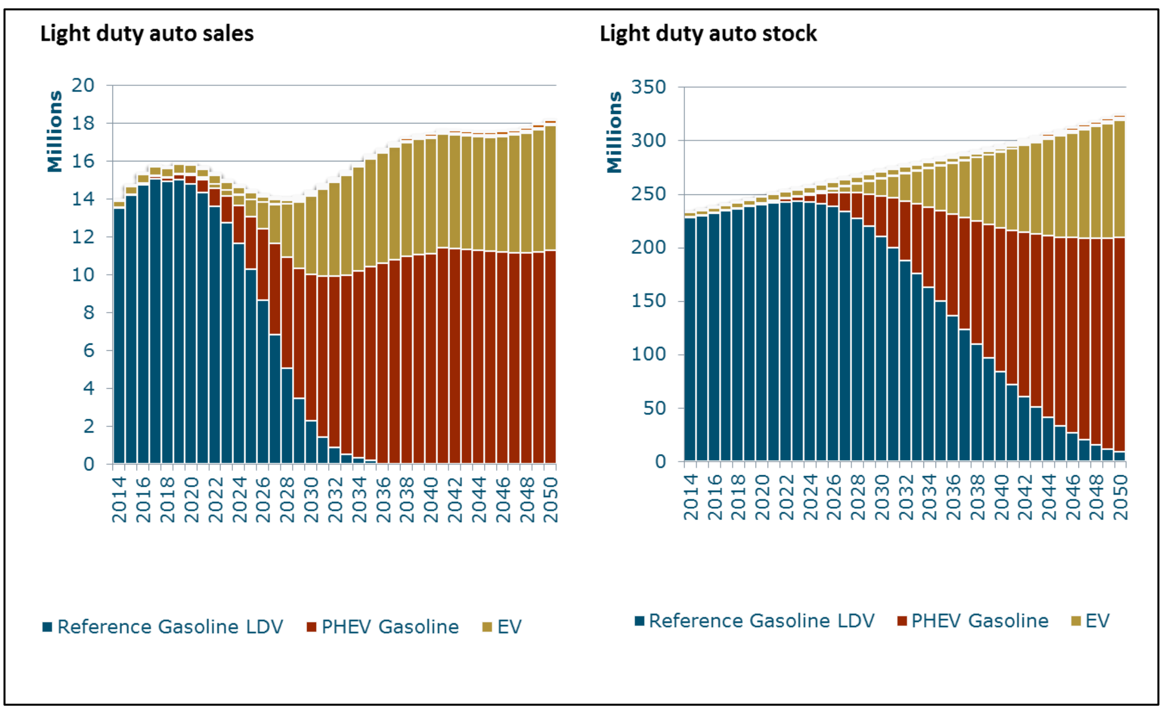
[4] EIA, National Energy Modeling System

on travel distance (VMT). In the industrial sector, they are based on sector output (value of shipments). All activity drivers are drawn from NEMS and the 2013 *Annual Energy Outlook's* (AEO's) Reference Case, which is effectively a linear extrapolation of the current U.S. economy. This approach is intended to reduce the uncertainty inherent in forecasting changes in relative prices over such a long timeframe and focus attention on the dynamics of energy system transformation. It is also intended to be conservative, to illustrate the scope and magnitude of energy system changes needed to reach 750 $MtCO_2$ of emissions in a world that resembles one very much like the current.

The Reference Case in PATHWAYS follows an emissions trajectory very similar to that in the 2013 AEO Reference Case, with total CO_2 emissions from fossil fuel combustion remaining over 5,000 $MtCO_2$ by 2050. To reach the 750 $MtCO_2$ target by 2050, users incorporate CO_2 emission reductions through three kinds of measures: (1) energy efficiency, including improved equipment and building envelopes; (2) fuel switching, including electrification and a shift to lower net CO_2 gas and liquid fuels in end use sectors (3) decarbonization of energy supplies.

Measures are incorporated in PATHWAYS through a stock rollover process. At the end of each year, some amount of energy supply and distribution equipment, buildings, and end use equipment ("energy infrastructure") is retired, based on a survival function. New energy infrastructure is needed to replace this retiring infrastructure and meet growth in energy service demand. Users implement measures by changing the composition of new energy infrastructure, by parameterizing an adoption curve for each measure. The use of adoption curves for new infrastructure moderates changes in the stock of infrastructure over time, as shown in Figure 5 for light-duty autos. Although users can retire infrastructure early, before the end of its useful life, this imposes a cost in the model. In all of the cases in this report infrastructure is allowed to retire naturally.

Figure 5. Stock-rollover Example in PATHWAYS: Light Duty Auto Sales and Stock by Model Year



PATHWAYS is a scenario model. Portfolios of measures that constitute a case are chosen manually by the user—the model does not choose measures based on price or other characteristics. The resulting technology pathways represent technically feasible and reasonable, but not optimized, strategies for deeply decarbonizing the U.S. energy system. This approach assumes a change in relative prices consistent with an explicit or implicit carbon price, which shifts adoption of energy technologies toward less CO_2-intensive alternatives. PATHWAYS makes no assumptions about the mechanisms, be they mandate or market, through which this change in relative prices is achieved.

The granularity in PATHWAYS's energy supply and end use modules is similar to that in NEMS. In the residential and commercial sectors, PATHWAYS tracks infrastructure stocks and energy demand by census region, building type, end use, and equipment. For passenger and freight transport, it tracks stock and demand by mode and vehicle type; in the industrial sector, by economic sector and end use. Granularity in the gas and liquid fuel supply in PATHWAYS is limited to the fuel mix. In the electricity sector, energy accounting is done regionally, to allow for differences in renewable resource endowments and the physical and political feasibility of nuclear power.

PATHWAYS incorporates three main, high-level constraints: energy resource constraints, energy distribution constraints, and power system operating constraints. Resource constraints apply to renewable resources, but in particular the availability of hydroelectricity and zero-net-CO_2 biomass. Distribution constraints limit the amount of electricity that can be exchanged across regions, and the amount of hydrogen that can be safely distributed in the existing gas pipelines. For the power system, PATHWAYS builds new generation, transmission, and distribution infrastructure to meet reliability needs in each census region, and dispatches generation resources to balance supply and demand in each of the three main interconnection regions in the U.S. When electricity supply exceeds demand, for instance in situations when nuclear, solar, or wind output exceeds demand and storage capacity, supply is curtailed, raising costs. The extent of load flexibility and energy storage are user determined, in the latter case via a consideration of cost-effective levels of curtailment.

Economic accounting in PATHWAYS is limited to energy system costs, which include the incremental capital and operating costs of energy supply and end use infrastructure. Incremental costs are measured relative to reference technologies in the 2013 *AEO* Reference Case. Incremental capital costs are annualized and tracked by vintage, which means that the total incremental capital cost in each year reflects the total additional, annual expenditure on infrastructure stock in a given year. In other words, annual stock costs are the annualized cost of the entire infrastructure stock, and not just new stock. Most capital cost estimates and fossil fuel prices are drawn from NEMS and the 2013 *AEO* Reference Case, extrapolated to 2050. Where appropriate, these estimates were supplemented with others, primarily U.S. government reports. PATHWAYS uses a static forecast of activity levels based on the *AEO*, and thus does not include pricing or macroeconomic feedbacks. Costs are not optimized in the model.

Technology cost and fossil fuel price projections 40 years into the future are very uncertain. To address this, uncertainty analysis was conducted by assigning distributions around base case estimates of petroleum costs, natural gas costs, and alternative fuel costs. These distributions were applied as a trajectory to 2050, so the maximum uncertainty (as a % of base case estimates) in all parameters occurs in 2050. The cost results in this report are presented with the results of this uncertainty analysis rather than only as point estimates. Base case technology cost assumptions are likely conservative, as they are based on current understanding of the potential for cost reductions in energy technologies.

2.2. GCAM

The version of PATHWAYS used in this study does not track non-CO_2 emissions or emissions from agriculture, land use, and land cover change. As a complementary analysis, GCAM was used to identify a feasible balance of CO_2 and non-CO_2 mitigation strategies consistent with an 80% reduction in 1990 GHG emissions by 2050. GCAM was also used to identify a level of domestic purpose-grown bioenergy crop production that would not add to global land use change emissions if implemented in conjunction with a retirement of the current Renewable Fuel Standard (RFS) requirements for corn ethanol. This amount of purpose-grown bioenergy (371 MMT of biomass) was used as the upper limit for domestic energy crop production in all PATHWAYS cases.

GCAM is a global integrated assessment model.[5] The model includes detailed representations of the global economy, global energy systems, and global land use, and a simplified representation of the earth's climate. Supply and demand for energy and other goods and services, and consequently land use patterns, are determined through a partial equilibrium economic simulation. The energy and land use market equilibrium is established in each period by solving for a set of market-clearing prices for all energy and agricultural good markets. This equilibrium is dynamic-recursively solved for every five years over 2005–2100. GHG mitigation in GCAM is achieved through a carbon pricing mechanism that alters the market equilibrium, thereby inducing both technological changes and demand responses according to the cost structures assumed for each technology. Activities emitting CO_2 are taxed directly, while non-CO_2 GHGs respond to carbon pricing through technology and GHG-specific marginal abatement cost curves (MACs) (EPA, 2013).

GCAM tracks 16 different GHGs, aerosols, and short-lived species. Aggregate gas emissions data are first disaggregated by sector and then converted into technology-based emission factors, which can be adjusted by changing the level of that technology. Table 3 provides the list of the gases and the data sources for calculating emission coefficients for each sector in GCAM.

Given large uncertainties in the total terrestrial carbon sink—which is poorly constrained in general and depends on both past and future land cover changes as well as land management practices, climate, and atmospheric CO_2 concentrations—the U.S. sink was held constant in the GCAM analysis at 1990 levels in most cases. The 1990 sink value is the lower than the 2012 value and so represents a conservative estimate based on recent historic values. The importance of changes in the sink for achieving the target emissions level was evaluated through a sensitivity analysis discussed in Chapter 9.

[5] The standard release of GCAM 3.2 was used in this analysis. The full documentation of the model is available at GCAM wiki: wiki.umd.edu/gcam/

Table 3. GCAM Greenhouse Gas Emission Modeling and Source Data[1]

Name	Treatment	Aggregate Emissions data	Sectoral disaggregation data
CO_2	Endogenous	CDIAC	IEA
CH_4	Endogenous	RCP	EDGAR
N_2O	Endogenous	RCP	EDGAR
F-Gases	Endogenous	EMF21	EMF21
Aerosols	Endogenous	RCP	EDGAR

CDIAC: Carbon Dioxide Information Analysis Center; IEA: International Energy Agency; RCP: Representative Concentration Pathway data; EDGAR: Emission Database for Global Atmospheric Research; EMF-21: Energy Modeling Forum Study 21.
Data sources are listed in the Bibliography section.

2.3. Biomass Budget

The primary basis for our estimate of biomass availability and costs is the DOE *Billion Ton Study Update* (BTS2), which includes resource potential estimates to 2030 for purpose-grown energy crops, agricultural and forest residues, and waste products. Table 4 shows the adjustments made in order to align biomass estimates for BTS2 with the PATHWAYS modeling framework. First, currently used resources in the *AEO* reference case were removed from the BTS2 estimates. These include fuel wood, mill residues, pulping liquors, and forest waste resources. These resources are primarily used by industry in combined heat and power (CHP), power generation, and direct fuel applications. PATHWAYS continues to satisfy this current demand and does not make these biomass resources available for other applications in the future. Second, the quantity of purpose-grown energy crops is constrained to a level (371 MMT) that does not result in indirect land use change (ILUC) GHG emissions based on GCAM analysis, described in greater detail Chapter 9. The composition of purpose-grown energy crops nationally is intentionally altered over time in the GCAM analysis, transitioning land currently used for corn ethanol production to second-generation energy crops (perennial grasses and woody purpose-grown feedstocks). With the remaining BTS2 biomass resources included, the upper limit on dry biomass supply in this report is 1,081 million metric tons, with a total primary energy value of 18.5 EJ.

Table 4. Biomass Supply in PATHWAYS Scenarios

Biomass Category	Data Source	Million Metric Tons
Purpose-grown energy crops	GCAM	371
Currently-used biomass resources	AEO Reference Case Demand	250
Other	DOE Billion Ton Study Update	460
Total		**1,081**

2.4. Key References and Data Sources

Many journal articles and technical reports were referred to in the development of the PATHWAYS model and as general points of reference for the assumptions and results in this study. Key sources include the Intergovernmental Panel on Climate Change, the International Energy Agency, the Energy Modeling Forum, U.S. federal government agencies, the National Research Council, national laboratories, university research organizations, state government agencies, and industry. Selected references are included in the Bibliography to this report.

The main data sources used for PATHWAYS model inputs and scenarios in this study are described in the Appendix. The most important single data source used was input files from the DOE National Energy Modeling System (NEMS) used to develop the Energy Information Administration's *Annual Energy Outlook 2013.* NEMS input files covered all major supply and demand sectors in PATHWAYS. These were supplemented by other data sources most of which were federal government reports, models, and databases from the U.S. Environmental Protection Agency, Department of Energy, Federal Highway Administration, and Federal Energy Regulatory Commission, along with similar types of materials from the National Research Council, national laboratories, and state governments.

3. Scenarios

3.1. Design Principles

Four deep decarbonization scenarios were developed in PATHWAYS for this analysis, in order to demonstrate a range of alternative pathways for reaching the 2050 emissions target. A set of twelve design principles was used to constrain these scenarios to be consistent with a conservative approach to engineering and economic feasibility. These principles cover a broad range of concerns—from technology readiness, to resource constraints, to infrastructure inertia, to power system reliability (Table 5). The deep decarbonization scenarios employ the same level of economic activity and demand for energy services as the *AEO* Reference Case, which assumes an economy and lifestyle similar to that of today. Emission reductions are achieved within the U.S., not through international offsets, and with no assumption of growth in the U.S. terrestrial CO_2 sink to offset energy emissions.

Technologies were limited to those that are currently commercial or are near-commercial now and can be reasonably expected to be commercial by the time of their application in the model (Table 5). For instance, electrification of the freight transport and industrial sectors is limited to plausible levels, taking into account foreseeable battery range and industrial process constraints. In the electricity sector, supply-demand balancing constraints are enforced for regional power systems, necessitating storage or curtailment and increasing costs in cases with high penetrations of non-dispatchable resources. For pipeline gas, an upper bound (7%) is enforced on the volumetric share of hydrogen based on safety constraints, requiring that any hydrogen gas produced beyond that from electricity is converted into synthetic natural gas (SNG), incurring additional energy penalties. The total supply of biomass available for energy use was limited based on analysis described elsewhere in this report. The development of new hydropower resources is also limited for sustainability reasons.

Table 5. Scenario Design Principles and Corresponding Modeling Approach

	Design Principle	Modeling Approach
1	Consistent, conservative activity levels	Assume same level of energy service demand in all cases, based on an AEO Reference Case vision of the future economy
2	Technological conservatism	Use commercially demonstrated or near-commercial technologies and conservative cost and performance assumptions
3	Robust emissions strategy	Develop and explore multiple cases with alternative emission reduction pathways and technologies
4	Robust input assumptions	Test sensitivity of results to assumptions about future demand drivers, fuel and technology costs
5	Infrastructure inertia	Enforce natural retirement of infrastructure in stock rollover model
6	Infrastructure conservatism	Minimize application of major new types of distribution infrastructure (e.g., hydrogen pipeline) when alternatives exist

7	Electric reliability	Use hourly dispatch model to ensure adequate capacity and flexibility for all generation mixes
8	Realistic sectoral approaches	Make all decarbonization measures granular and explicit, including challenging sectors (e.g. freight, industry)
9	Environmental sustainability	Apply reasonable sustainability limits to biomass use and hydropower
10	Domestic emissions focus	Do not assume international offsets will be available to reduce U.S. emissions
11	Energy system focus	Focus on reducing energy system CO_2 as the pivotal transition task, do not assume large forestry sink will be available
12	Regional flexibility	Employ decarbonization strategies consistent with regional infrastructure, resources, and policy preferences

3.2. Decarbonization Strategies

The scenarios were developed around portfolios of measures used to implement three main decarbonization strategies:

1. **Energy Efficiency**—making final energy consumption more efficient;
2. **Energy Supply Decarbonization**—reducing net CO_2 emissions from energy conversion;
3. **Fuel Switching**—switching to energy carriers that have lower net CO_2 emission factors.

The menu of key measures used to implement these strategies in different energy supply and demand sectors are shown in Table 6.

Table 6. Key Decarbonization Measures by Sector and Decarbonization Strategy

Strategy and Sector	Measures
Energy Efficiency Strategies	
Residential and commercial energy efficiency	• Highly efficient building shell required for all new buildings • New buildings require electric heat pump HVAC and water heating • Existing buildings retrofitted to electric HVAC and water heating • Near universal LED lighting in new and existing buildings
Industrial energy efficiency	• Improved process design and material efficiency • Improved motor efficiency • Improved capture and re-use of waste heat • Industry specific measures, such as direct reduction in iron and steel
Transportation energy efficiency	• Improved internal combustion engine efficiency • Electric drive trains for both battery and fuel cell vehicles (LDVs) • Materials improvement and weight reduction in both LDVs and freight

Energy Supply Decarbonization Strategies	
Electricity supply decarbonization	• Different low-carbon generation mixes with carbon intensity <50 gCO_2 /kWh that include renewable, nuclear, and CCS generation
Electricity balancing	• Flexible demand assumed for EV charging and thermal building loads • Flexible intermediate energy production for hydrogen and power-to-gas processes to take advantage of renewable overgeneration • Hourly/daily storage and regulation from pumped hydro • Natural gas w/CCS
Pipeline gas supply decarbonization	• Synthetic natural gas from gasified biomass and anaerobic digestion • Hydrogen and SNG produced with wind/solar over-generation provides smaller but potentially important additional source of pipeline gas
Liquid fuels decarbonization	• Diesel and jet-fuel replacement biofuels • Centralized hydrogen production through electrolysis • Centralized hydrogen production through natural gas reformation w/CCS
Fuel Switching Strategies	
Petroleum	• LDVs to hydrogen or electricity • HDVs to LNG, CNG, or hydrogen • Industrial sector petroleum uses electrified where possible, with the remainder switched to pipeline gas
Coal	• No coal without CCS used in power generation or industry by 2050 • Industrial sector coal uses switched to pipeline gas and electricity
Natural gas	• Low carbon energy sources replace most natural gas for power generation; non-CCS gas retained for balancing in some cases • Switch from gas to electricity in most residential and commercial energy use, including majority of space and water heating and cooking

3.3. Pathway Determinants

This study finds five critical elements that strongly determine pathways, the ensemble of technologies and measures deployed over time to decarbonize energy supply and demand. These elements, once determined by explicit policy choices, market realities, resource endowments, or institutional inertia, can significantly constrain or enable other resource and technology options and shape the overall features of the resulting energy system:

- **CCS availability and application.** The question of the commercial viability of CCS in different applications, its availability in different geographic locations, its capture rates and associated energy requirements, and its storage capacity and throughput fundamentally determine how much fossil fuel combustion can remain in the energy system. In this study, CCS is used in two of the four cases: for power generation only in the mixed case, and for power, industry, and bio-refining in the high CCS case.
- **Biomass supply and allocation.** Because biomass is a versatile energy feedstock that can displace different kinds of fossil fuel, the amount available with zero or low net lifecycle CO_2 emissions, and

its allocation to different forms of final energy supply, has a strong impact on other aspects of the energy system. In this study, biomass supply is used primarily for production of renewable gas and liquid fuels. Negative emissions bioenergy-CCS is applied only to bio-refining in the high CCS case.

- **Primary energy for electricity generation.** Electricity generation, including that used for production of intermediate energy carriers, becomes the dominant form of delivered energy in all deep decarbonization cases. The forms of primary energy used for electricity generation thus have a strong impact on cost, balancing requirements, system design, siting, and secondary environmental impacts. In this study, the effects of generation mix are explored using "corner cases" with high renewables, high nuclear, and high CCS generation portfolios, plus a mixed case includes roughly equivalent generation from all three decarbonized options.
- **Electricity balancing resources.** The choice of primary energy for generation strongly affects electricity balancing requirements. For systems with high levels of inflexible generation (e.g., variable wind and solar, conventional baseload nuclear), a variety of balancing strategies are needed to maintain reliable system operation, including regional coordination, natural gas generation, curtailment, energy storage, and flexible loads. In this study, power-to-gas hydrogen and synthetic natural gas production are also used as balancing resources, providing low carbon fuels in the process.
- **Fuel switching.** Energy efficiency is widely considered the first option to pursue in a low carbon portfolio, with value independent of other pathway determinants. In deep decarbonization cases, coordinating end use choices with the other design choices (e.g., whether CCS exists, how biomass is allocated) is required to make optimal tradeoffs between fuel type and efficiency level from the standpoint of cost and emissions. In this study, significant efficiency improvements come from thermodynamic advantages inherent in certain kinds of fuel switching (e.g., from internal combustion to electric drive train vehicles, from natural gas heat to ground-source heat pumps).

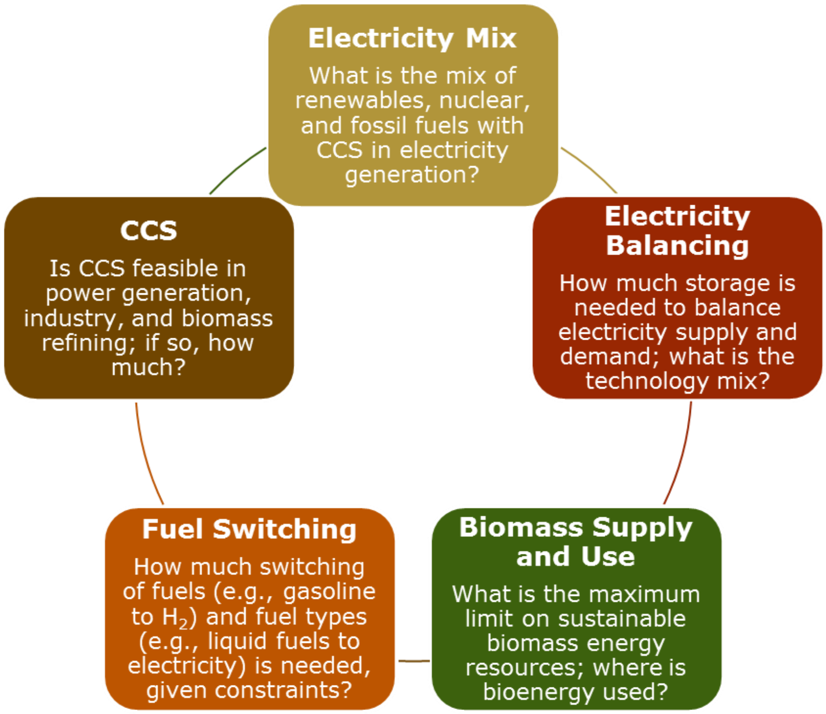
An example illustrates how these critical elements interact to shape a low carbon pathway. If CCS is not an option in power generation, the choices for low carbon electricity are narrowed to renewable energy and nuclear power. The amount of electricity storage required to balance either of these resources depends on the mix of generation resources (e.g., wind, solar, hydropower, nuclear), their location, and load flexibility (e.g., EV stock and charging schedules). Electricity can be stored in different carriers—electricity (pumped hydro, batteries), gas (electrolysis, electrolysis-methanation), or liquids (electrolysis-liquefaction). The energy storage technology mix, limits on biomass supply and how it is used, and CCS feasibility influence fuel switching decisions, both within a given fuel type (e.g., gasoline to liquid hydrogen) and across fuel types (e.g., liquid fuels to electricity).

The interactions between these critical elements affect the balance of electricity, gas, and liquid fuels across end use sectors and the extent of fuel decarbonization required.[6] Decarbonizing pipeline gas with gasified biomass and power-to-gas (hydrogen or synthetic methane) limits the need for fuel switching (e.g., pipeline gas to electricity) in industry, but it also enables liquid-to-pipeline gas fuel switching for freight transport. Decarbonizing liquid fuels with biofuels and electric fuels (hydrogen) limits the need

[6] Throughout this report, gas and liquid fuels are distinguished by how they are distributed. Liquefied pipeline gas, for instance, is considered a gas, whereas liquefied hydrogen, which is distributed in liquid form, is considered a liquid.

for switching fuel types (e.g., liquids to electricity or gas) in transport, but can require greater switching of fuel types in buildings and industry, depending on how decarbonized the liquid fuel mix is.

Figure 6. Pathways Determinants: Critical Elements that Determine the Features of a Low Carbon Energy System



3.4. Four Deep Decarbonization Scenarios

The four deep decarbonization cases created for this analysis represent a range of pathways that result from significantly different technology choices among the critical elements in Figure 6, organized around the three primary energy choices for electricity—renewable energy (High Renewables Case), nuclear (High Nuclear Case), and fossil fuels with CCS (High CCS Case). The Mixed Case includes a balanced mix of all three primary energy resources. All cases have similar strategies for and levels of energy efficiency. The four cases are intended to illustrate a broad suite of consistent, interrelated technology choices, while still remaining tractable for purposes of presentation. They are not intended to be exhaustive.

Figure 7 characterizes each scenario as a function of the pathway determinants in Figure 6. The figure shows a column for each determinant and a row for each scenario, with a colored "donut" showing the mix of options following the legend at the top, and the full scale value of a complete "donut" shown at the bottom of the figure. For example, the fifth column from the left shows generation mix, with the "donut" for each scenario showing the percentage of each type of primary energy used in generation, in each case adding up to 100%. As another example, the second column from the left shows CCS. For each scenario, the "donut" shows how much of the total reduction in fossil fuel CO_2 across all scenarios, 4890 Mt CO_2 (the difference between the 750 Mt target and the 2050 Reference Case emissions of 5640 Mt) results from non-CCS measures and CCS measures of different kinds, which are used only in the Mixed and High CCS cases.

The Mixed Case has no deployment of CCS outside the electricity sector, and a balanced mix of renewable energy, nuclear power, and natural gas with CCS in electricity generation. Non-dispatchable renewables and nuclear power are balanced with electricity storage (pumped hydro), flexible end-use electric loads (electric vehicles and thermal loads like water heating), and electric fuel loads. Hydrogen and synthetic natural gas (SNG) produced from electricity (referred to here as power-to-gas (P2G)) and biomass are used to decarbonize pipeline gas, which is used in freight transport and industry.

In the High Renewables Case, high penetrations of wind and solar energy require higher levels of electricity balancing, still in the form of P2G, than in the Mixed Case. Due to safety limits on hydrogen in the gas pipeline, SNG production (methanation of hydrogen from electrolysis) is used to balance the renewable portfolio on a seasonal (weeks to months) basis, which takes advantage of existing gas distribution system storage capacity to produce only when there are over-generation conditions on the electricity grid. Most available biomass resources are gasified and used in the pipeline, which, combined with high volumes of P2G, leads to a low net CO_2 pipeline gas mix. Pipeline gas becomes the dominant non-electric fuel, primarily used in industry and freight transportation.

Liquid fuels are the dominant non-electric fuel in the High Nuclear Case. Electricity imbalances in this case are on shorter timescales (days to weeks), and do not require longer-term fuel storage as in the High Renewables Case. Electricity balancing is done primarily through liquid hydrogen production. Hydrogen and biofuels are used in tandem to decarbonize the transportation (liquid) fuel supply. This allows higher levels of natural gas to remain in the gas pipeline, with pipeline gas primarily used in industry.

The High CCS Case seeks to preserve a status quo energy mix, both on the supply and consumption sides. Coal remains a significant share of the electricity generation mix, requiring large volumes of CCS and creating a large CO_2 residual (i.e., capture is not 100% effective) that must be balanced by reductions elsewhere. This is accomplished by significant use of CCS in industry and the use of CCS to capture CO_2 emissions in biomass refining, which creates a source of negative net CO_2 emissions. End-use fuel switching is limited to building and passenger vehicle electrification. The primary energy sources of fuels do change, however, with the major transition occurring in freight transport, where there is a shift to “renewable diesel”—a Fischer-Tropsch biofuel. The use of biomass energy CCS (BECCS) gives the transportation sector net negative CO_2 emissions,[7] allowing higher CO_2 emissions in industry.

The Mixed Case serves as the main case in this report. This is not the result of a judgment that the Mixed Case is inherently more plausible than the three “High” cases, but is rather intended to incorporate a greater mix of technologies for illustrative purposes. The analysis does not seek to evaluate or rank these cases.

[7] For new energy sources, we allocate CO_2 emissions for upstream refining to end use sectors, rather than to the industrial sector.

Figure 7. Pathway Determinants by Scenario in 2050

Table 7 shows key metrics for all of the scenarios referred to in this report.

Table 7. Scenario Summary for 2014, 2050 Reference Case, and Four 2050 Deep Decarbonization Scenarios

Indicator	Units	2014	Reference	Mixed	High Renewables	High Nuclear	High CCS
Emissions							
Residential	MMT	1,053	1,128	28	35	54	119
Commercial	MMT	942	1,080	48	57	73	141
Transportation	MMT	1,797	1,928	450	385	247	-73
Industry	MMT	1,361	1,503	220	263	374	555
Total all sectors	MMT	5,153	5,639	746	740	747	741
Final Energy Demand							
Residential	EJ	11	13	7	7	7	7
Commercial	EJ	9	11	8	8	8	8
Transportation	EJ	27	29	15	15	14	15
Industry	EJ	22	27	24	24	23	26
Total all sectors	EJ	68	80	54	55	53	56
Electricity Share (Final Energy)							
Buildings - Residential	%	46.0%	51.9%	94.2%	94.2%	94.2%	94.2%
Buildings - Commercial	%	57.8%	61.2%	89.9%	89.9%	89.9%	89.9%
Transport - Passenger (primarily LDV)	%	0.1%	0.2%	28.2%	45.8%	20.2%	46.1%
Transport - Freight (primarily HDV)	%	0.0%	0.0%	3.7%	2.5%	3.4%	2.6%
Industry	%	22.7%	18.9%	27.1%	24.9%	28.2%	20.4%
Total all sectors	%	20.8%	24.1%	42.9%	42.9%	43.0%	40.5%
Electric Fuel (Hydrogen and SNG) Share (Final Energy)							
Buildings - Residential	%	0.0%	0.0%	0.4%	0.8%	0.2%	0.0%
Buildings - Commercial	%	0.0%	0.0%	0.9%	1.7%	0.5%	0.0%
Transport - Passenger (primarily LDV)	%	0.0%	0.0%	29.3%	1.7%	55.4%	1.5%
Transport - Freight (primarily HDV)	%	0.0%	0.0%	21.5%	31.4%	39.3%	5.7%
Industry	%	0.0%	0.0%	4.9%	8.3%	2.8%	0.0%
Total all sectors	%	0.0%	0.0%	8.5%	8.8%	12.3%	0.9%
Electric generation							
Total net generation	EJ	15	20	30	32	32	24
Delivered electricity (final energy)	EJ	14	19	23	23	23	23
Share wind	%	5.4%	7.2%	39.2%	62.4%	34.1%	14.2%

Indicator	Units	2014	Reference	Mixed	High Renewables	High Nuclear	High CCS
Share solar	%	0.4%	4.0%	10.8%	15.5%	11.3%	5.3%
Share biomass	%	1.1%	0.9%	0.6%	0.6%	0.6%	0.8%
Electric generation (continued)							
Share geothermal	%	0.5%	1.0%	0.7%	0.6%	0.6%	0.8%
Share hydro	%	6.2%	7.0%	5.6%	5.3%	5.4%	7.0%
Share nuclear	%	19.2%	15.2%	27.2%	9.6%	40.3%	12.7%
Share gas (CCS)	%	0.0%	0.0%	12.2%	0.0%	0.0%	26.3%
Share coal (CCS)	%	0.0%	0.0%	0.0%	0.0%	0.0%	28.6%
Share gas (non-CCS)	%	21.9%	31.4%	0.5%	2.8%	4.6%	0.1%
Share coal (non-CCS)	%	41.5%	28.1%	0.0%	0.0%	0.0%	0.0%
Share other (fossil)	%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Share CHP	%	3.3%	5.2%	3.3%	3.1%	3.2%	4.2%
Gas							
Final energy	EJ	16.2	17.1	11.8	16.0	8.2	10.6
Fossil Share of Final Energy	%	100.0%	100.0%	6.4%	17.1%	58.1%	81.2%
Biomass share of final energy	%	0.0%	0.0%	81.9%	60.2%	35.3%	6.1%
H2 share of final energy	%	0.0%	0.0%	6.7%	6.7%	6.6%	0.0%
SNG share of final energy	%	0.0%	0.0%	5.0%	16.0%	0.0%	0.0%
Fossil w/CCS Share of Final Energy		0.0%	0.0%	0.0%	0.0%	0.0%	12.7%
Liquids and Solids							
Final energy	EJ	34	37	15	12	18	19
Share biomass	%	2.0%	2.3%	0.8%	1.0%	24.0%	28.8%
Share liquid H2	%	0.0%	0.0%	20.7%	10.3%	32.6%	2.6%
Share petroleum	%	80.6%	78.7%	43.4%	41.8%	13.9%	32.5%
Share coal and coke	%	4.6%	4.0%	1.1%	1.3%	0.8%	6.7%
Share feedstocks	%	12.8%	15.1%	34.1%	45.5%	28.7%	29.3%
Intensity metrics							
US population	Million	323	438	438	438	438	438
Per capita energy use rate	GJ/person	211	183	123	125	121	128
Per capita emissions	t CO_2/person	16.0	12.9	1.7	1.7	1.7	1.7
US GDP	B 2012$	16,378	40,032	40,032	40,032	40,032	40,032
Economic energy intensity	MJ/$	4.17	2.00	1.35	1.37	1.32	1.40
Economic emission intensity	kG CO_2/$	0.31	0.14	0.02	0.02	0.02	0.02
Electric emission intensity	g CO_2/kwh	510.9	413.5	13.5	16.0	23.4	54.7

4. Results: High Level Summary

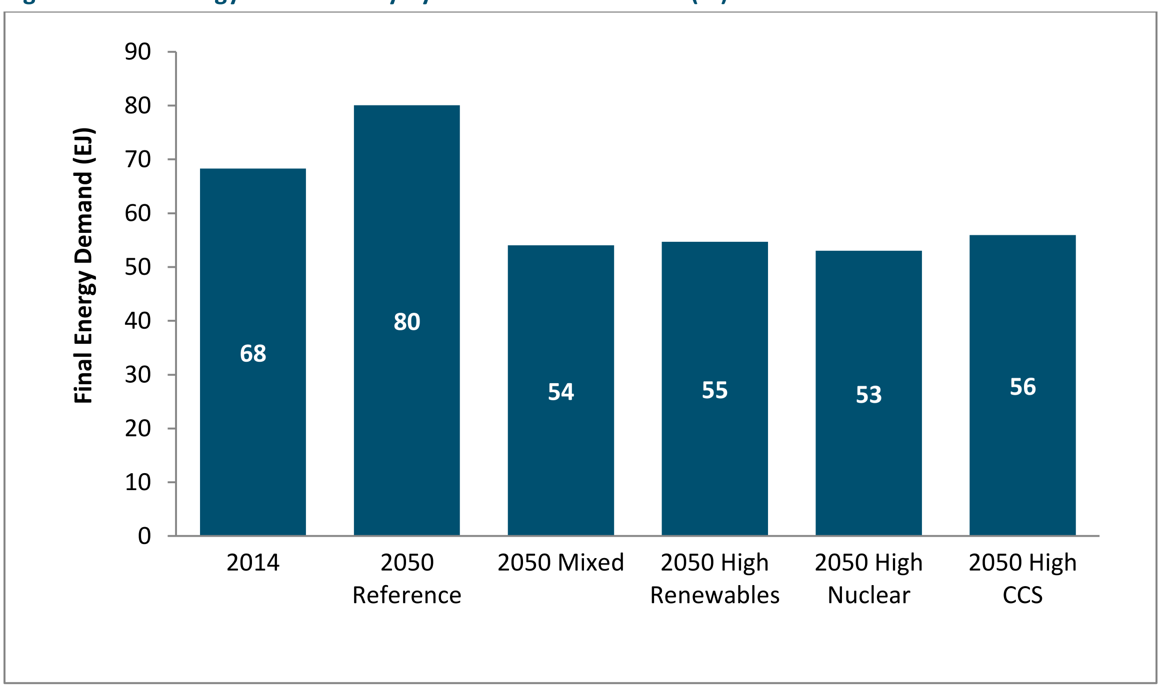
This section summarizes the high level results of this analysis across the four deep decarbonization scenarios and the Reference Case. Subsequent sections contain the following results:

- **Energy Demand—**results for end use efficiency and fuel switching in the residential, commercial, transportation, and industrial sectors;
- **Energy Supply—**results for electricity, gas, and liquid fuel mixes, and illustrative results for regional power system dispatch;
- **CO_2 Emissions—**CO_2 emissions results for end use, sectors, and regions;
- **Costs—**incremental costs results by sector and cost component, household and electricity costs; comparison to cost results from EMF-24.
- **GCAM Results—** results for technical feasibility and cost of non-energy and non-CO_2 emissions mitigation

4.1. Final Energy

By 2050, the Reference Case shows a modest 17% increase in total final energy use relative to 2014 levels, from 68 to 80 EJ (Figure 8). The underlying drivers of energy use—population (+35%), building floor area (+44%), industrial output (+81%)—all grow significantly over this time period, but their impact on energy use is partially offset by increases in the efficiency of energy use, which are a continuation of current policy and technology trends. Final energy use in the deep decarbonization cases ranges from 53 to 56 EJ, a reduction of 30-34% below the Reference Case in 2050, and 18-22% below 2014 levels.

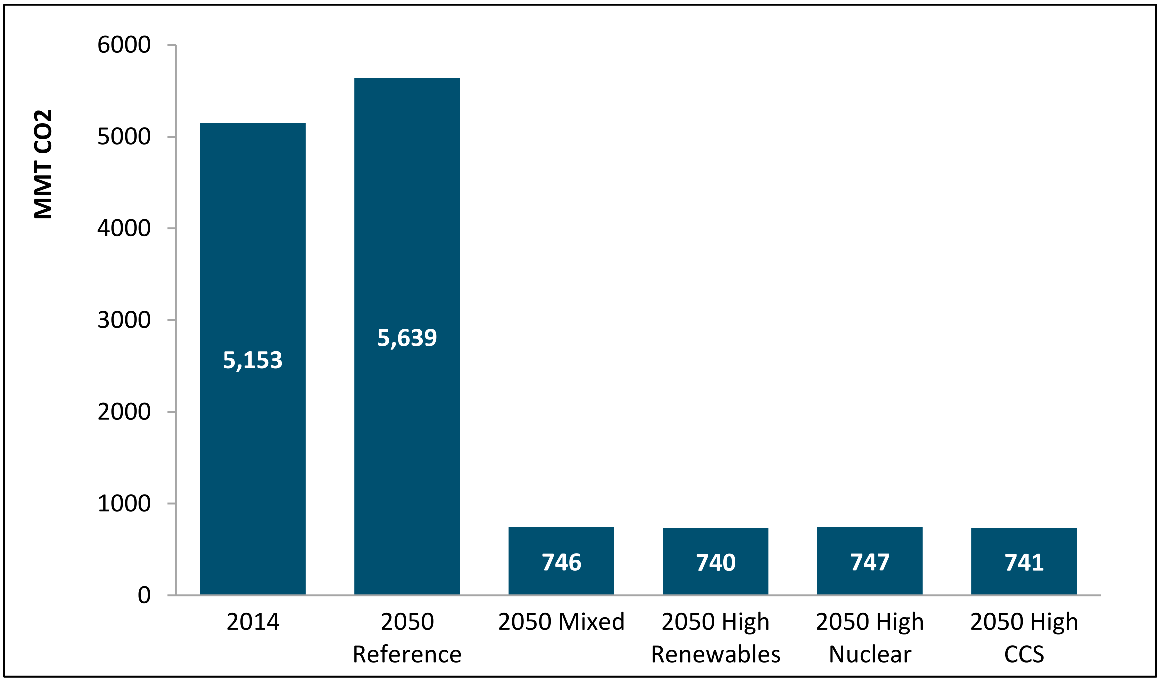
Figure 8. Final Energy Use Summary by Case in 2014 and 2050 (EJ)



4.2. Emissions

Energy-related CO_2 emissions levels experience more dramatic change (Figure 9). Reference Case CO_2 emissions reach 5,639 $MtCO_2$ by 2050, a 9% increase from total 2014 emissions and a 19% reduction in emissions per capita—from 16.0 to 12.9 tCO_2 per person. All four deep decarbonization cases reach emissions below 750 $MtCO_2$, or 1.7 tCO_2 per person, an 85% reduction in total emissions and an 89% reduction in emissions per capita relative to 2014 levels.

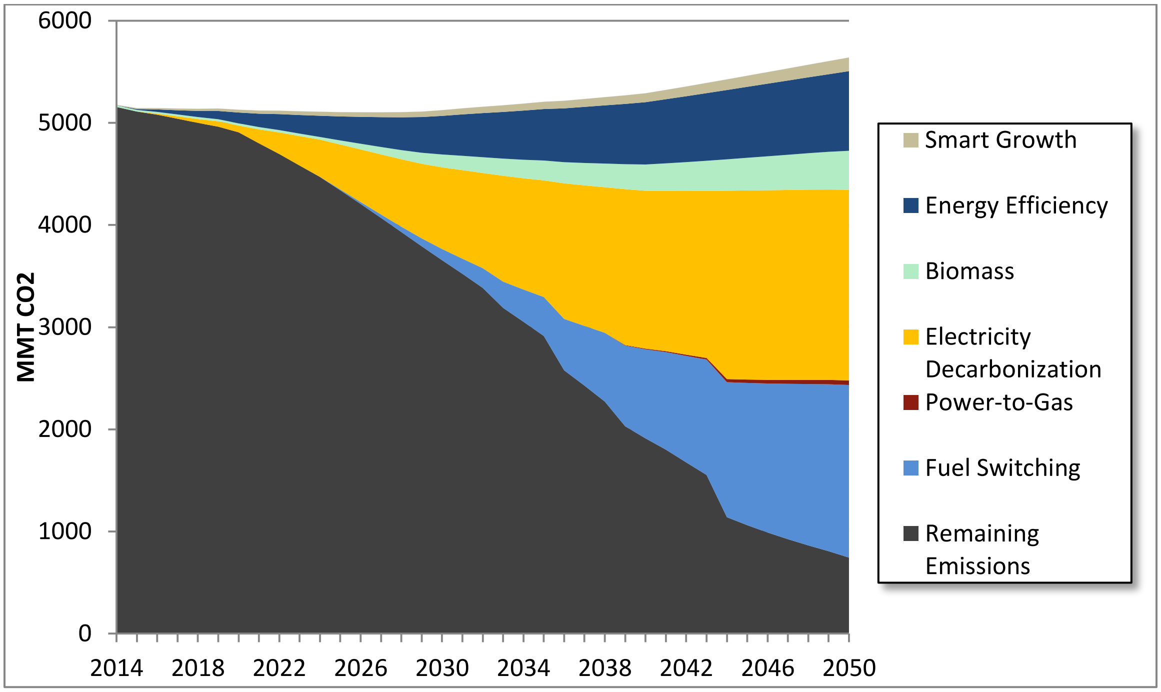
Figure 9. CO_2 Emissions by Case in 2014 and 2050



4.3. Emission Reductions

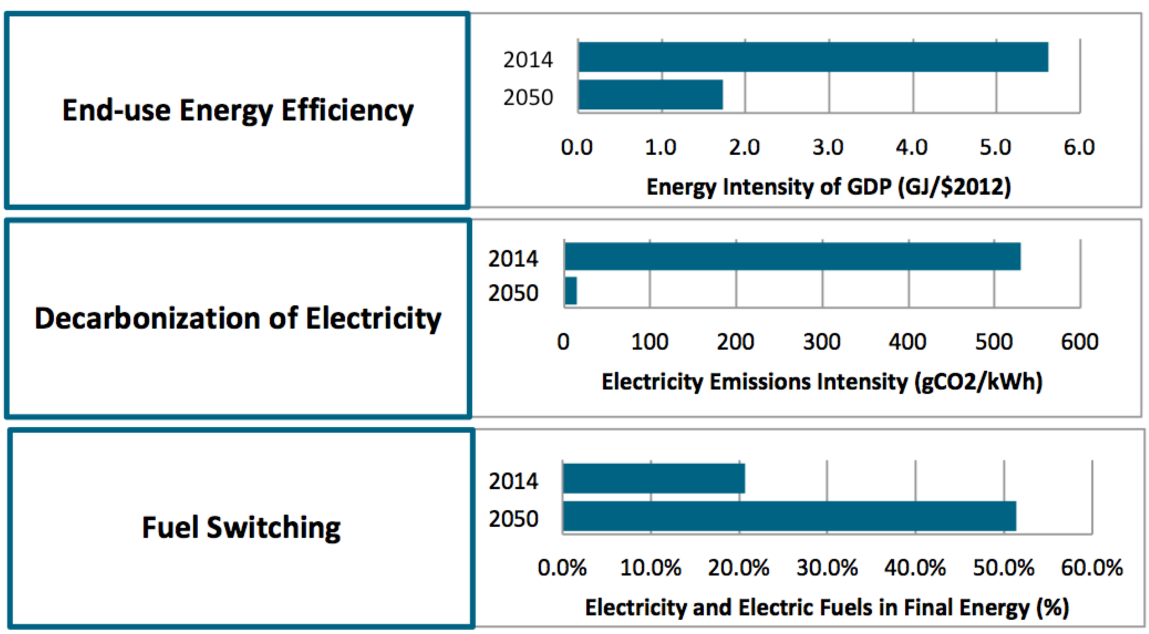
The transition to a low-carbon energy system entails three main strategies: (1) highly *efficient end use* of energy in buildings, transportation, and industry; (2) *decarbonization* of electricity and other fuels; and (3) *fuel switching* of end uses from high-carbon to low-carbon supplies, primarily electric. All three of these strategies must be applied to achieve the 2050 decarbonization goal. For the case shown in Figure 10, these measures together account for 90% of the reduction from Reference Case emissions of about 5500 Mt in 2050 to the target level of 750 Mt, with energy efficiency accounting for 20%, fuel switching for 31%, and electricity decarbonization for 39%. (Note that the allocation of emission reductions to different decarbonization wedges is subjective due to interactive effects between the measures. For example, the replacement of an inefficient internal combustion engine automobile with an efficient electric vehicle that charges on a low carbon electricity grid simultaneously employs all three main strategies.)

Figure 10. Decarbonization Wedges for the U.S., Mixed Case



Indicators for the three main decarbonization strategies are shown for the Mixed Case in Figure 11. The share of end-use electricity or electrically-produced fuels increases from 20% in 2010 to over 50% in 2050. The carbon intensity of electricity is reduced from more than 500 g CO_2/kWh in 2014 to less than 15 g CO_2/kWh in 2050. Energy intensity of GDP decreases by 70% over this period as final energy use declines from 68 to 54 EJ while GDP nearly doubles.

Figure 11. Indicative Metrics for the Three Main Decarbonization Strategies, Mixed Case Compared to 2014

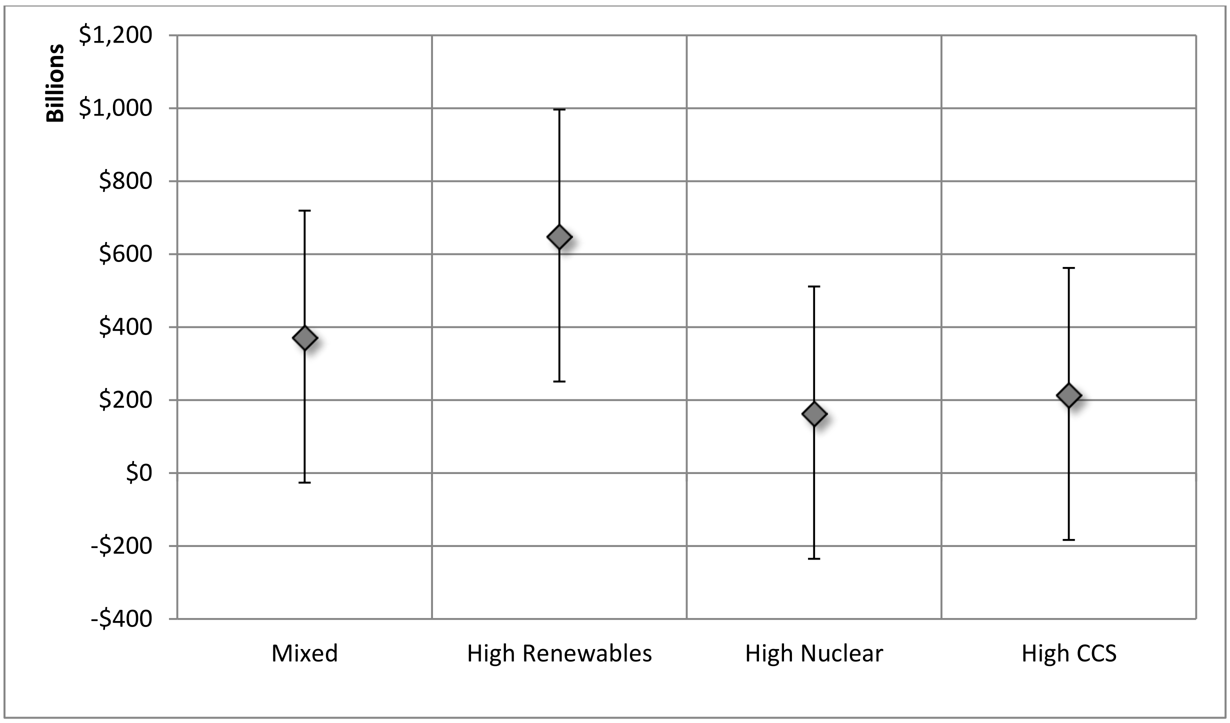


4.4. Cost

Incremental energy system costs—incremental capital costs plus net energy costs—exhibit a broad range in 2050, reflecting the significant uncertainty in technology costs and fossil fuel prices over such a long timeframe. Under base assumptions of technology costs and fossil fuel prices, the median value of incremental costs ranges from $160 billion (2012 $) to $650 billion across scenarios, with the difference driven primarily by the relative quantities and prices of residual natural gas and petroleum fuels remaining in the energy system in 2050.[8] The average median value across cases is just over $300 billion.

Based on an uncertainty analysis of key cost parameters, the interquartile range of incremental energy system costs extends from negative $250 billion to $1 trillion across all cases (Figure 12). To put these numbers in context, the activity drivers in PATHWAYS that drive energy service demand in all of the cases are consistent with a U.S. GDP that grows by a real annual average rate of just over 2% per year over the next four decades, to around $40 trillion in 2050. The average 75th percentile estimate of net incremental energy system costs ($730 billion) across cases is equivalent to 1.8% of this GDP level. The average 25th percentile value is negative $90 billion.

Figure 12. Incremental Energy System Costs in 2050



Note: The error bars in the figure show the 25th and 75th percentile values.

[8] Petroleum fuel prices are significantly more expensive than natural gas by 2050 in the AEO 2013 Reference Case. Thus, scenarios in which more petroleum fuels are displaced are lower net cost.

5. Results: Energy Demand

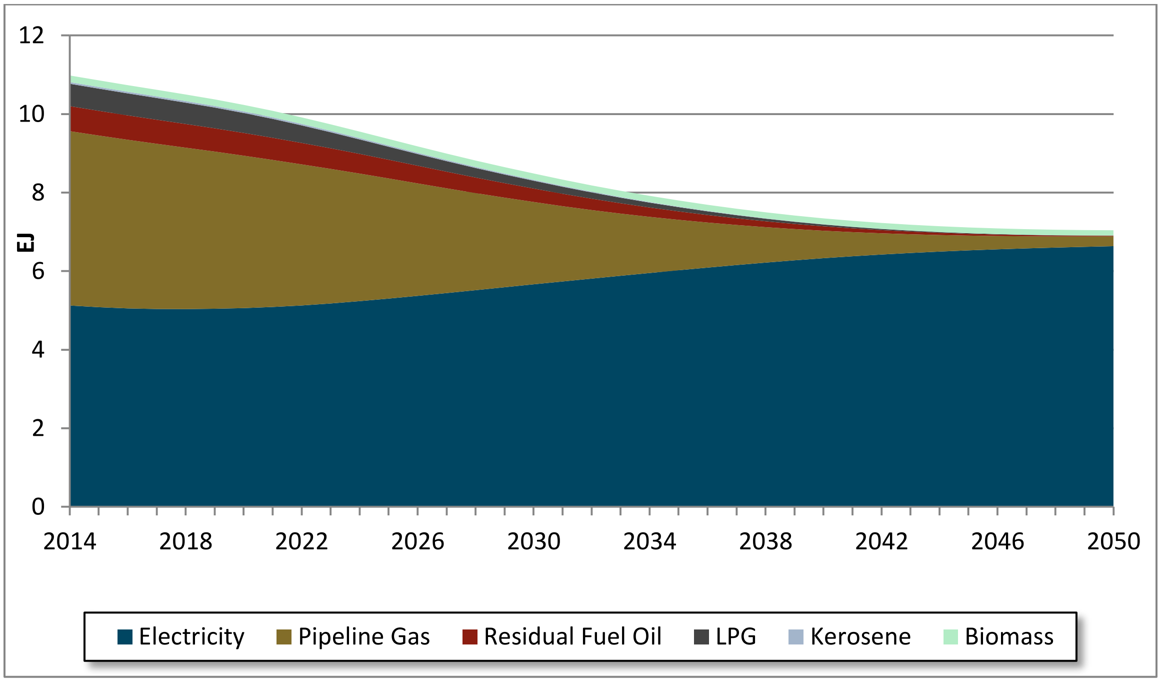
5.1. Residential

In all four decarbonization cases, significant gains in end use energy efficiency offset a 36% increase in population from 2014 to 2050. Improvements in efficiency result from three primary strategies:

1. Electrification of space and water heating, the two primary residential energy end uses;
2. Aggressive efficiency improvements in electric end uses, such as clothes washers, dishwashers, and lighting;
3. Improving residential building envelopes (e.g., windows, roofs, insulation) to reduce the demand for space heating and cooling.

As a result of the electrification of space and water heating, electricity accounts for the vast majority of final energy demand by 2050 in all decarbonization cases (Figure 13).

Figure 13. Residential Energy Demand, All Decarbonization Cases

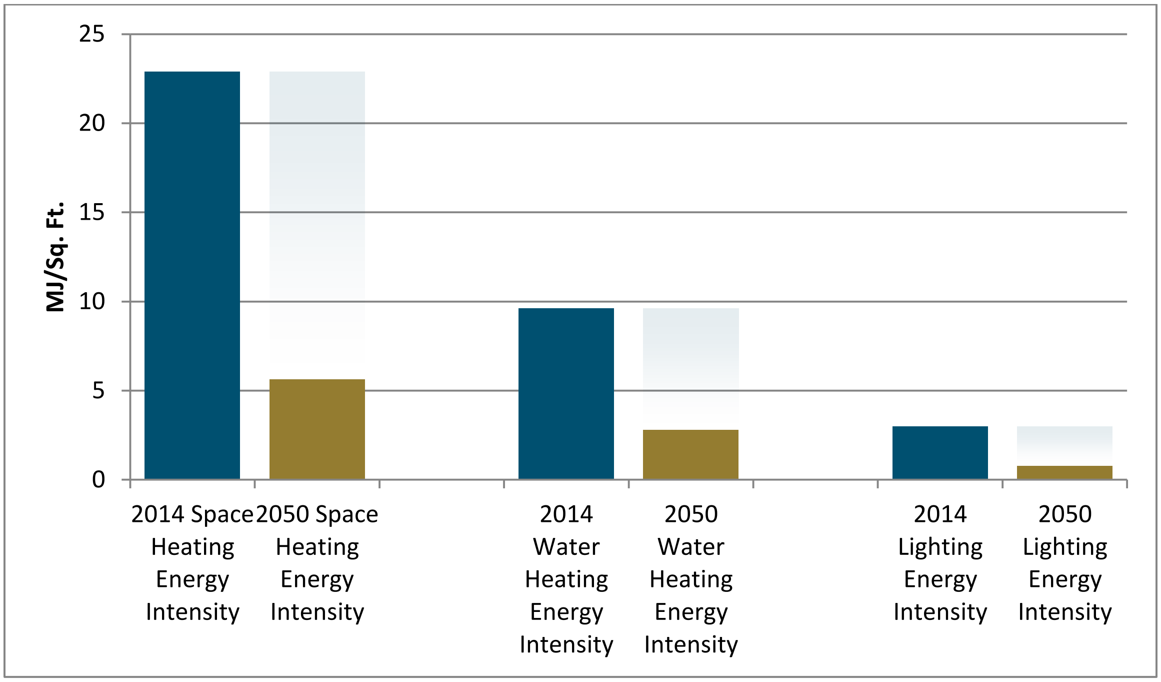


The largest declines in residential energy intensity are seen in three end uses:

1. Space heating, due to the higher efficiency of heat pumps and the effect of building envelope measures that reduce heating demand;
2. Water heating, due to the higher efficiency of heat pumps and hot water savings from high-efficiency dishwashers and clothes washers;
3. Lighting, due to the high penetration of very efficient LEDs.

Figure 14 shows the magnitude of these efficiency improvements by 2050 relative to 2014, normalized by floor space.

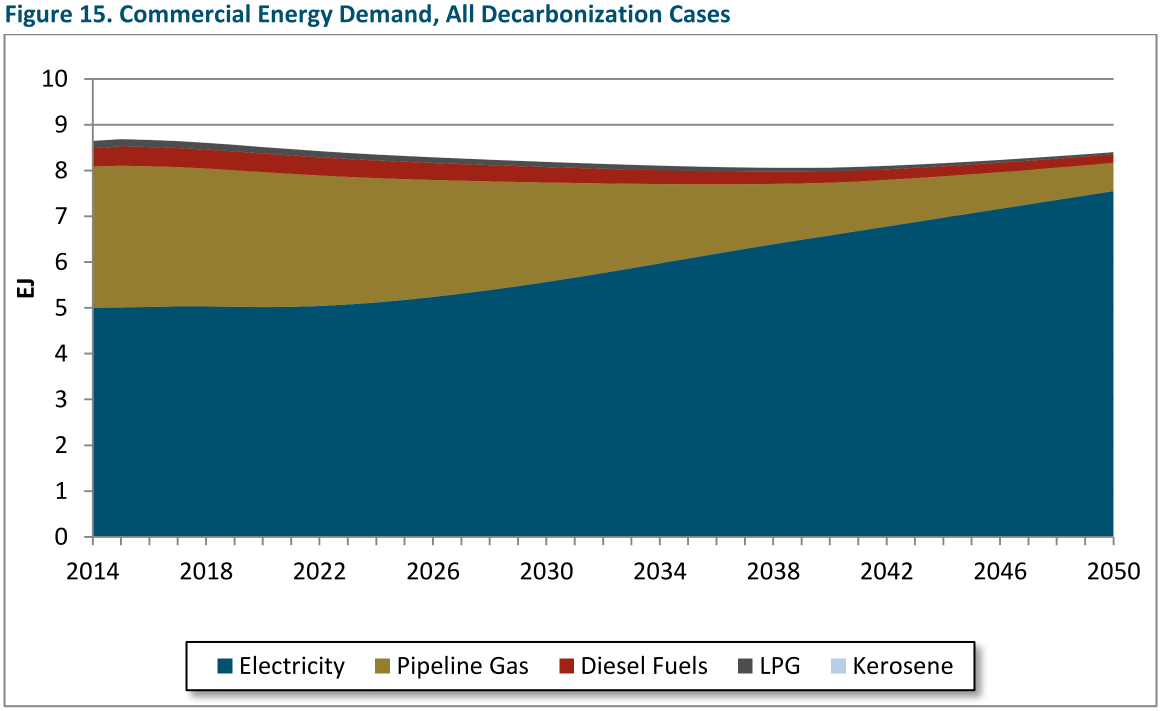
Figure 14. Residential Energy Intensity Comparison: 2014 and 2050 Decarbonization Case Results



5.2. Commercial

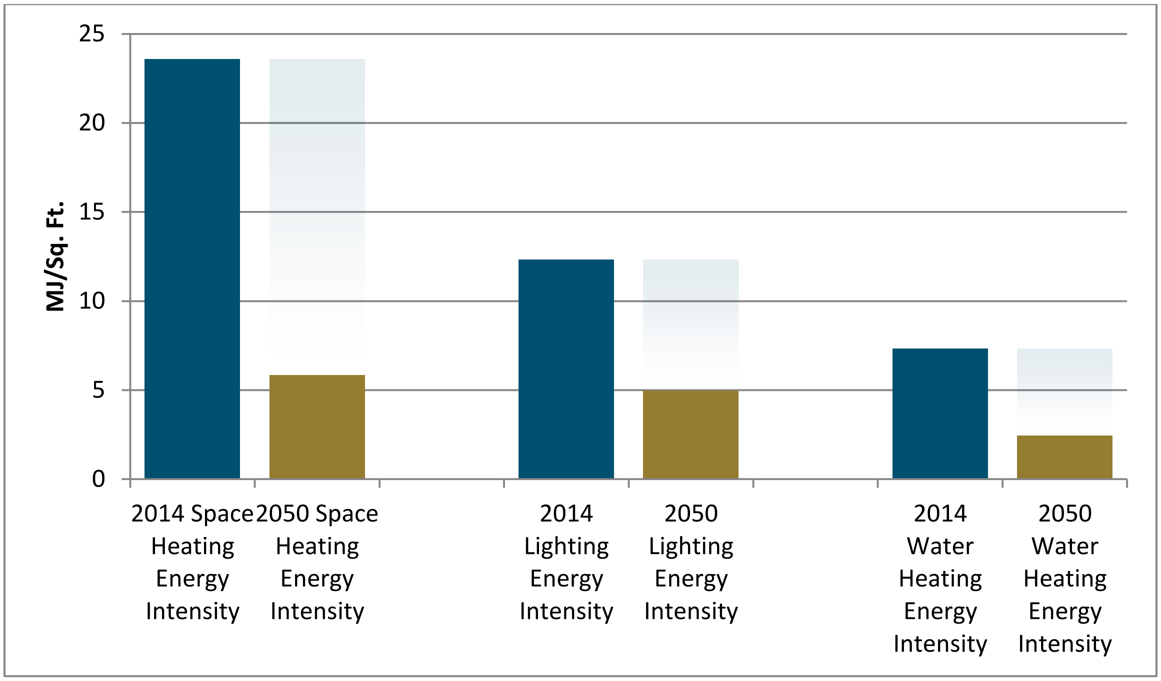
Like the residential sector, most commercial sector end uses are electrified, and electricity becomes the dominant energy carrier across all four decarbonization cases (Figure 15). Through improvements in efficiency, commercial final energy use remains relatively flat over 2014-2050, despite a more than 40% increase in commercial floor area.

Figure 15. Commercial Energy Demand, All Decarbonization Cases



Similar to the residential sector, the largest gains in commercial sector end use efficiency are in space heating, lighting, and water heating, with improvements in space and water heating due to the use of high efficiency electric heat pumps and improvements in lighting efficiency to the prevalence of LEDs. The magnitude of improvements in these three areas by 2050, relative to 2014, is shown in Figure 16.

Figure 16. Commercial Energy Intensity Comparison: 2014 and 2050 Decarbonization Case Results



5.3. Transportation

5.3.1. Light-Duty Vehicles

LDV stocks evolve from the fossil fuel-powered internal combustion engines (ICEs) prevalent today to a mix of electric vehicles (EVs), plug-in hybrid electric vehicles (PHEVs), and hydrogen fuel cell vehicles (HFCVs). None of the technology options modeled here achieves significant stock penetration until the 2030 timeframe, as shown in Figure 17 for the Mixed Case. Electricity is the dominant energy carrier for passenger vehicle transport in all cases except for the High Nuclear Case, where hydrogen produced from electrolysis is the primary energy carrier. Gasoline is used as the residual fuel for PHEVs traveling beyond their electric range, and thus gasoline continues to be a non-trivial portion of LDV energy use in the High Renewables and High CCS Cases, which have large PHEV stocks (Figure 19).

By 2050, however, no significant numbers of ICE LDVs remain in any of the cases (Figure 18), as a result of high penetrations of non-ICE vehicles in new car sales by 2035. In the High Renewables and High CCS Case, EVs and PHEVs dominate the vehicle fleet. In the High Nuclear Case, HFCVs and EVs dominate. The Mixed Case has a roughly equal blend of EVs, PHEVs, and HFCVs by 2050.

Figure 17. Annual LDV Stock

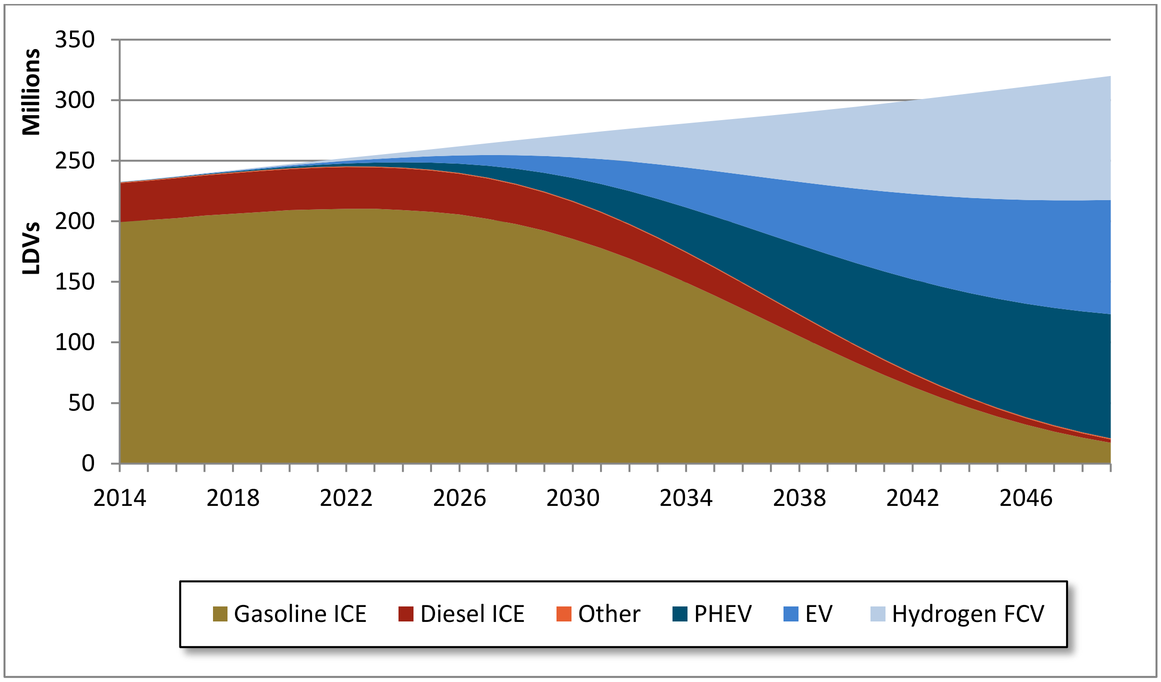


Figure 18. 2050 LDV Stock

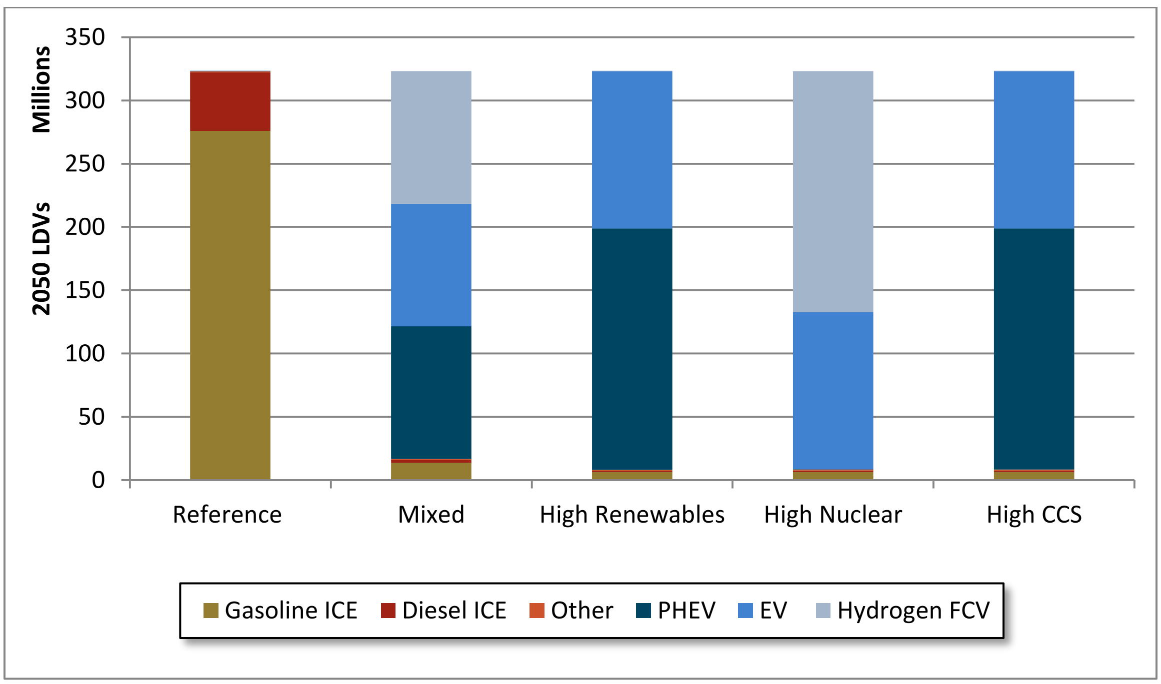
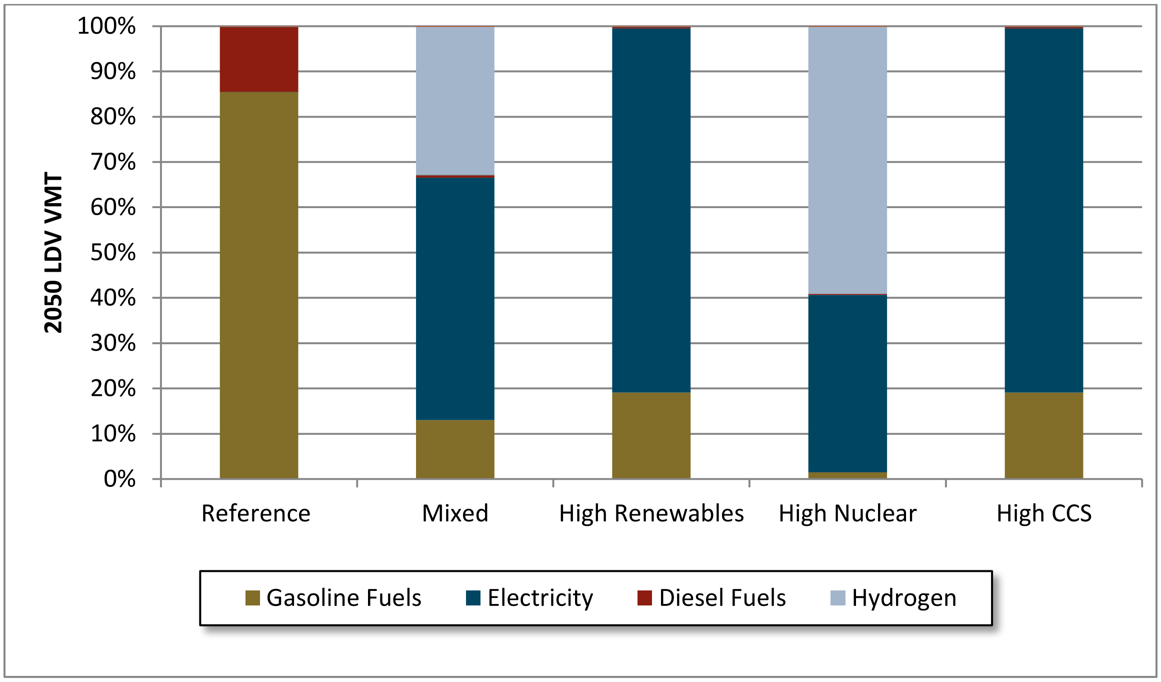
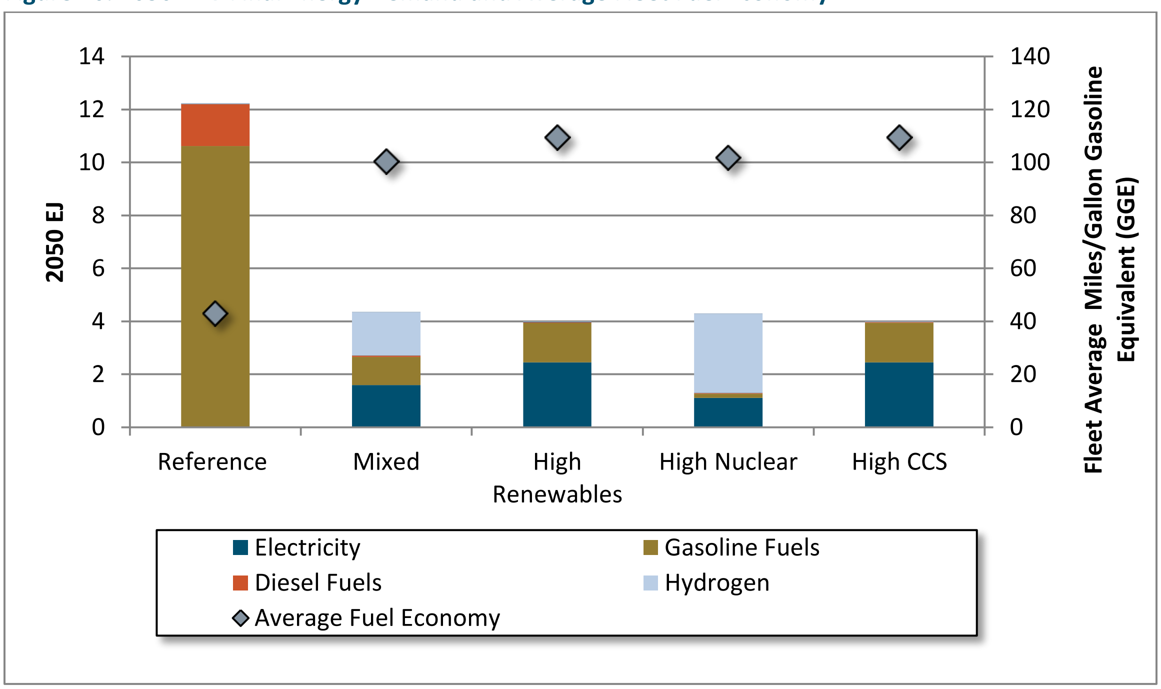


Figure 19. 2050 LDV VMT by Fuel



Across all cases, LDV final energy demand declines by nearly 70% from the Reference Case by 2050. This decline results primarily from a more than doubling of the LDV fleet's fuel economy, with the average fleet fuel economy of exceeding 100 miles per gallon gasoline equivalent (GGE) in all four decarbonization cases (Figure 20).

Figure 20. 2050 LDV Final Energy Demand and Average Fleet Fuel Economy



5.3.2. Heavy Duty Vehicles

The heavy duty vehicle (HDV) fuel mix in 2050 is primarily determined by whether biomass is used to make a diesel "drop-in" fuel or to make synthetic natural gas that is blended into the pipeline gas mix. In cases where the former dominates (High Nuclear, High CCS), ICE diesel vehicles remain the main form of heavy duty transport. If biomass is used to make gas, this necessitates a transition to liquefied pipeline gas or hydrogen HDVs. We do not model a complete conversion of the HDV fleet due to hydrogen in

Figure 21. HDV VMT by Fuel

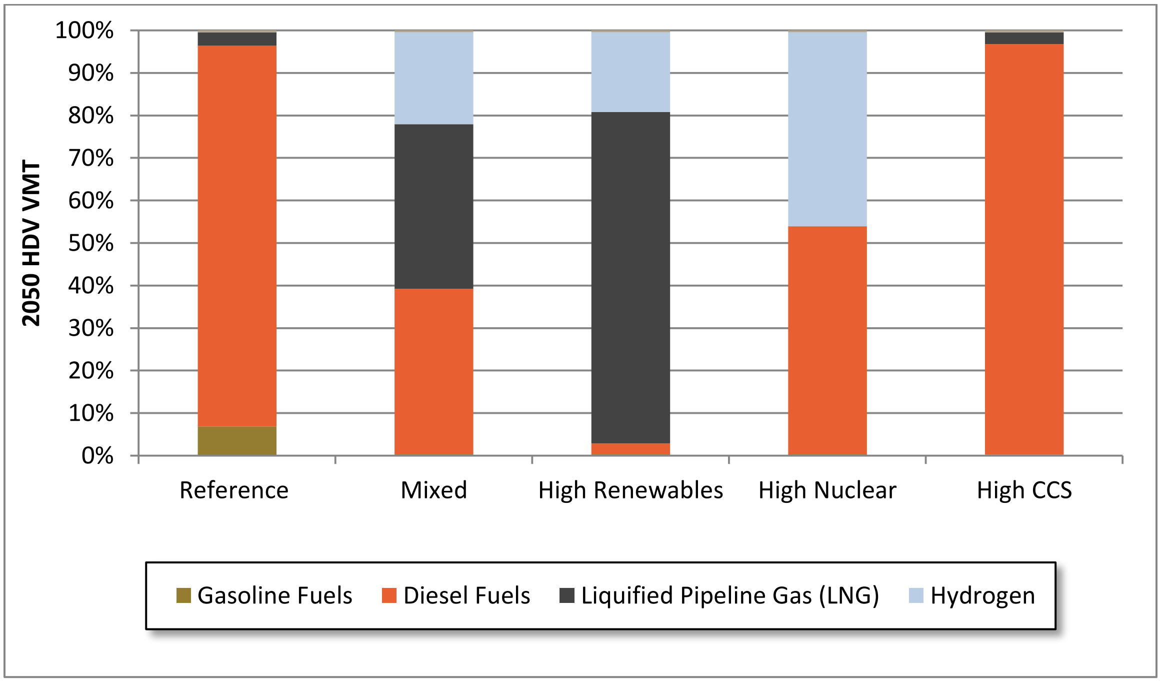
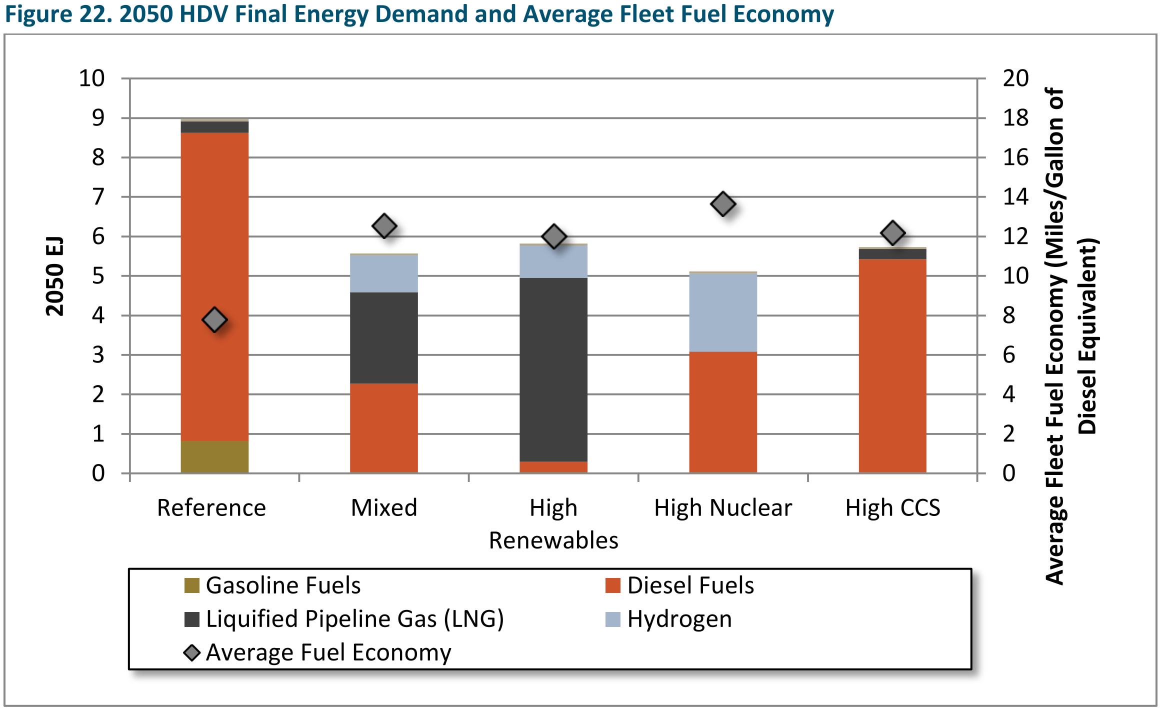


Figure 22. 2050 HDV Final Energy Demand and Average Fleet Fuel Economy



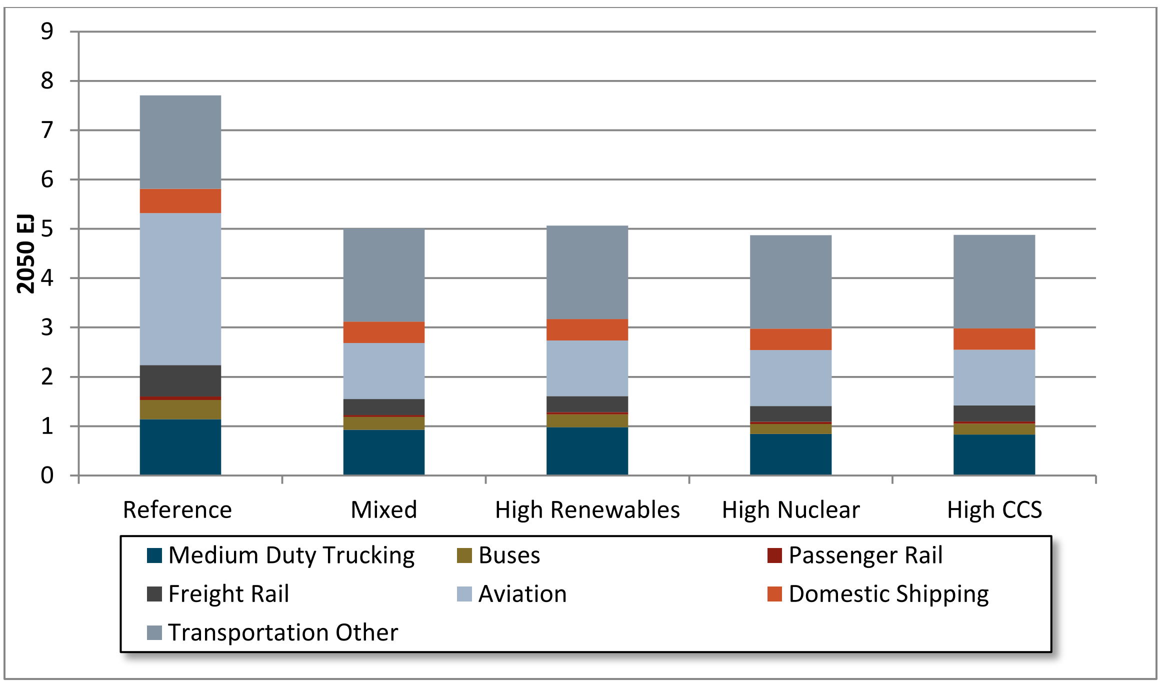
any of the four cases, due to questions about commercialization timelines and energy density limitations. The High Nuclear Case, which also has HFCVs in its LDV fleet, has the highest penetration of HDV HFCVs (50%) (Figure 21).

In addition to decarbonizing the HDV fuel supply, alternative fuel HDVs improve the average fleet fuel economy in the four decarbonization cases to greater than 12 miles per gallon diesel equivalent (GDE). The highest average HDV fleet efficiency is found in the High Nuclear Case, due to the prominence of HFCVs (Figure 22).

5.3.3. Other Transportation

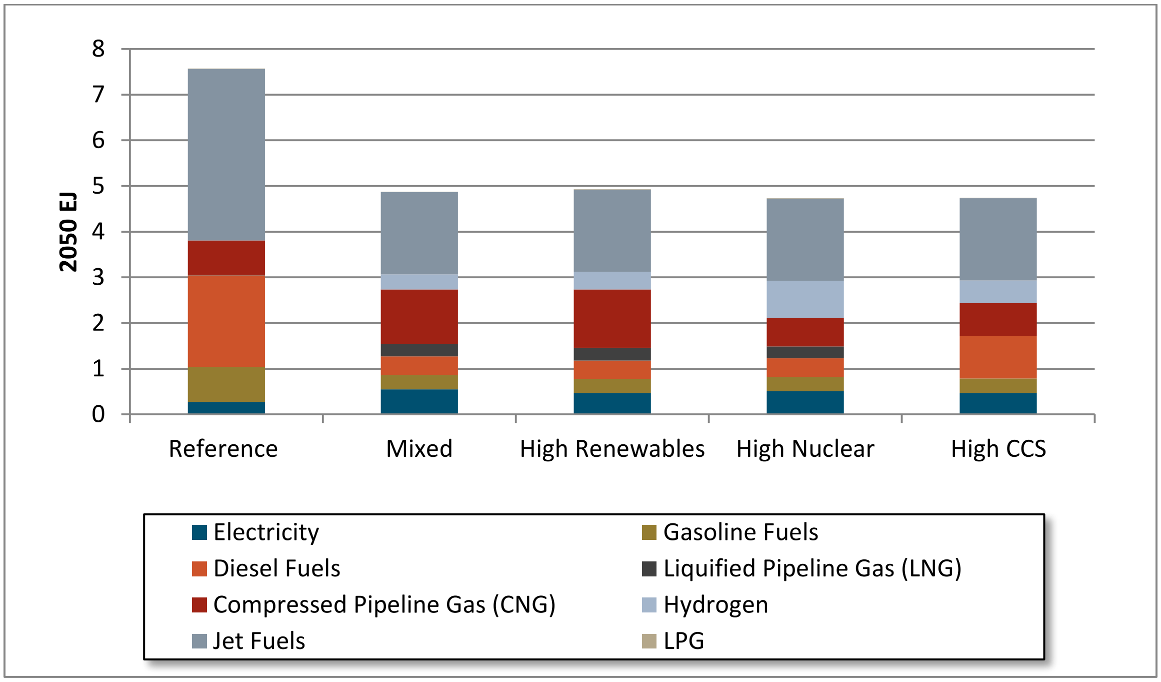
HDVs and LDVs account for roughly two-thirds of transportation sector energy demand in all cases. The remaining one-third includes aviation, freight rail, passenger rail, medium-duty trucking, buses, and military use. For these modes, a combination of biofuels (aviation), electrification, hybridization, and fuel cells (freight rail, passenger rail, medium-duty trucking, buses) were employed to reduce emissions. These changes in technology are accompanied by energy efficiency improvements, resulting in around 35% reductions in final energy demand relative to the Reference Case (Figure 23).

Figure 23. Other 2050 Transportation Subsector Energy Demand



In the High Renewables and Mixed Cases, fleet vehicles like medium-duty trucks and buses are fueled by compressed pipeline gas and the majority of freight rail and some shipping switches to liquefied pipeline gas, using decarbonized pipeline gas. In the High Nuclear Case, fleet vehicles are powered by hydrogen fuel cells. In the High CCS Case, fleet vehicles are powered by renewable diesel—a drop-in synthetic diesel fuel produced from biomass. Aggressive aviation efficiency reduces the relative importance of jet fuel demand by 2050 in all four cases (Figure 24).

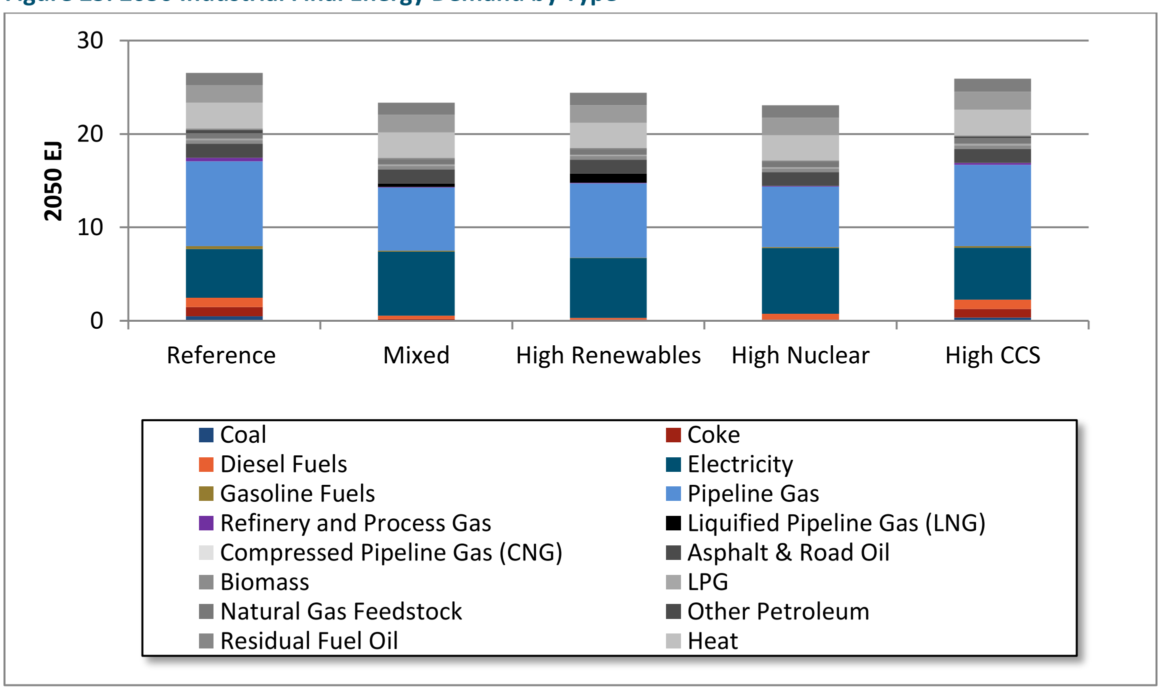
Figure 24. 2050 Other Transportation Subsector Energy Demand by Energy Type



5.4. Industrial

In the four decarbonization cases, industrial final energy demand does not significantly change from Reference Case levels (Figure 25). All four cases achieve efficiency gains from some electrification of heating (heat pumps) and, except for in the High CCS Case, some steam production (boilers). Additionally, there is fuel switching from diesel in areas like agricultural pumping and construction

Figure 25. 2050 Industrial Final Energy Demand by Type

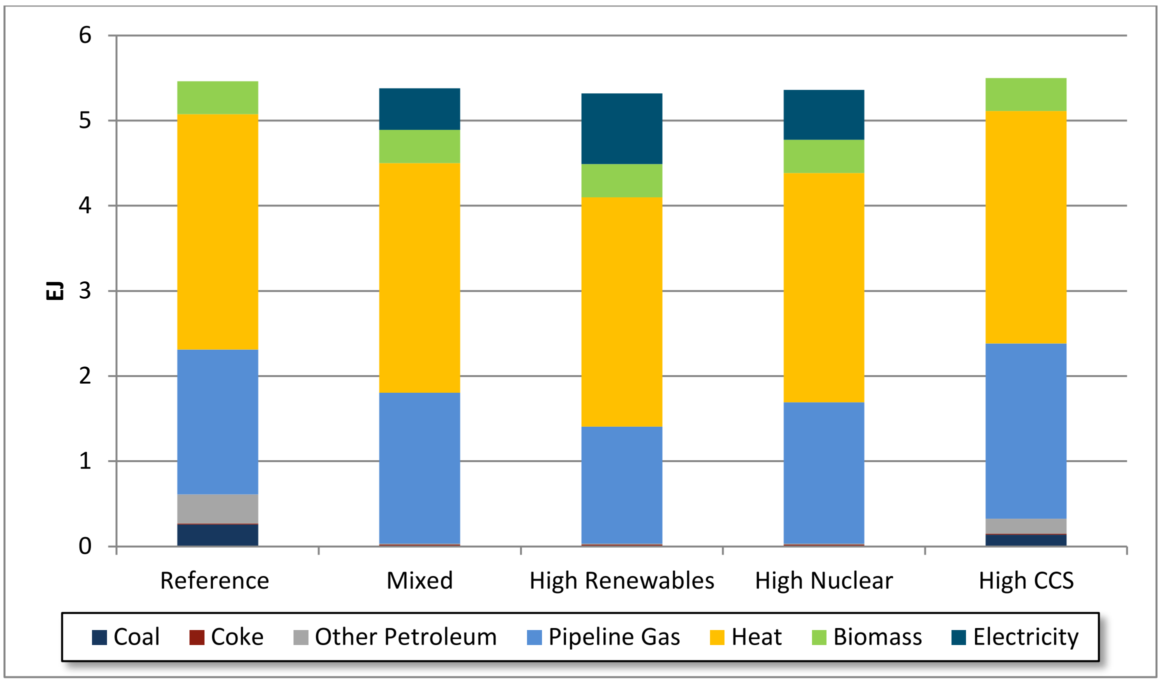


vehicles, as well as process change-related fuel switching in iron and steel, in all cases except for the High CCS Case. A lack of fuel switching-related efficiency, in addition to CCS energy penalties, makes industrial final energy demand in the High CCS Case higher than in other scenarios.

5.4.1. Steam Production

While the level of steam produced for industrial processes (all sectors) is roughly the same across the Reference Case and the four decarbonization cases, the mix of energy sources for steam production varies across cases. In all decarbonization cases, coal, coke, and petroleum fuels are replaced by electricity (Mixed, High Renewables, High Nuclear Cases) and pipeline gas (High CCS Case). Levels of steam generated by combined heat and power (CHP) facilities ("Heat" in Figure 26) and with biomass-fueled boilers are kept at Reference Case levels across all cases. The largest share of boiler output is electrified in the High Renewables Case, while no boilers are electrified in the High CCS Case, which instead relies on CCS in large-scale applications to reduce the net CO_2 intensity of fuels.

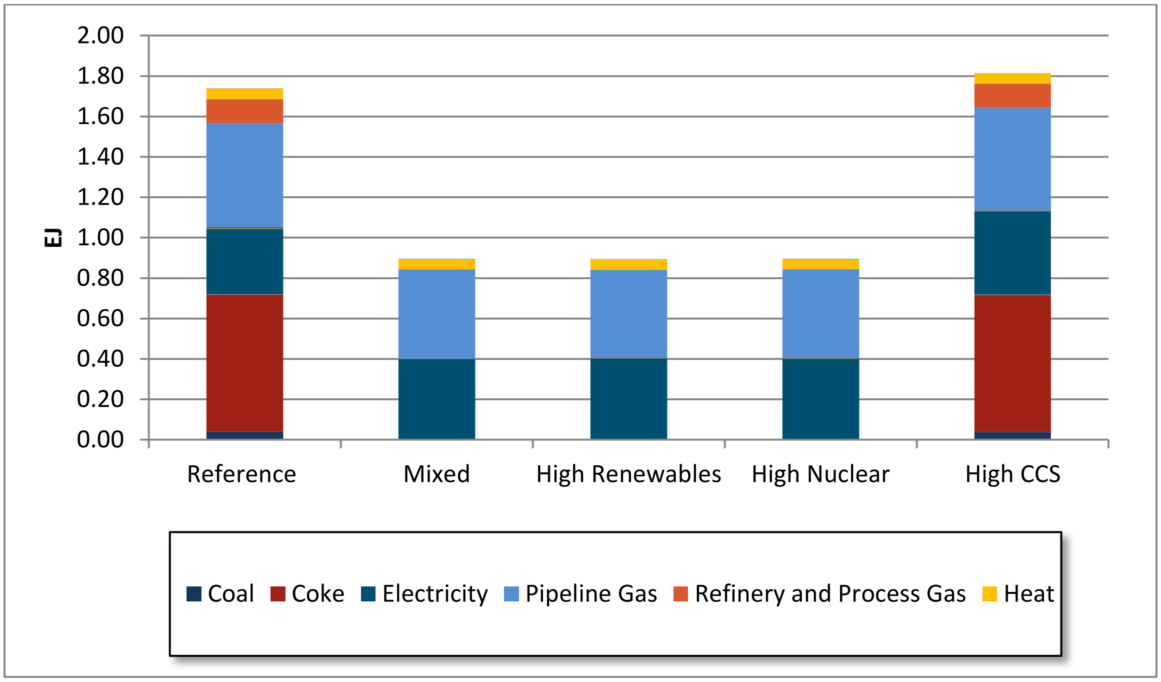
Figure 26. 2050 Steam Production Final Energy Demand by Type



5.4.2. Iron and Steel

The most significant fuel switching in the industrial sector is in iron and steel, with an acceleration of the Reference Case trend of converting basic oxygen furnaces (BOF) utilizing pig iron as a feedstock to electric arc furnaces (EAF), which use scrap steel or direct reduced iron (DRI). This strategy is used in all cases except the High CCS Case, which instead utilizes CCS to capture combustion-related emissions. These alternative strategies result in significant final energy demand differences among the cases (Figure 27). The CCS Case increases final energy demand relative to the Reference Case, because of the energy penalties associated with CCS. In the Mixed, High Renewables, and High Nuclear Cases, there is an increase in final electricity demand from EAF/DRI relative to the Reference Case, but total final energy demand falls significantly with reductions in coal, coke, and process gas use.

Figure 27. 2050 Iron and Steel Industry Final Energy Demand by Type

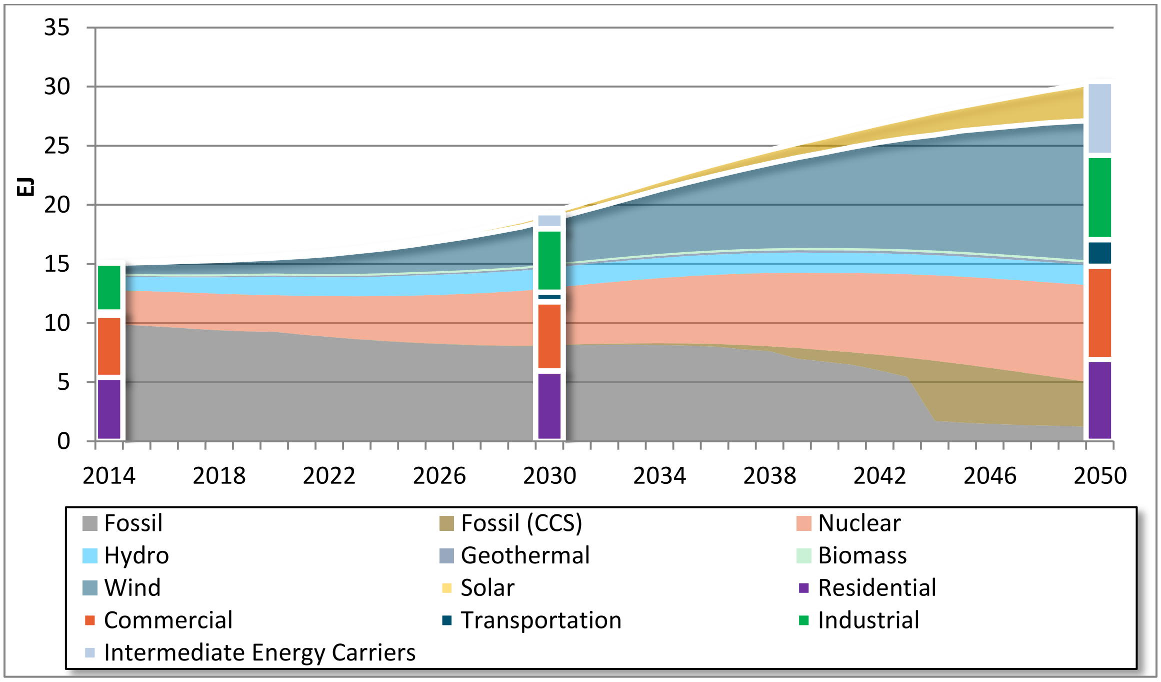


6. Results: Energy Supply

6.1. Electricity

The Mixed Case illustrates the interaction between supply decarbonization and end use electrification that occurs, to different extents, in all of the decarbonization cases (Figure 28). In the Mixed Case, end use electrification doubles demand for electricity by 2050, with particularly rapid growth after 2030.

Figure 28. Mixed Case Electric Sector Supply and Demand



Some of this growth occurs as a result of the electrification of end uses, such as electric water heating or vehicles, but a large portion results from the electrification of fuels ("Intermediate Energy Carriers" in Figure 28), such as hydrogen produced through electrolysis. Fossil fuel generation declines gradually over 2014-2050, and beginning in the late 2030s remaining coal-fired generation is retired and replaced with gas-fired generation equipped with CCS. The only remaining uncontrolled fossil fuel generation in 2050 is a small amount of gas generation that operates as a peaking resource. Much of the increase in demand for electricity after 2030 is met by significant increases in wind, nuclear, and solar power output.

Case names are indicative of final 2050 generation mixes, shown in Figure 29. The High Nuclear, High CCS, and High Renewables Cases have the highest amount of each respective type of generation, though they do not exclusively rely on this type of generation. For instance, the High Renewables Case has roughly the same amount of nuclear power as in the Reference Case. The High CCS Case relies primarily on fossil fuel generation, but includes an expansion of wind and solar generation.

Figure 29. 2050 Electric Generation by Resource Type

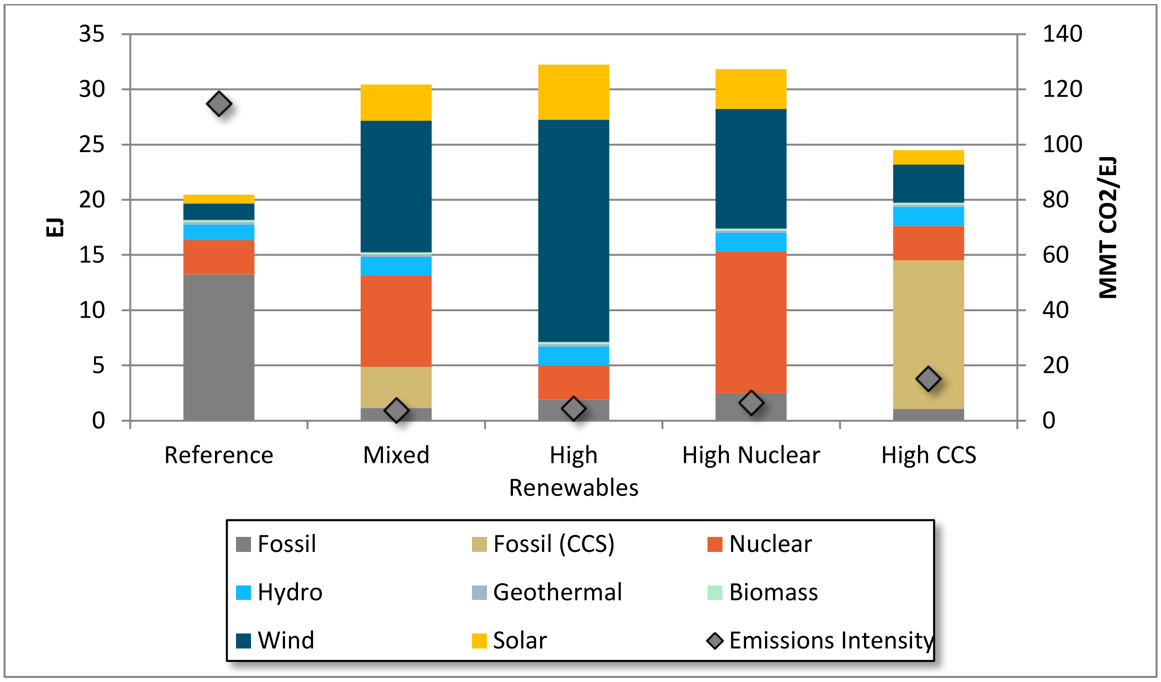
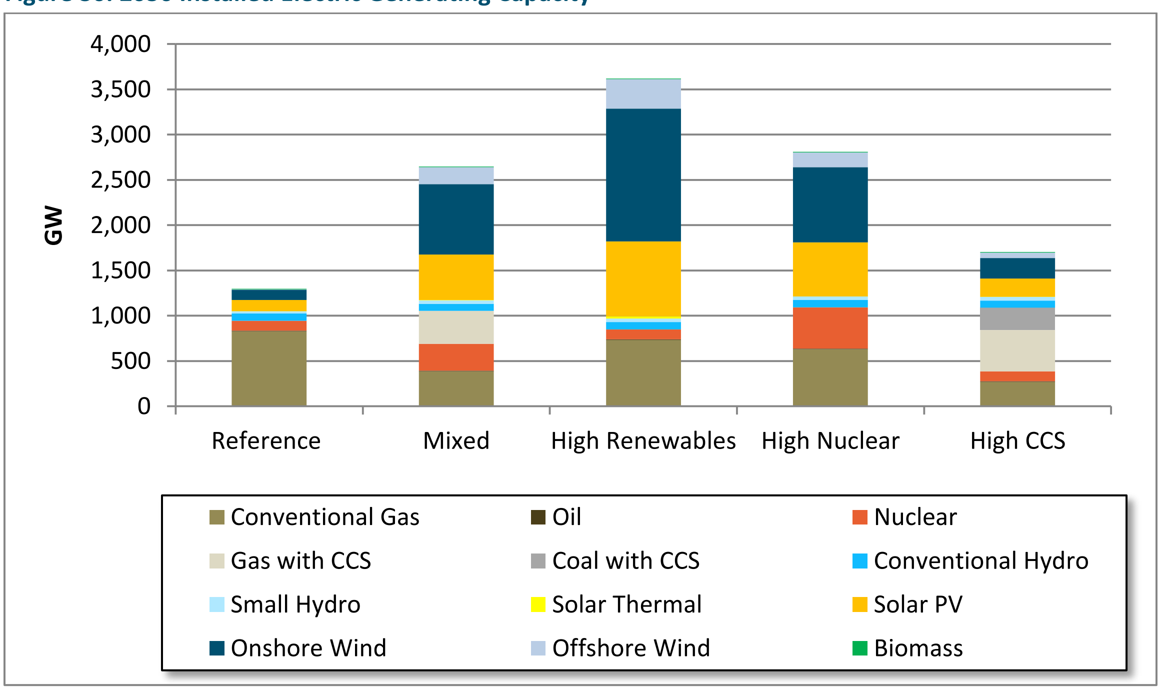


Figure 30. 2050 Installed Electric Generating Capacity



The Mixed Case includes a more balanced expansion of renewable, nuclear, and fossil fuel CCS generation. CO_2 emission factors fall precipitously in all decarbonization cases, from 329 gCO_2/kWh in the Reference Case to at most 54 gCO_2/kWh (High CCS) and at least 14 gCO_2/kWh (Mixed).

Figure 30 shows the installed capacity implications of the generation mixes in Figure 29. The Mixed, High Renewables, and High Nuclear Cases have significantly higher capacity requirements than the Reference or High CCS Cases, as a result of their higher electricity demand and lower capacity factors for wind and solar generation relative to fossil fuel generation.

6.1.1. Electricity Balancing

Large penetrations of non-dispatchable decarbonized resources (wind, solar, nuclear) present challenges for balancing electricity supply and demand (load). Due to the lack of coincidence between these generation sources and conventional loads, high penetrations require supporting dispatchable generation or greater flexibility in load. By 2050, this dispatchable generation must be primarily low carbon—either generation from electricity storage facilities or gas power plants with carbon capture—in order to meet a 2050 GHG target. For dispatchable loads, flexibility in newly electrified loads like water heating, space heating, and electric vehicles was incorporated in the model.

Much of the balancing on the load side comes in the form of electric fuel production—hydrogen and synthetic natural gas (SNG)—in which facilities were oversized in production capacity in order to allow them to operate flexibly and absorb excess generation. While these electric fuels may be inefficient from a primary energy perspective, their ability to operate flexibly reduces curtailment, which represents a system-wide inefficiency caused by large amounts of non-dispatchable generation. When this flexible load reduces curtailment, it can provide significant value as a component of an integrated energy system, despite its potentially high cost when viewed in isolation.

Figure 31. 2050 Mixed Case Eastern Interconnection Electricity Dispatch

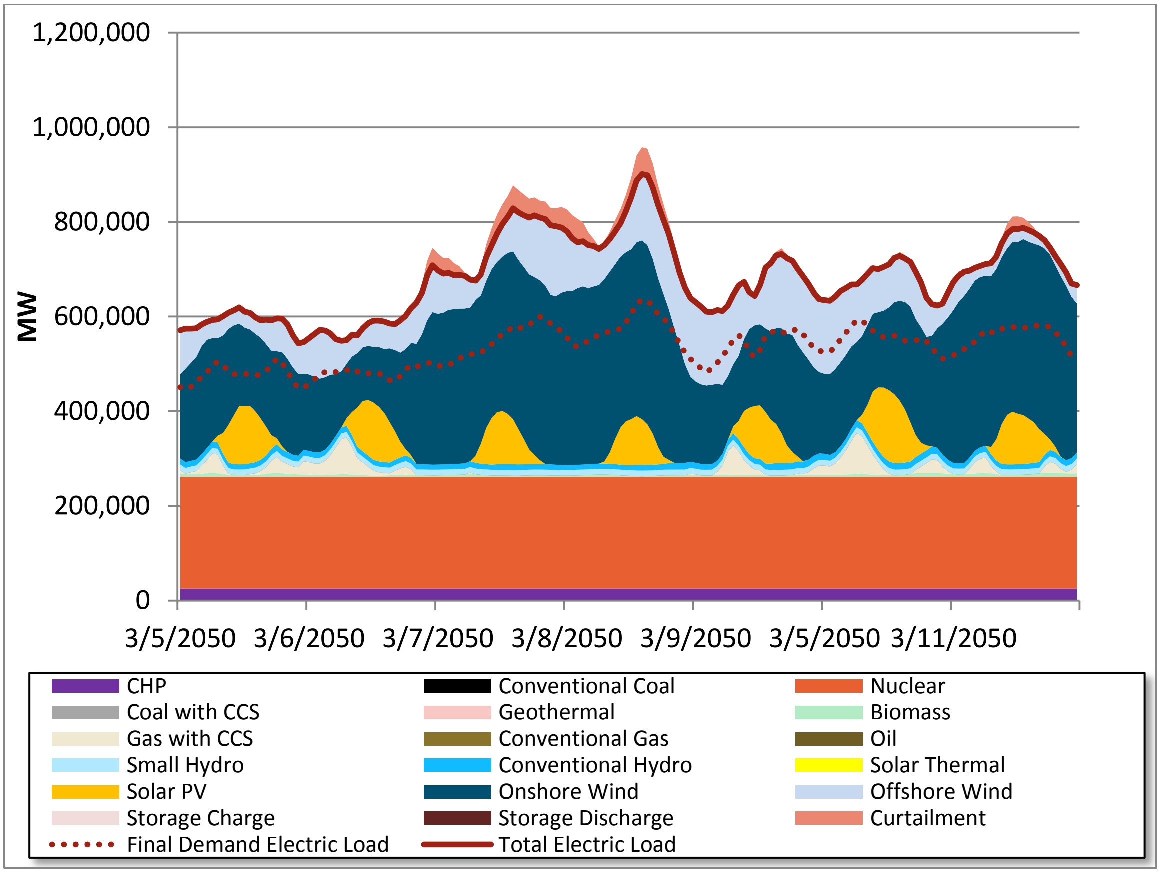
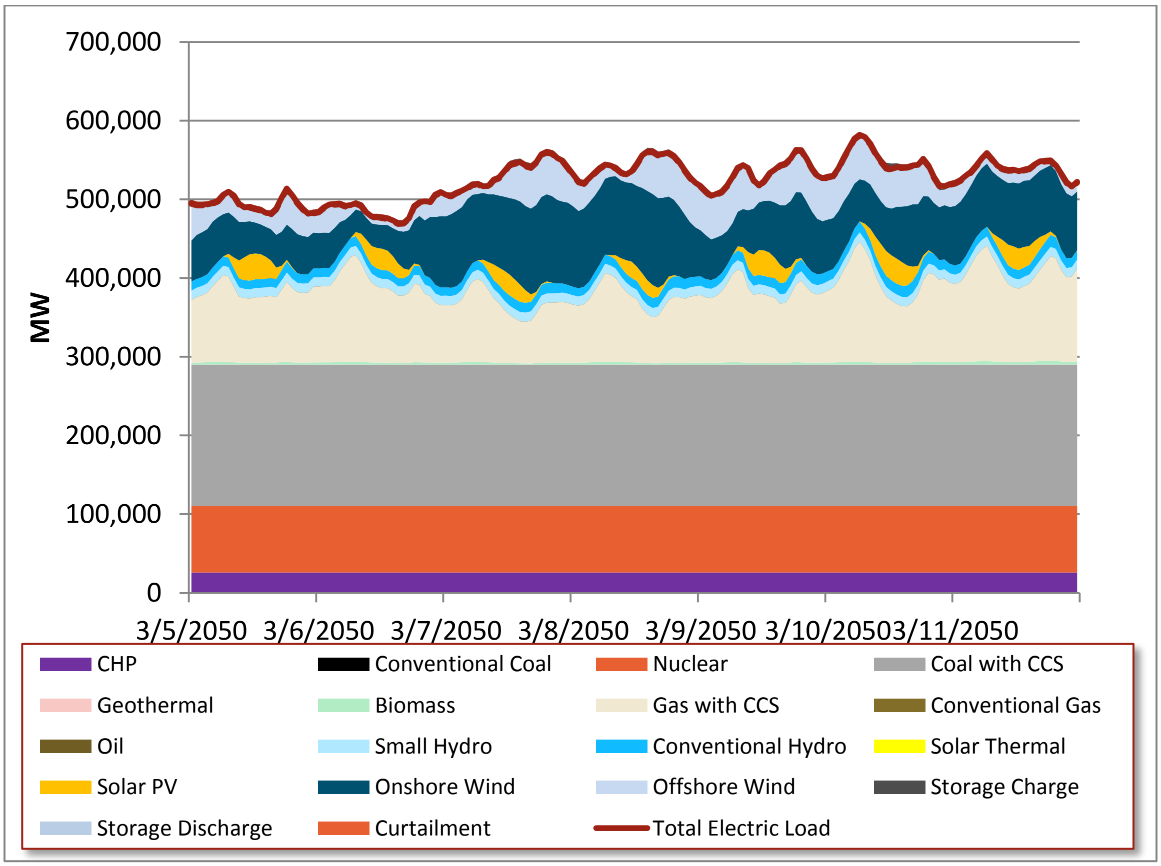


Figure 31 illustrates these challenges, showing dispatch in the Mixed Case for a week in March 2050 in the Eastern Interconnect. The coincidence of significant nuclear generation online and large wind power output means that total electric load (the solid red line) exceeds final demand for electricity (the dotted red line). The majority of the difference is absorbed by facilities producing electric fuels, and a small amount of wind output is curtailed. The use of flexible loads for balancing, as in this case, would represent a new paradigm in power system operations, as system operators have traditionally relied on the flexibility of supply, rather than the flexibility of demand, to address load-resource imbalances.

The High CCS Case, which has lower penetrations of non-dispatchable resources, has a more traditional generation dispatch, shown in Figure 32 for the Eastern Interconnection in the same week of March 2050. Here, nuclear and coal with CCS operate as baseload resources and gas CCS operates as a load-following resource to balance modest penetrations of wind and solar.

Figure 32. 2050 CCS Case Eastern Interconnection Electricity Dispatch



6.2. Gas

Pipeline gas blends vary by case as a function of three factors:

1. Whether biomass has been used primarily to produce gas or liquid fuels;
2. Need for intermediate energy production loads (P2G hydrogen and SNG) to provide grid balancing services;
3. Assumed availability of CCS.

Due to its higher balancing needs, for instance, the High Renewables Case has the highest gas energy demand and the largest amount of electric fuels, in addition to a significant biogas blend (mainly bio-SNG) (Figure 34, also present in the Mixed Case in Figure 33). The High CCS Case uses only a limited amount of biomass (wet biomass for anaerobic digestion) in the pipeline, instead using CCS in industry to reduce the CO_2 intensity of pipeline gas. The High Nuclear Case has residual biomass to use in the pipeline because demand for liquid biofuels is reduced by using HFCVs in heavy duty trucking.

Figure 33. Mixed Case Pipeline Gas Supplies and Sector Demand

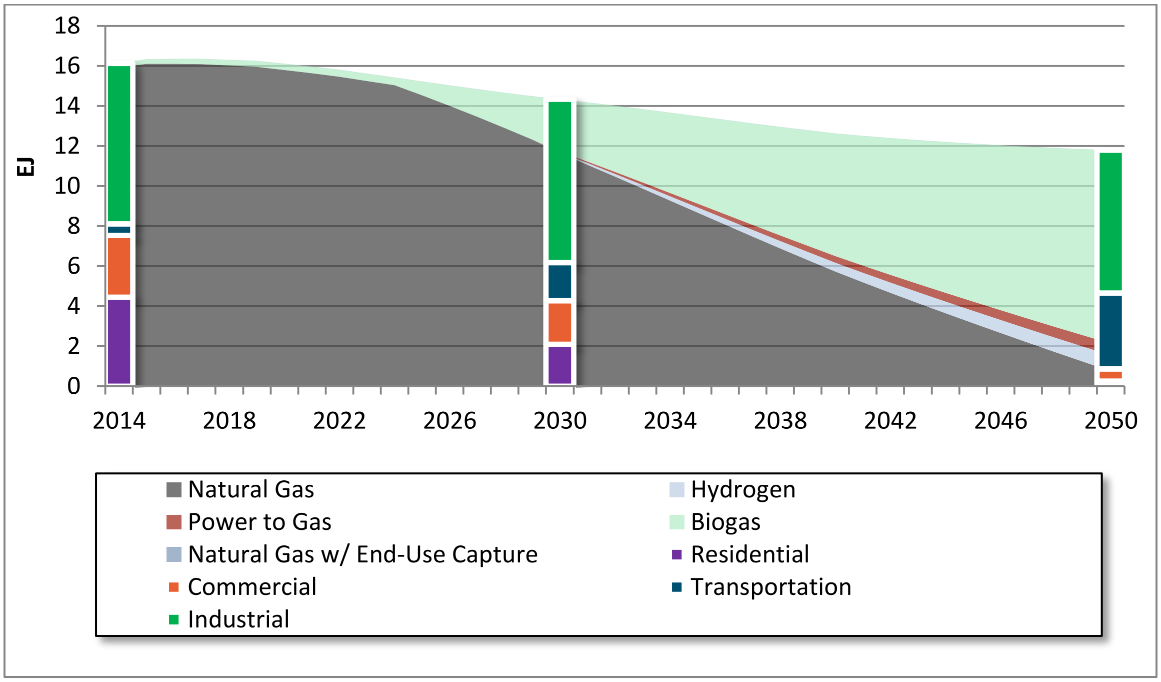


Figure 34. 2050 Pipeline Gas Portfolios

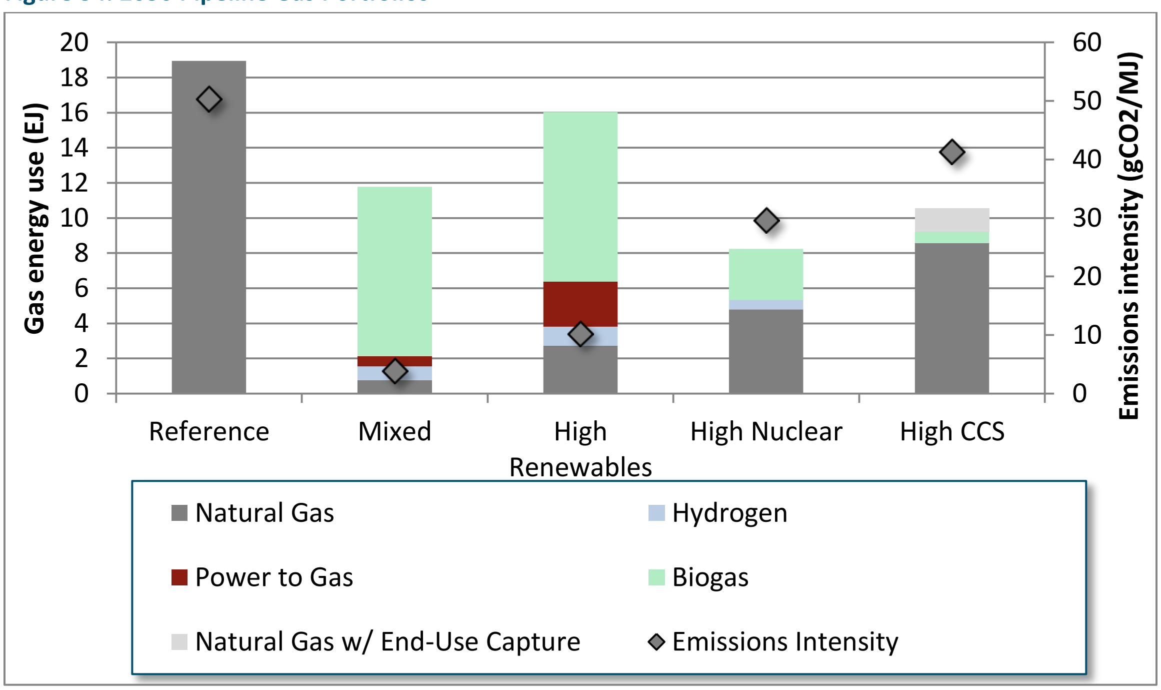


Figure 33 illustrates the dynamics of gas supply and demand from 2014 to 2050, using the Mixed Case. In this case, demand for gas remains relatively high because the gas supply is decarbonized using biomass (mainly gasification to bio-SNG) and, to a lesser extent, P2G hydrogen and SNG. Most of this gas is used in the heavy duty transportation and industrial sectors, where electrification is less practical.

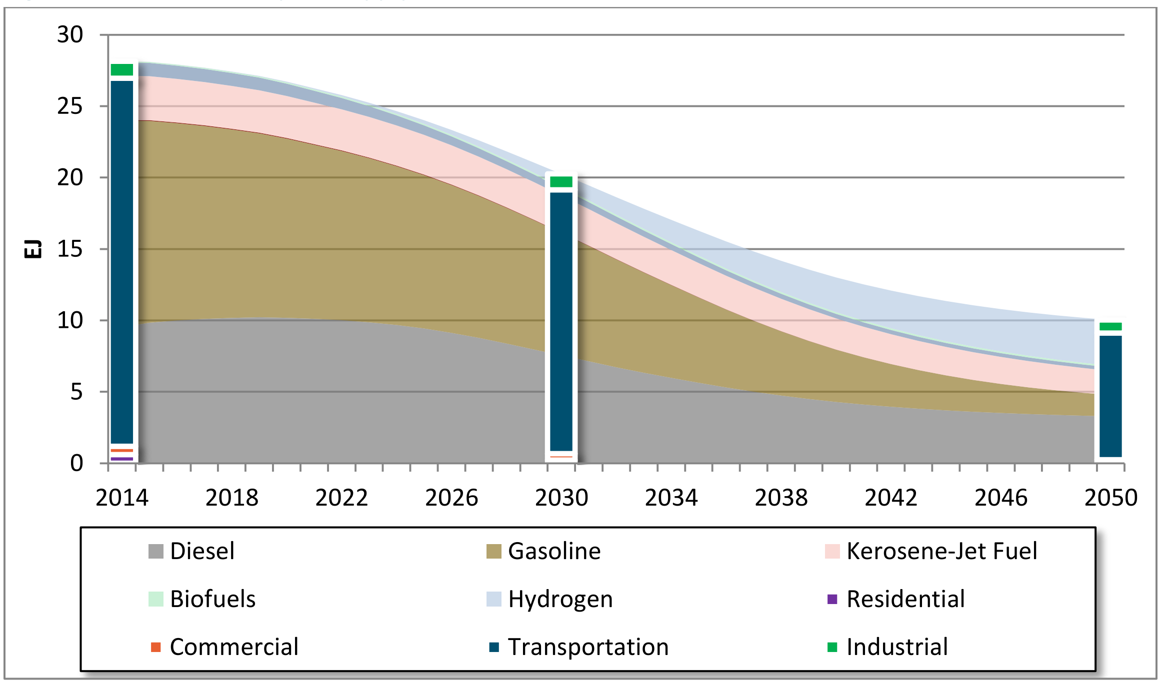
Pipeline gas blends vary by case as a function of three factors: (1) whether biomass has been used primarily to produce gas or liquid fuels, (2) the need for intermediate energy production loads (P2G hydrogen and SNG) to provide grid balancing services, and (3) the assumed availability of CCS. Due to its higher balancing needs, for instance, the High Renewables Case has the highest gas energy demand and the largest amount of electric fuels, in addition to a significant biogas blend (mainly bio-SNG) (Figure 34). The High CCS Case uses only a limited amount of biomass (wet biomass for anaerobic digestion) in the pipeline, instead using CCS in industry to reduce the CO_2 intensity of pipeline gas. The High Nuclear Case has residual biomass to use in the pipeline because demand for liquid biofuels is reduced by using HFCVs in heavy duty trucking.

Average CO_2 emission intensities for gas fuels vary across cases, depending on the final demand for gas and the share of natural gas remaining in the gas mix. In the Mixed and High Renewables Cases, gas use is higher, very little natural gas remains and gas emissions intensities are less than 11 gCO_2/MJ. In the High Nuclear and High CCS Cases, gas use is lower and emissions intensities are higher because larger emission reductions are occurring for liquid fuels.

6.3. Liquids

Figure 35 shows the supply portfolio evolution for liquid fuels. In the Mixed Case, and in all four decarbonization cases, demand for liquid fuels falls dramatically as a result of efficiency improvements

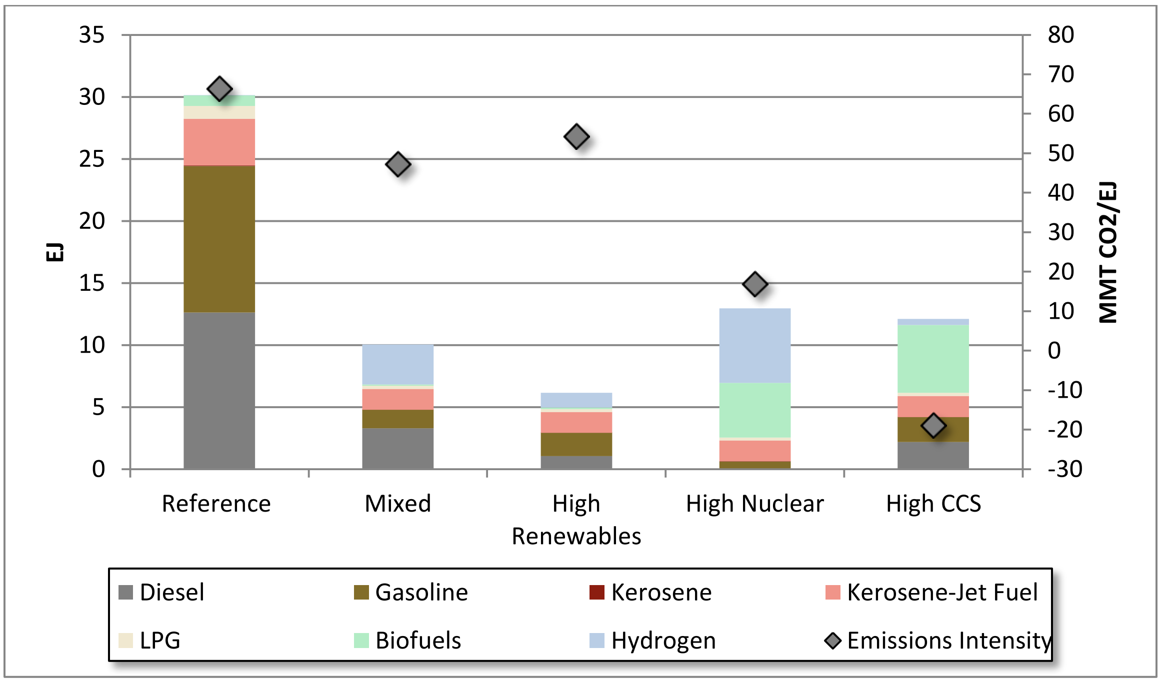
Figure 35. Mixed Case Liquids Supply and Demand



and fuel switching. Biomass in the Mixed Case is largely used in the gas pipeline, which limits the use of liquid biofuels in transportation. Instead, on-road transportation transitions primarily to electricity (LDVs) and pipeline gas (HDVs), with some hydrogen use in LDVs, jet fuel used in aviation, gasoline used in PHEVs, and diesel used in HDV and “other” transportation modes.

The same factors that shape the 2050 gas blend also shape the 2050 liquid fuel mix. The highest liquid fuels demand occurs in the High Nuclear and High CCS Cases, where HDVs use a combination of biofuels (renewable diesel) and hydrogen rather than pipeline gas (Figure 36). The lowest demand for liquid fuels is in the High Renewables Case, where the transportation sector shifts from liquid fuels to electricity and gas. In cases where liquid fuel use remains high, their average CO_2 emissions factors are much lower. The negative CO_2 emission factor for liquid fuels in the High CCS Case results from the use of BECCS in this case.[9]

Figure 36. 2050 Liquid Fuel Supply Mix



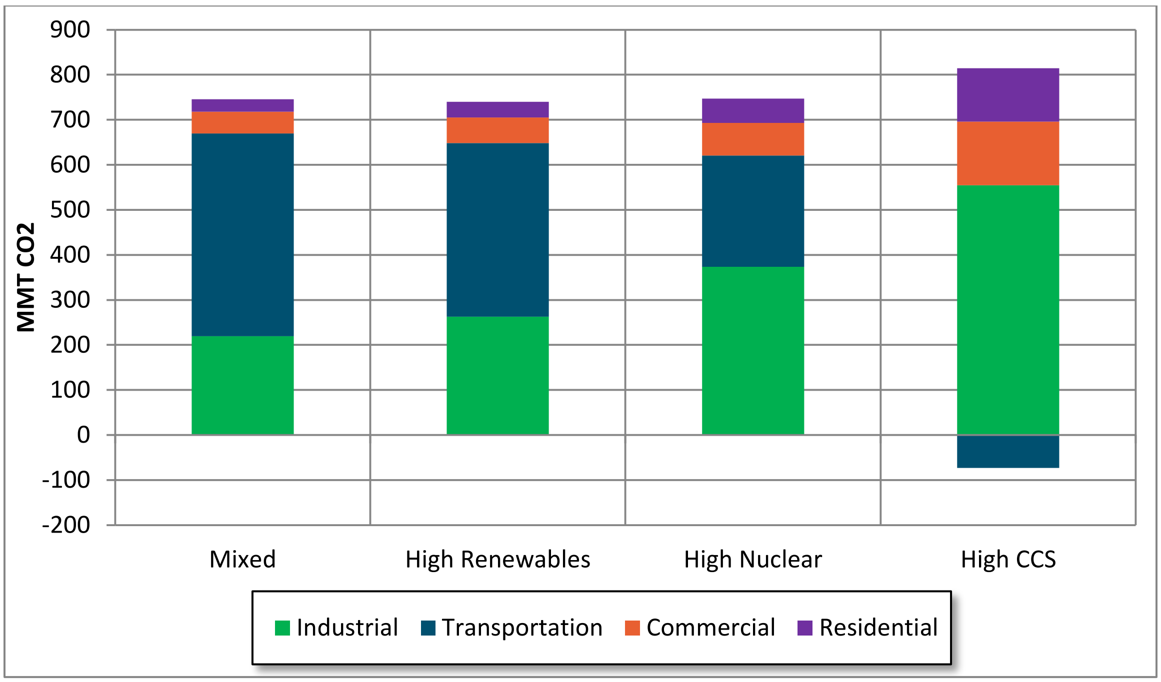
[9] Sustainably harvested biomass is generally given a net CO_2 emission factor of zero, because the CO_2 released to the atmosphere through combustion is offset by subsequent sequestration of CO_2 in plant biomass. By capturing and storing CO_2 from the bioenergy refining process, BECCS can lead to negative emissions. We only use BECCS in the High CCS Case, consistent with our case development criteria.

7. Results: CO_2 Emissions

7.1. CO_2 Emissions by End Use Sector

In all decarbonization cases, the transportation and industrial sectors have the largest remaining CO_2 emissions by 2050 (Figure 37). These remaining emissions are mainly from direct combustion of fossil fuels rather than upstream CO_2 emissions associated with electricity consumption. The ratio of transportation to industrial sector emissions across cases is determined primarily by the allocation of biomass between gas and liquid fuels. Biomass conversion to liquid fuels reduces the transportation sector's emissions relative to industry (High Nuclear, High CCS), whereas conversion to gas and greater use of gas in transportation increases them. Differences between residential and commercial sector emissions among cases are driven primarily by the emissions intensity of electricity; the CCS Case, which has the highest electricity emissions intensity, has twice the residual emissions in these sectors as any other case.

Figure 37. 2050 CO_2 Emissions by Sector



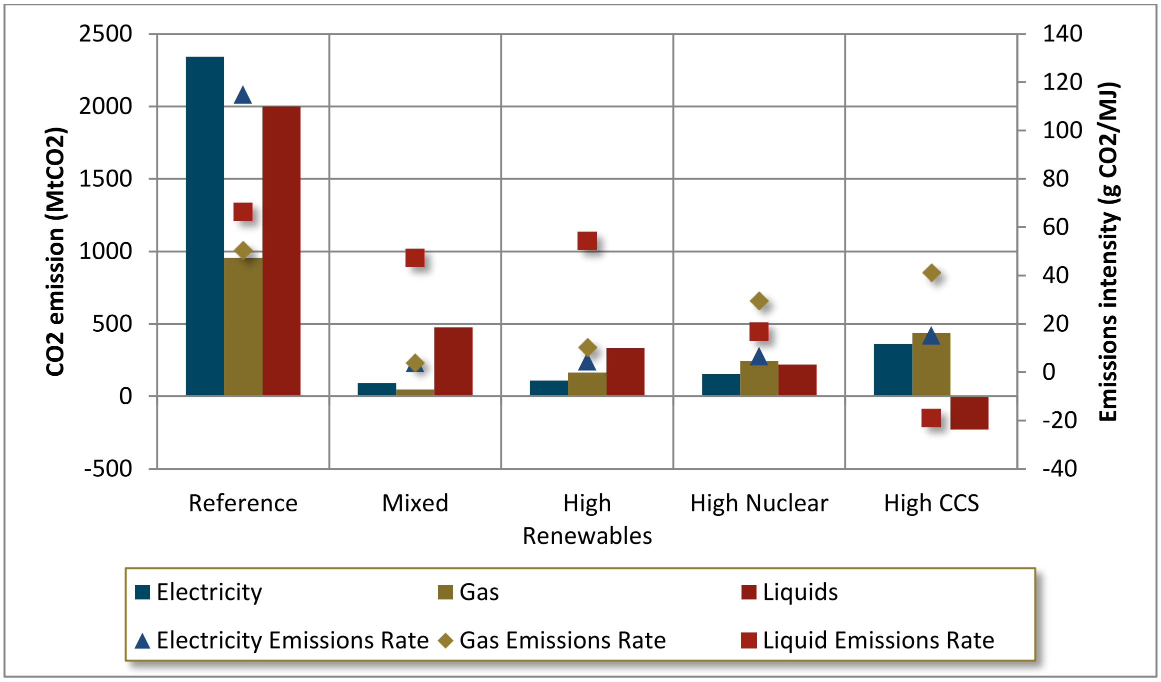
The starkest allocation of CO_2 emissions among cases is in the High CCS Case, which has limited fuel switching in industry and no decarbonization of pipeline gas, leaving over two-thirds of residual emissions in the industrial sector. Such a high level of residual emissions is feasible because of the use of BECCS and renewable diesel in the High CCS Case, which creates a diesel fuel with net negative emissions that are allocated to the transportation sector.

7.2. CO_2 Emissions by Energy Type

End use sector CO_2 emissions are consistent with the emissions intensities of their main energy sources—electricity, gas, or liquids. Buildings, which are largely electrified using very low CO_2 electricity by 2050 in all cases, are small contributors to overall emissions. Industry, where gas dominates final energy demand, has the lowest emissions in cases where the pipeline has been significantly decarbonized. Transportation sector emissions depend on the relative balance and CO_2 emissions intensities of liquid and gas fuels.

Figure 38 illustrates this balancing act among electricity, gas, and liquid fuel CO_2 emissions. The Mixed and High Renewables Cases emphasize electricity and gas decarbonization, and most residual CO_2 is in liquid fuels, which have an emissions intensity only slightly less than the Reference Case. The High Nuclear Case has significant reductions in both gas and liquid fuels emissions intensity, and roughly equivalent CO_2 emissions from each. The use of BECCS in the High CCS Case allows for a net negative CO_2 emissions intensity in liquid fuels, a much higher gas emissions intensity, and a slightly higher electric emissions intensity. Across decarbonization cases, electric emissions intensities fall dramatically relative to the Reference Case.

Figure 38. CO_2 Emissions and Emissions Intensities by Energy Type in 2050

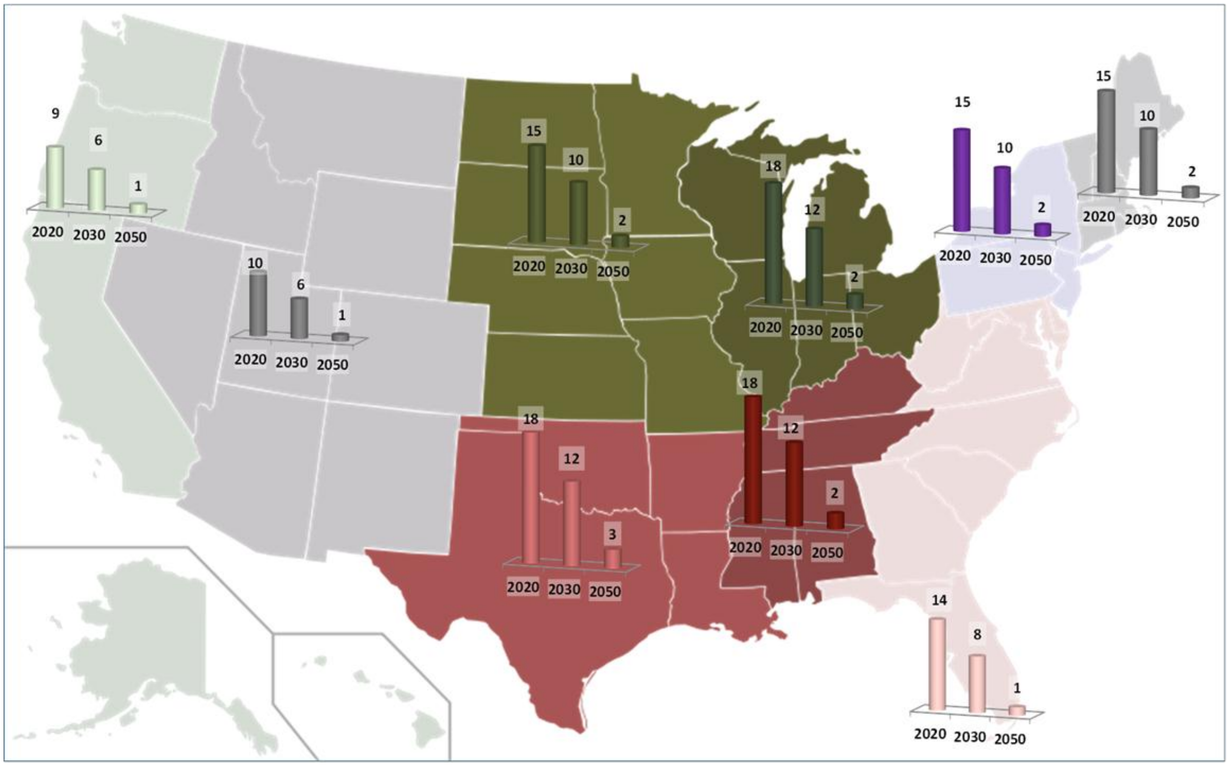


The total average CO_2 emissions intensity in all four decarbonization cases ranges from 13 to 14 gCO_2 per MJ of final energy consumed, which is a useful reference point. Electricity, gas, and liquid fuel emissions intensities, weighted by their respective shares of final energy demand, must add up to this total average. In cases without very high end use electrification where liquid fuels have a higher emissions intensity, gas intensities will need to be lower and gas use be higher than liquids (Mixed and High Renewables Cases). In cases where the combined average gas and liquid fuel intensities are high, electricity intensity must be very low and a greater share of end uses must be electrified, a scenario that we do not model in this study.

7.3. CO_2 Emissions Intensity by Region

Figure 39 illustrates the change in regional emissions intensities for the years 2020, 2030, and 2050 for the nine U.S. census divisions represented in PATHWAYS. These differences are a result of different initial infrastructure, energy supply and demand characteristics, and regional electricity sector

Figure 39. Mixed Case Regional Per Capita CO_2 Emissions Intensity (Tonnes CO_2 Per Person)



generation mixes. They show relatively steeper emission intensity reductions trajectories in the Midwest and Eastern regions of the U.S. in comparison to the Mountain West and Pacific regions, a function of the higher initial per capita emissions intensity.

8. Results: Costs

8.1. Incremental Costs by End Use Sector and Cost Component

Across end use sectors, the timing of energy system costs varies according to investment needs and changes in technology costs. Figure 40 shows energy system costs, net of Reference Case costs, by sector for the Mixed Case. Annual costs are shown with uncertainty distributions. Residential, commercial, and industrial costs grow slowly to 2050. Transportation costs are higher in the mid-term and then decline by 2050, a result of declining costs of alternative fuel vehicles and higher avoided costs of conventional fossil fuels.

Figure 40. Mixed Case Incremental Energy System Costs to 2050

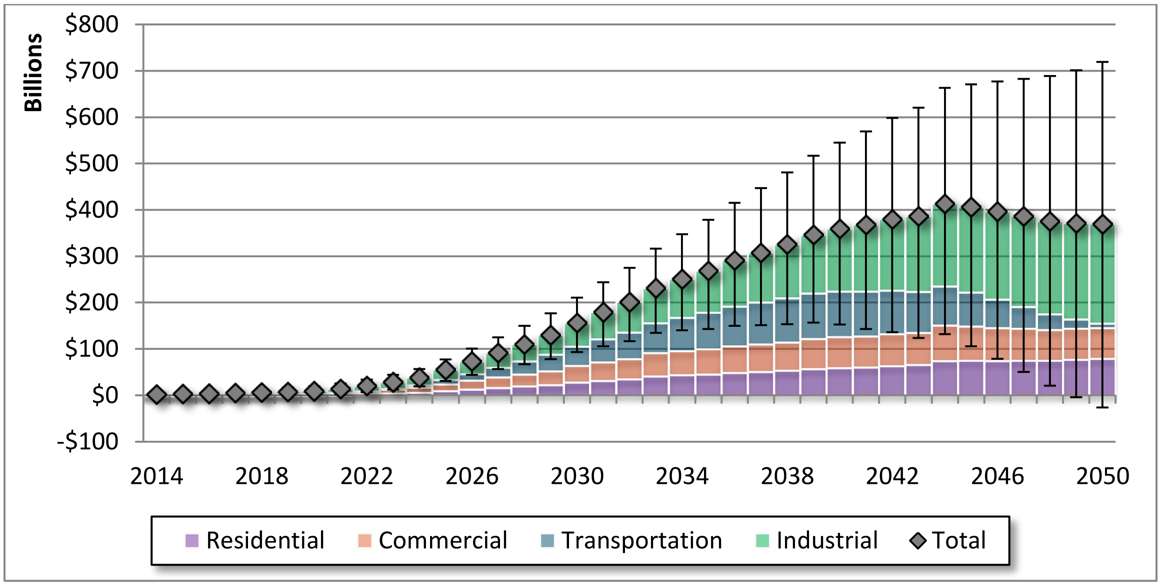


Figure 41. 2050 Mixed Case Incremental Costs by Component

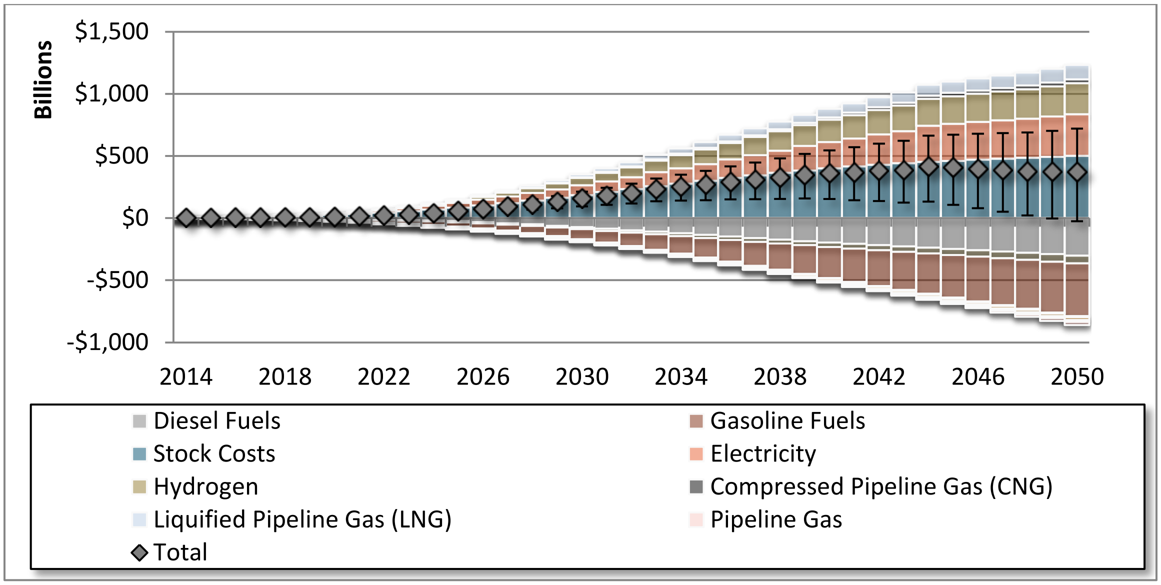
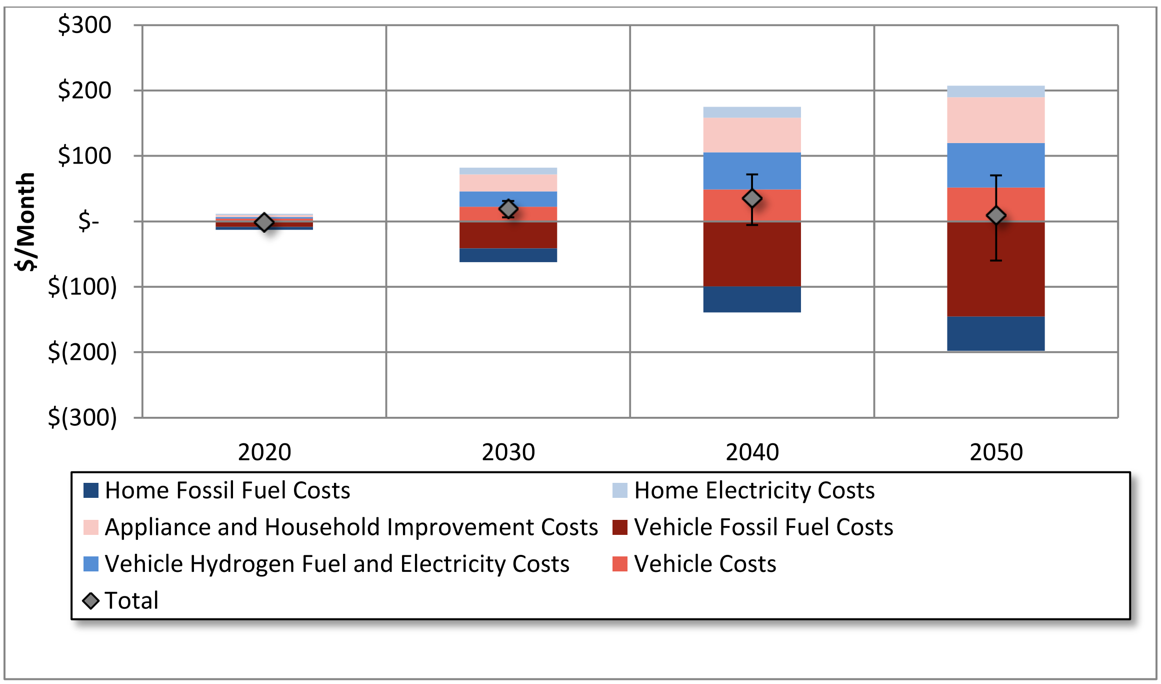


Figure 41 shows incremental costs by component for the Mixed Case, with fossil fuel savings shown as a negative value. In this case, savings are primarily from avoided liquid fossil fuels (gasoline and diesel). Increased costs are from stock costs (end-use capital equipment like vehicles and appliances), electricity (due to slight rate increases and higher electricity demand from electrification), hydrogen, and compressed and liquefied pipeline gas (due to higher demand as well as higher delivered costs from the low-carbon blend in the pipeline). In broad terms, Figure 41 illustrates a shift from fossil fuel expenditures to investments in electric generating capacity and equipment that uses electricity.

8.2. Household Costs

Figure 42 shows the progression in incremental household energy costs from 2020 to 2050 in the Mixed Case. Initial decarbonization costs peak in the 2030 timeframe, as fossil fuel prices are not yet high enough to offset incremental costs of appliances and alternative fuel vehicles. Costs decline by 2040 as the costs of alternative fuel vehicles converge with those of gasoline ICE vehicles, and by 2050 households save money over the Reference Case due to the avoidance of gasoline, natural gas, and some diesel costs.

Figure 42. Mixed Case Incremental Household Monthly Costs



8.3. Electricity Costs

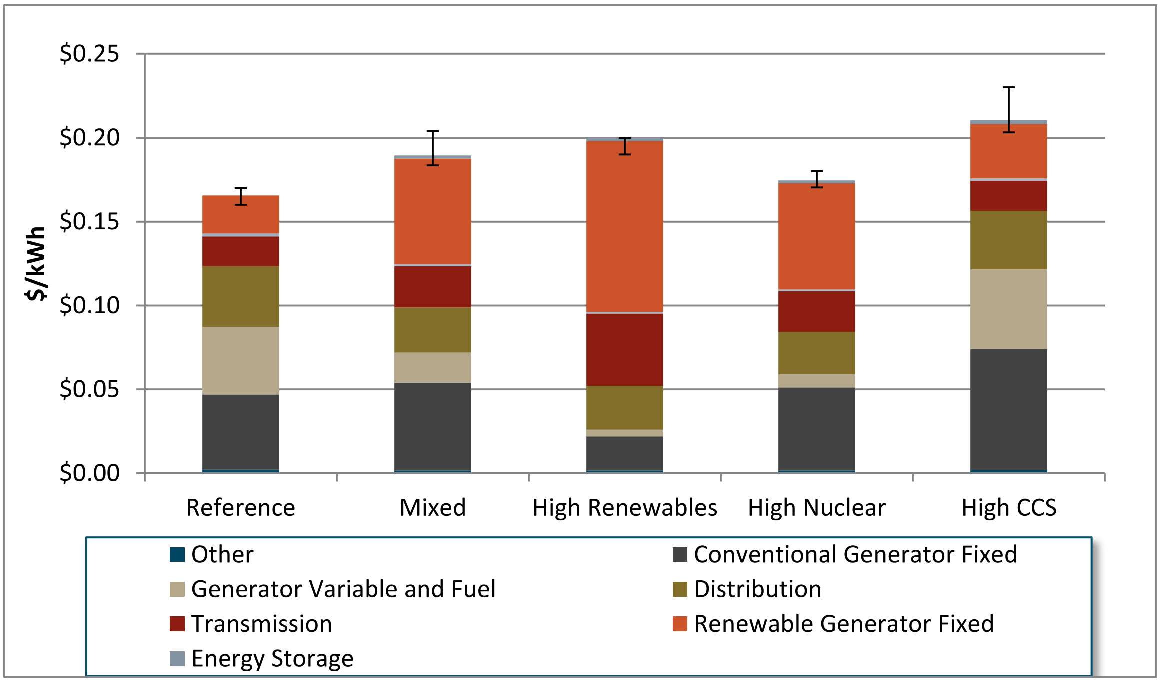
One of the main incremental cost drivers in the four decarbonization cases is the cost of electricity generation and delivery, measured in electricity rates. Differences from Reference Case rates result primarily from four factors:

1. Penetration of renewables, which adds renewable generator fixed costs and associated transmission costs while reducing conventional generation fixed, variable, and fuel costs;
2. Assumed nuclear capacity expansion, which adds conventional generation fixed costs but reduces variable and fuel costs;

3. Assumed CCS capacity expansion, which adds conventional fixed (CCS costs) and variable costs (heat rate penalties);
4. Amount of electricity used in the production of intermediate energy carriers, which reduces the share of electricity that needs to be delivered on the distribution system and thus lowers average distribution costs.

Despite significant differences in rate components, average rates in all cases are similar to Reference Case levels (Figure 43), with the High CCS Case representing the only significant rate increase (27% over Reference Case rates) and the High Nuclear Case showing only a slight rate increase (5%) under base technology cost assumptions.

Figure 43. 2050 Average Electricity Rate



8.4. Electricity Investment

In addition to showing average rates, we also calculate the incremental investment in electricity generation facilities, relative to the Reference Case. This is a way of conceptualizing the necessary capital that needs to be directed towards the electricity system, as well as identifying specific technology sectors that would experience rapid growth under mitigation cases. In the Mixed Case, increases in annual electricity generation investments would increase $15 billion per year from 2021-2030 (Figure 44). From 2031 to 2040, incremental investments would need to more than double to over $30 billion per year. By 2050, the electricity sector would need more than $50 billion per year of incremental investment from Reference Case projections.

The High Renewables case would require increased annual investment in renewable generation of over $70 billion per year by 2050 (Figure 45). The High Nuclear Case would need investment in nuclear facilities, both new and repowered existing, of $20 billion per year along with $30 billion in renewable investment increases. The High CCS Case would require nominal increases in renewable generation, with most of the increased investment needed in fossil power plants with CCS. The Mixed Case would require increased investment in all decarbonized generation sources. All cases would see a decline in traditional fossil power plant investment of up to $10 billion.

Figure 44. Mixed Case Incremental Annual Electricity Generation Investment by Decade

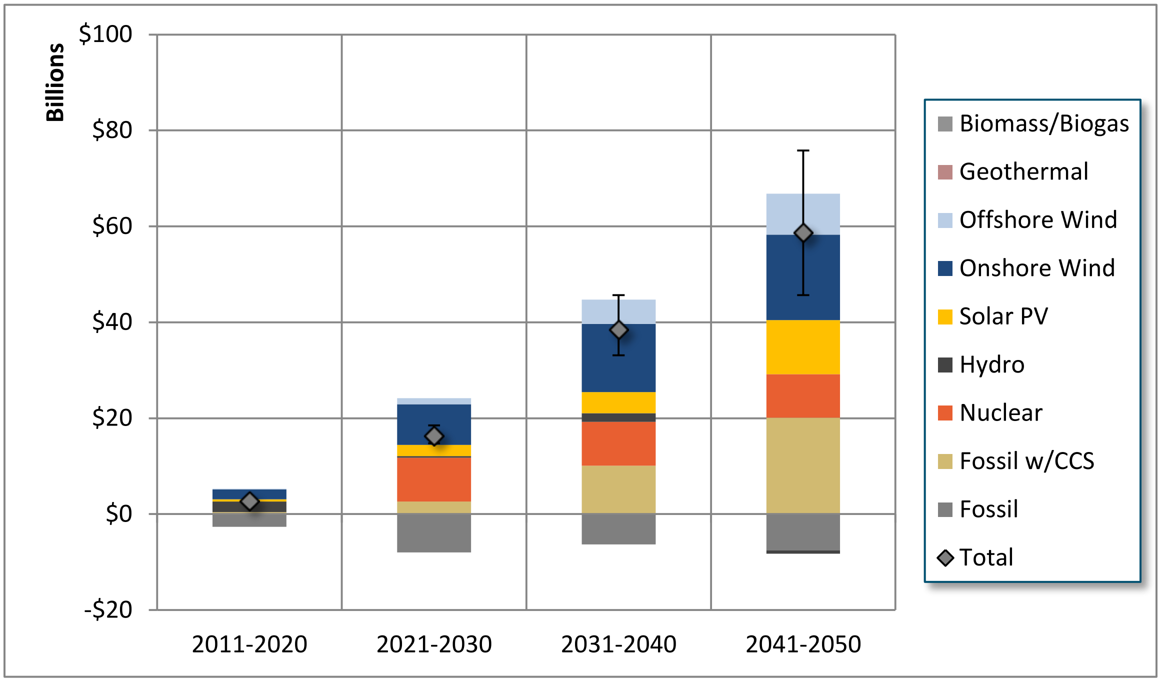
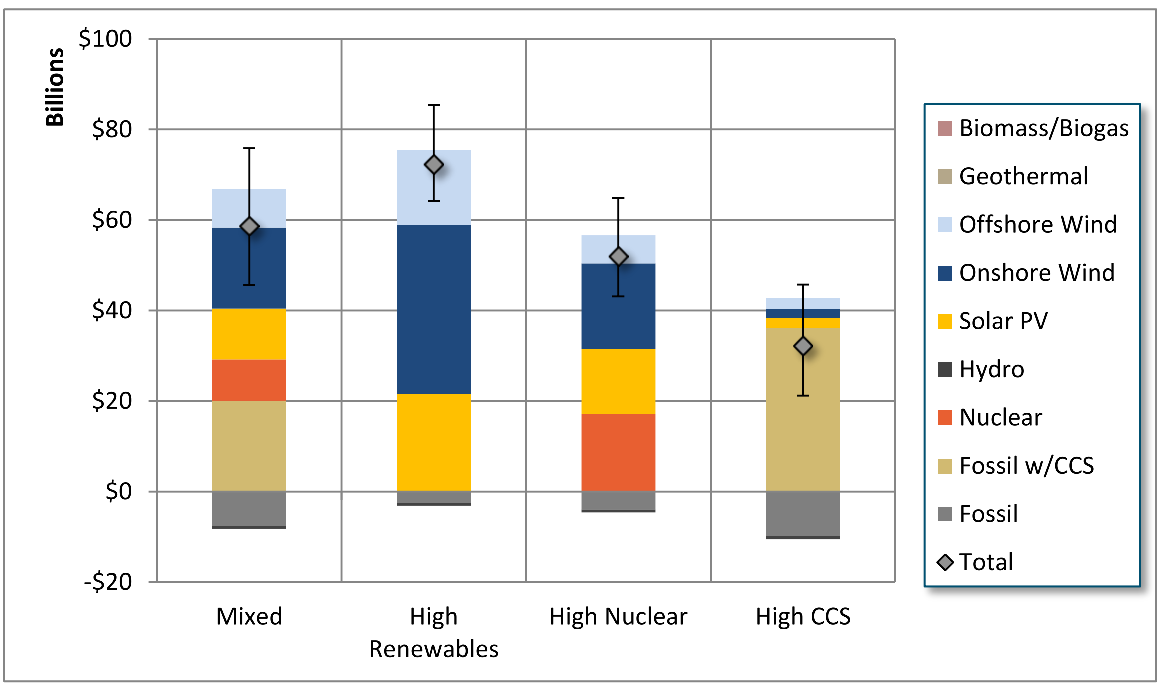


Figure 45. Annual Incremental Investments from 2041-2050



9. Results: GCAM Analysis

This section describes the results of the non-CO_2 emissions analysis conducted in GCAM, organized into three sections:

- **Non-CO_2 mitigation—**describes key results from the GCAM analysis of non-CO_2 mitigation
- **Sensitivity to terrestrial carbon sink assumptions**—explores sensitivity of results to levels of the terrestrial carbon sink
- **Biomass production and indirect land-use change emissions**—describes net zero GHG emission levels of purpose-grown biomass production

9.1. Non-CO_2 Mitigation

Using GCAM, we examined several cases of CO_2 and non-CO_2 mitigation in 2050, with the aim of identifying a reasonable set of low-cost non-CO_2 GHG mitigation measures that would complement the CO_2 emission reductions modeled in PATHWAYS, achieving an overall net GHG reduction of at least 80% below 1990 levels.[10]

Emissions of CH_4, N_2O, and fluorinated gases (f-gases)[11] represented nearly 20% of U.S. total gross GHG emissions in 1990, and are approximately 20% of GCAM reference emissions (without mitigation) in 2050. Some non-CO_2 emissions are associated with fossil energy production, such as CH_4 leakage from coal and natural gas extraction and processing. CO_2 mitigation strategies that reduce fossil fuel production therefore also result in non-CO_2 emissions reductions. We refer to this phenomenon as 'co-mitigation.' Deeper reductions in non-CO_2 emissions require active measures, such as CH_4 flaring, catalytic reduction of N_2O from industrial processes, and switching to low-global warming potential (GWP) refrigerants.

In order to maintain consistency with most of the PATHWAYS cases, we eliminated CCS on biofuel facilities as a technology option in GCAM, and limited purpose-grown bioenergy production to a level consistent with the cap identified in the *Biomass and Indirect Land-use Change* section below, while removing the current Renewable Fuel Standard (RFS) requirements for corn ethanol. We also assume that the rest of the world is participating in GHG mitigation efforts consistent with a 2°C warming target. However, we do examine a Reference Case in which no mitigation takes place globally. For these cases, we made the assumption that in 2050 the U.S. terrestrial carbon sink is at its 1990 level of 831 $MtCO_2$, although we explore sensitivity to this assumption in the next section.

Active mitigation of non-CO_2 emissions in GCAM is driven by the same carbon price that induces CO_2 mitigation, based on marginal abatement supply curves (MACs) for each technology and each non-CO_2 gas represented by the model. The MACs, which are based on EPA estimates, specify percent reductions feasible at various carbon price levels.[12] Many non-CO_2 mitigation measures are available at low or even

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[10] Achieving the U.S. government's Copenhagen target of 83% below 2005 levels requires an additional reduction of 2% (24 $MtCO_2e$) beyond what is required to meet the 80% below 1990 target.

[11] These include HFC125, HFC134a, HFC245fa, CF_4, and SF_6.

[12] United States EPA (2006), Global Mitigation of Non-CO2 Greenhouse Gases, report 430-R-06-05.

negative carbon prices. However, even with high carbon prices (greater than $150 per tCO_2), technological limitations prevent complete non-CO_2 mitigation.

The GCAM results, shown below in Table 8, achieve non-CO2 emissions (992 $MtCO_2e$) that are consistent with the PATHWAYS goal (750 $MtCO_2$ + 46 $MtCO_2$ in additional non-energy industrial CO_2) and an overall net GHG target of less than 1,080 $MtCO_2e$, given an assumed terrestrial carbon sink of 831 $MtCO_2$.

Table 8. GCAM 2050 Case Results, Relative to U.S. 1990 and 2005 GHG Emissions ($MtCO_2e$)[13]

Emissions Category	1990	2005	2012	2050 case	% below 1990	% below 2005
Fossil fuel and industrial CO_2 emissions	5,108	6,112	5,383	796	84%	87%
Non-CO_2 emissions (all)	1,125	1,141	1,143	992	12%	13%
Gross CO_2e emissions	6,233	7,253	6,526	1,788	71%	75%
Terrestrial CO_2 sink	831	1,031	979	831	0%	19%
Net CO_2e (including sink)	5,402	6,222	5,547	957	82%	85%

The GCAM scenario was constructed to match the PATHWAYS energy CO_2 target of 750 $MtCO_2$ in 2050, which corresponds to an 84% reduction from 1990 levels. Since GCAM accounts for some industrial CO_2 emissions not accounted for by PATHWAYS, the GCAM fossil fuel and industrial emissions target was adjusted up to 796 $MtCO_2$, preserving the 84% decline for this class of emissions. The carbon price required to achieve this level of fossil fuel and industrial emissions leads to a 12% decline in non-CO_2 GHG emissions (detailed below by sector and gas), which together with a terrestrial sink held at the low range of recent values (831 MtCO2), is sufficient to surpass the 80% below 1990 target for all emissions.

As discussed below, the sink would need to decline to 15% below its 1990 value or 27% below its 2012 value before more aggressive mitigation measures would be required to meet the 80% target for all emissions. Furthermore, technological limits on additional non-CO_2 reductions mean that additional GHG mitigation on the deep reduction frontier must come primarily from CO_2 mitigation and associated co-mitigation of non-CO_2 emissions rather than active non-CO_2 mitigation.

The figures below show each non-CO_2 gas category (CH_4, N_2O, and f-gases) by sector in 2050 for our central case, compared to historical values, a 2050 reference with no mitigation, and a 2050 reference with CO_2 mitigation but no active non-CO_2 mitigation. The CO_2-only mitigation case is included to provide insight into the degree of non-CO_2 co-mitigation present in each sector. We decompose the sectors differently for each gas category to reflect the diversity of primary sources among them.

As the figures show, co-mitigation of non-CO_2 emissions is greatest for CH_4, which is a by-product of fossil fuel extraction and processing. The greatest co-mitigation reductions are in the coal and natural gas sectors, and would presumably be greater if CCS were less widely deployed as a CO_2 mitigation

[13] Fossil fuel and industrial CO_2 emissions were chosen to match the 84% reduction found in the PATHWAYS cases. Note that the GCAM case includes some industrial CO_2 emissions not accounted for in PATHWAYS. Data for 1990, 2005, and 2012 are from the EPA 2014 GHG inventory.

technology, which would require even deeper reductions in fossil fuel use. Active mitigation measures further reduce coal-related CH_4 emissions, as well as CH_4 emissions from landfills, industrial emissions of N_2O and f-gases, and f-gases associated with air conditioning in both commercial and residential buildings.

Figure 46. CH_4 Emissions

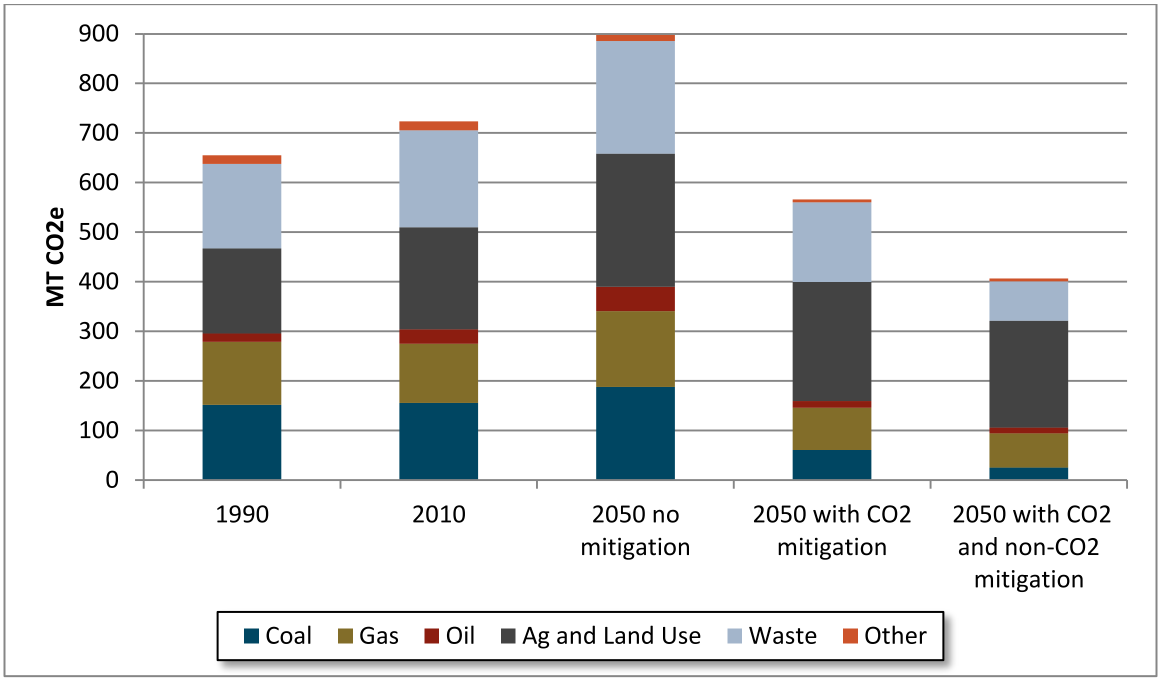


Figure 47. N_20 Emissions

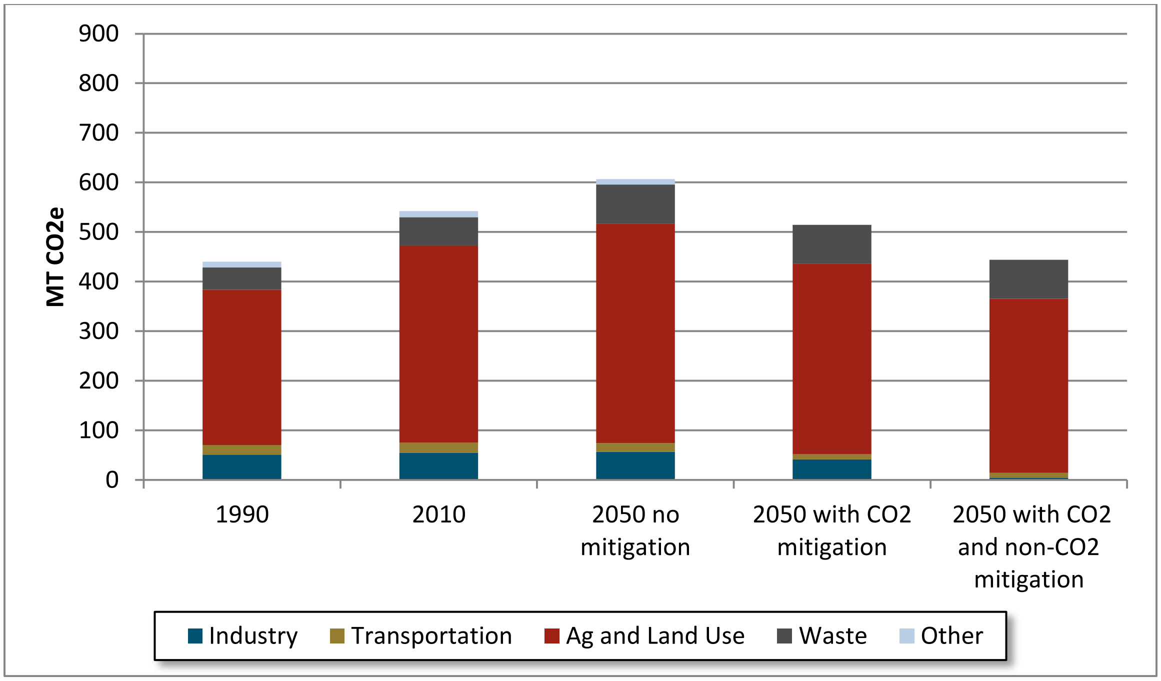


Figure 48. Fluorinated Gas Emissions[14]

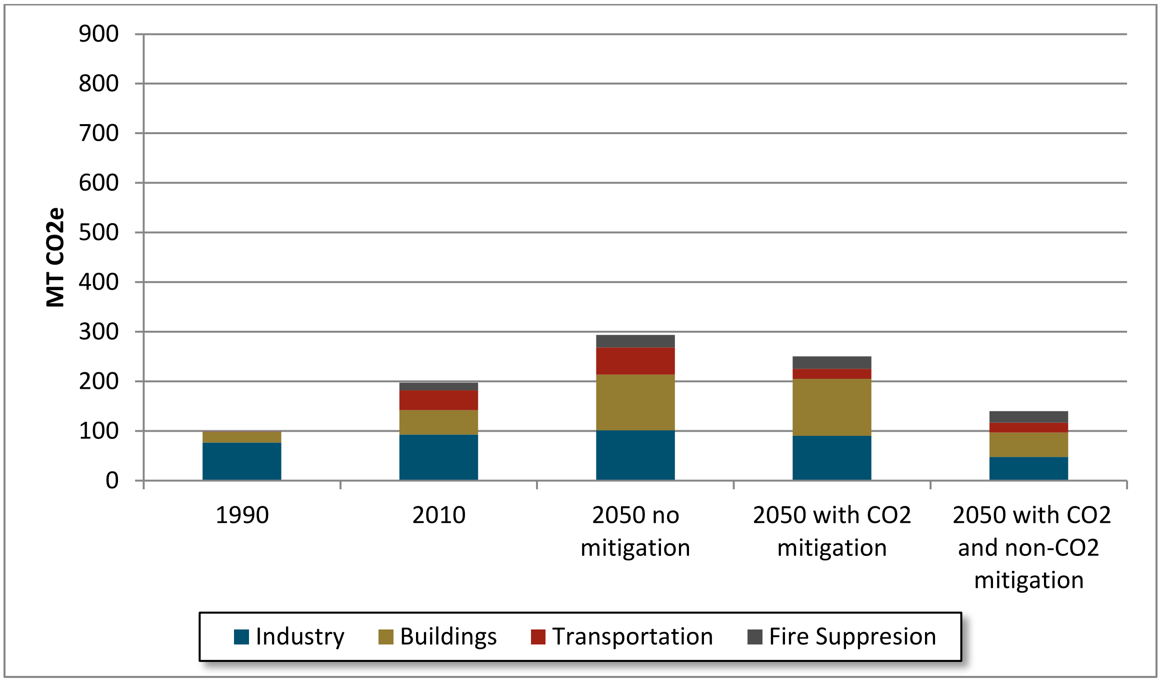


Table 9 shows the largest active mitigation measures by subsector required to reduce non-CO_2 emissions to 992 MtCO_2e in 2050. The largest three measure areas are CH_4 reductions from landfills, N_2O

Table 9. Principal Non-CO_2 Mitigation by Gas and Subsector[15]

Subsector	Absolute Reduction (MtCO_2e)	Percent Reduction
	CH_4	
Landfills	82	73%
Coal	35	58%
Enteric Fermentation	16	9%
Natural Gas	16	19%
	N_2O	
Agricultural Soils	33	9%
Adipic Acid Production	27	96%
Nitric Acid Production	10	89%
	Fluorinated Gases	
Air Conditioning	64	63%
Solvents	32	82%

[14] Note that fire suppression and transportation data are not available for 1990.

[15] Absolute and percent reduction in 2050 versus an alternative 2050 case with CO_2 mitigation only.

reductions in industrial processes, and f-gas reductions. Without these active mitigation measures, we would only reach a 76% reduction in total net GHG emissions by 2050.

9.2. Sensitivity to Terrestrial Carbon Sink Assumptions

Terrestrial carbon sinks play an important role in the global carbon cycle, removing approximately 25% of anthropogenic emissions from the atmosphere annually [*Canadell et al.,* 2007]. Yet, the magnitude, mechanisms, and geographic location of terrestrial sinks are poorly understood. The EPA estimates the US sink to be 831 MtCO_2 in 1990, increasing to 1,031 in 2005 and 979 in 2012 [*EPA*, 2014]. The largest term in the EPA inventory results from carbon sequestration on existing forestland, which is regaining carbon as a result of past clearing. Net terrestrial carbon dynamics are also sensitive to forest harvest and the growth of product pools, agricultural management that affects soil carbon, and the uncertain role of climate change and CO_2 fertilization.

Given these uncertainties, we have opted to perform a simple sensitivity analysis to demonstrate the impact of sink strength on our results. Table 10 shows the required emissions reductions in 2050 to meet GHG reduction target for various levels of sink strength. The central GCAM case was chosen to match the 84% reduction in energy-related CO_2 emissions relative to 1990 levels present in the PATHWAYS cases, which results in a slight overshoot of the 80% total GHG target. Given this overshoot, the sink would need to decrease to 710 MtCO_2 (15% below the 1990 sink level, or 27% below the 2012 sink level) in order to require more aggressive reductions in non-CO_2 emissions than the case already outlined.

Table 10. Terrestrial Carbon Sink Sensitivity Analysis (MtCO_2e)

Sink sensitivity	1990 sink +50%	1990 sink +25%	Central Case	1990 sink -25%	1990 sink -50%
2050 terrestrial CO_2 sink	1,247	1,039	831	623	416
Allowable 2050 gross CO_2e	2,327	2,119	1,911	1,704	1,496
Fossil fuel + industrial CO_2	1,312	1,109	796	711	513
Non-CO_2 emissions (all)	1,017	1,009	992	991	983
% Reduction in fossil fuel + industrial CO_2	74%	78%	84%	86%	90%
% Reduction in non-CO_2	10%	10%	12%	12%	13%
% Reduction in net CO_2e	80%	80%	82%	80%	80%

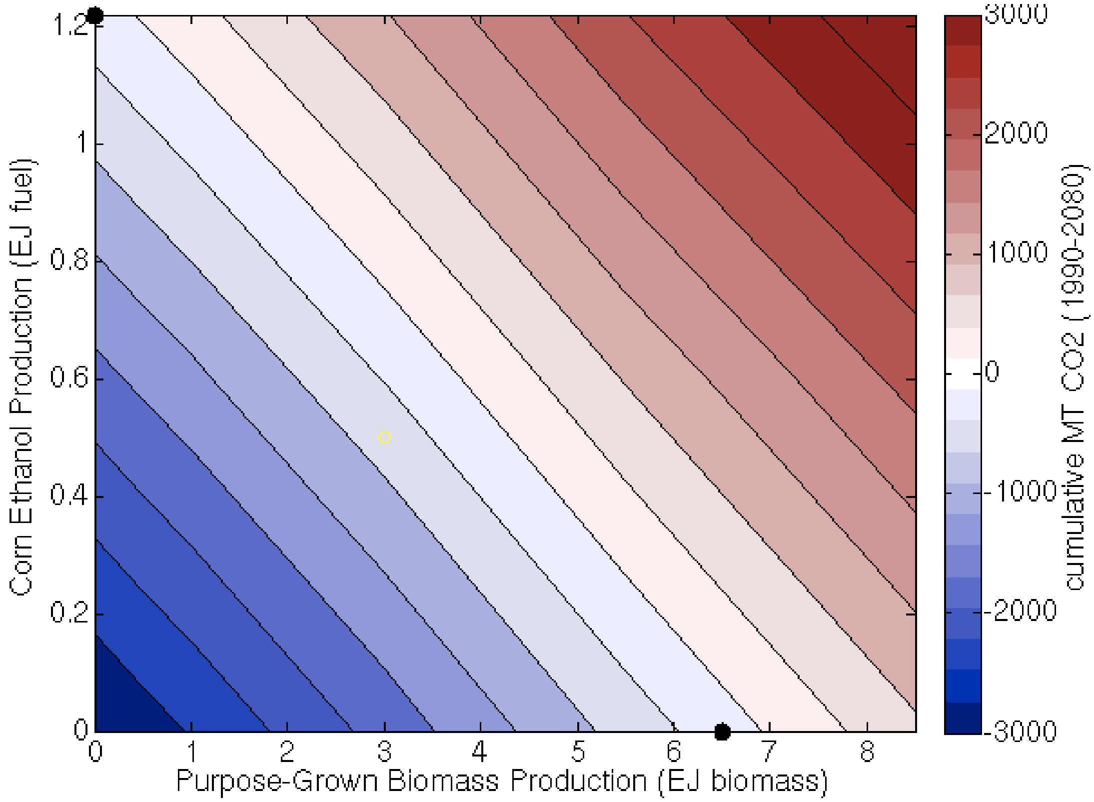
Due to the difficulty of mitigating non-CO_2 emissions beyond a certain point, most of the additional reductions required in the event of a lower than expected sink would need to come via additional reductions in fossil fuel use. For instance, with a sink that is 50% below 1990 levels, fossil fuel and industrial CO_2 emissions decrease by 90% versus 84% in the central case, whereas non-CO_2 emissions decrease by 13% compared to 12% in the central case.

9.3. Biomass Production and Indirect Land-Use Change Emissions

Domestic bioenergy production induces changes in agricultural markets that result in land-use emissions worldwide [*Searchinger et al.,* 2008; *Plevin et al.*, 2010]. To address this issue in PATHWAYS, we performed a series of simulations in GCAM designed to identify a level of purpose-grown biomass that would not increase GHG emissions from global land use change if the increase in bioenergy production were implemented in conjunction with a contraction in corn ethanol production currently required by the RFS. In these cases, we eliminated international trade in bioenergy in order to isolate the effect of domestic production and consumption of purpose-grown bioenergy crops and/or corn ethanol. We systematically varied the level of these two bioenergy sources while imposing an 80% reduction in fossil fuel and industrial CO2 emissions both in the U.S. and globally. To account for co-products of corn ethanol that are not included in GCAM, we assume that one-third of the corn land used for ethanol production would need to remain in production to meet animal feed demands currently met by co-products. This effectively reduces the carbon benefit of retiring corn ethanol production by one-third.

As a baseline, we choose a world in which the RFS corn ethanol requirements of 1.22 EJ (15 billion gallons) of fuel production are maintained until 2050. Figure 49 shows the change in cumulative global land use emissions from 2005 to 2080 that would result from various levels of either corn ethanol or purpose-grown bioenergy production. We focus on cumulative emissions because the effect of land-use change on terrestrial carbon can take several decades to be realized. Reducing corn ethanol to zero and increasing purpose-grown production to 6.5 EJ (371 MMT) of biomass yields a net zero change in global emissions (i.e., moving from the black circle on the y axis of Figure 49 to the black circle on the x axis).

Figure 49. Change in Cumulative GHG Emissions from Global Land Use Change from Purpose-Grown Biomass Production



10. Comparison of PATHWAYS Results with EMF-24

The existence of multiple technologically feasible pathways to an 80% emissions cut in the US by 2050 is supported by the energy-economic model literature, most notably the 24th Energy Modeling Forum intercomparison effort (EMF-24; [*Fawcett et al.*, 2014a]), which examined both 80% and 50% emissions reduction scenarios in 2050 across nine energy-economic models of varying degrees of sectoral and process resolution. These models included integrated assessment models, computable general equilibrium models, and optimization models, in which some concept of economic optimality (e.g., cost minimization, supply-demand equilibrium) drives the future evolution of the energy system subject to technology and emission constraints.

The PATHWAYS model differs from most of these energy-economic models in several important ways. It features a relatively high level of sectoral granularity tied to stock rollover constraints, and an electricity dispatch sub-model requiring that regional load curves be satisfied on an hourly basis. Perhaps most distinctively, PATHWAYS outcomes are not arrived at through economic optimization (although it tracks costs), but rather by calculating the energy system and emissions consequences of detailed user-specified technology investment and deployment constraints. Given these differences between PATHWAYS and the models that have been used to examine deep emissions cuts in the US so far, it is worthwhile to identify common outcomes and unique insights offered by the different approaches. Pathway's highly granular approach provides the opportunity to flesh out in unprecedented detail what deep decarbonization scenarios look like for the US, while the combination of user flexibility and detailed constraints offers the possibility of discovering unique technology solutions that simply would not emerge from a model that doesn't represent, for example, hourly electrical dispatch.

Consistent with PATHWAYS, one common feature of deep emissions reduction scenarios in the EMF-24 effort is significant decarbonization of the electricity sector, reflecting the relatively low cost of mitigation in this sector. The EMF-24 effort paid particular attention to the role of energy technology assumptions (e.g. cost, availability, and performance) in shaping future scenarios. For example, within the context of 80% emissions reduction scenarios, the effort examined a "pessimistic renewables" scenario that tended to favor nuclear and fossil fuel generation with CCS, as well as a "pessimistic nuclear/CCS" scenario that tended to favor renewables. From a cost and feasibility perspective, no one technological strategy emerged from these scenarios as dominant. That is, effectively eliminating individual technologies did not consistently increase costs across model, indicating (1) that there is a "flat optimum" with respect to different energy system configurations, and (2) that factors other than technological characteristics (e.g. social acceptability of nuclear energy or bioenergy) may play a relatively important role in the future trajectory of the energy system [*Clarke et al.*, 2014].

Energy efficiency also played an important role in the EMF-24 scenarios. Both of the 80% emissions cut scenarios assumed that a 20% reduction in primary energy consumption was possible as a reference level of energy efficiency improvement. Some models (5 of 9) found reductions in electricity supply above and beyond this level, reflecting additional end-use efficiency and service demand reductions in response to emission policies and associated prices [*Clarke et al.*, 2014].

The remaining EMF-24 models showed an increase in electricity supply in the 80% reduction scenarios relative to their 2050 reference scenarios [*Clarke et al.*, 2014]. In these models, end-use electrification outweighed additional energy efficiency improvements in its influence on total electricity supply. With the data currently available from the EMF-24 effort, it is not possible to disaggregate the relative contributions of end-use energy efficiency and fuel switching on electricity supply, nor can one identify which end-use sectors undergo the largest degree of electrification. This is one area that the PATHWAYS model identifies some compelling solutions, particularly in the high renewables scenario, in which electrical load-matching constraints are met by absorbing excess renewable generation with intermediate energy carrier (e.g. H_2 and synthetic natural gas) production. PATHWAYS is able to quantify the degree of end-use fuel switching required to balance this excess generation.

From a cost standpoint, the PATHWAYS results ($1 to $2 trillion) are consistent with those found in the EMF 24 studies, which ranged from $1 to $4 trillion[16] for most of the 80% emission reduction scenarios, although one outlying model found costs as high as $6 trillion [*Clarke et al.*, 2014]. Not all models were able to report the same cost metrics due to structural differences, so the costs reported for each model reflect different ways of handling, for example, the value of leisure time and costs associated with reduced service demands. The above values reflect either total consumption loss, the area under the marginal abatement cost curve, or equivalent variation. A thorough description of the differences among these metrics can be found in Fawcett et al. [2014b]. PATHWAYS calculates the total energy system costs, and does not model changes in service demands in response to higher prices. Finally, there was no consistent trend among models in the EMF 24 studies in terms of the relative costs of the pessimistic renewables vs. the pessimistic nuclear and CCS scenarios.

[16] Net present value of cumulative costs through 2050 in 2005 dollars using a 5% discount rate.

11. Energy System Transitions

11.1. Introduction

This section presents several different kinds of graphical representations of the low carbon transition in energy supply and demand sectors as a different way of considering the results in the previous chapters. PATHWAYS was developed in part to allow broad aggregate trends in energy mix and CO_2 emissions to be seen side by side with the underlying details of stock composition, timing of stock turnover, and rates of uptake of new low carbon infrastructure and equipment. This kind of granular visualization of the low carbon transition can help policy makers, researchers, business, investors, and the public understand what kinds of concrete changes are required, at what scale, with what timing, over the next three to four decades.

11.2. System-Wide Transition

One potential low-carbon transition of the U.S. energy system is illustrated in the Sankey diagrams below. Sankey diagrams use arrows to represent the major flows of energy from supply to end use, with the width of the arrows being proportional to the magnitude of the flows. Figure 50 represents the current U.S. system, and Figure 51 represents the system in the 2050 Mixed Case. In both figures, primary energy supplies are shown on the left.[17] The middle of the figure shows conversion processes, with conversion losses implied but not explicitly shown. The right side of the figures shows final energy consumption, with all end uses allocated to the three aggregate categories of buildings, transportation, and industry.

The main results are illustrated by comparing the two figures. Overall, both primary and final energy use are reduced in the 2050 Mixed Case through improvements in energy efficiency. On the primary energy side, fossil fuels are greatly reduced, including the complete elimination of coal and a dramatic reduction of petroleum use. A substantial amount of natural gas remains in the system due to the availability of CCS for power generation in this scenario. Renewable and nuclear primary energy for generation are dramatically increased, and biomass-derived pipeline gas and liquids become the dominant combustion fuels. Conversion processes that are small or negligible at present—biomass refining and the production of hydrogen and synthetic natural gas from electricity—play an important role in the 2050 energy system. End uses show dramatic fuel switching away from fossil fuels toward electricity, electricity-derived fuels, and biomass-derived fuels.

[17] Primary energy here is calculated using the "captured energy" approach in which renewable and nuclear electricity are converted to primary energy on a 1:1 basis.

Figure 50. Sankey Diagram for U.S. Energy System in 2014

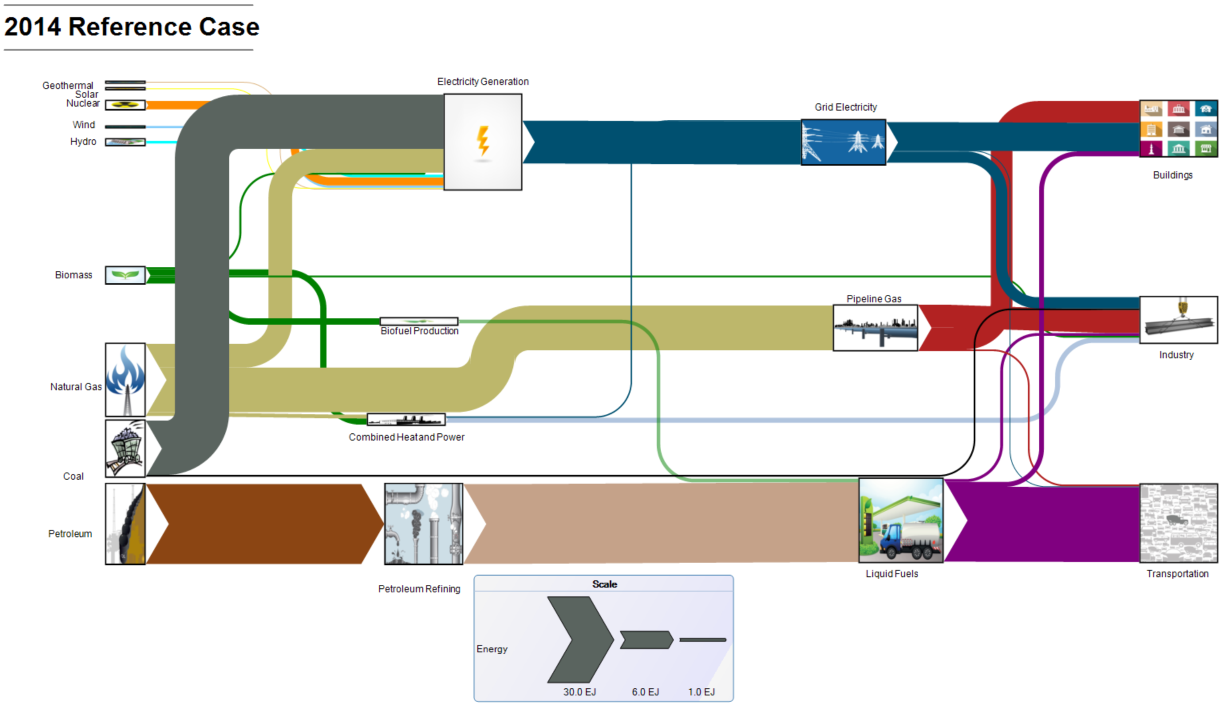
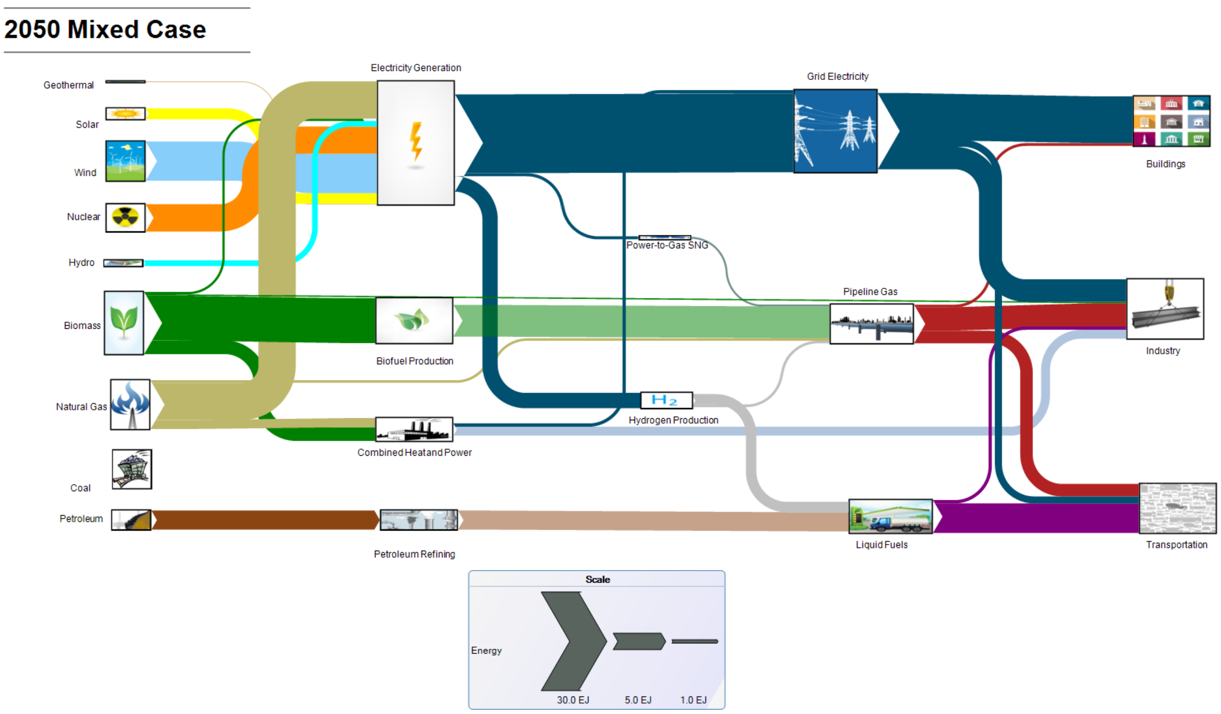


Figure 51. Sankey Diagram for 2050 Mixed Case U.S. Energy System



11.3. Supply Sector Transition

The figures below show the transition in energy supplies for each of the four low carbon scenarios in this study, illustrating how the strategies differ by case. In each figure there are three columns representing three main types of final energy supply—electricity, pipeline gas, and liquid fuels. The middle row of each figure shows how the composition of the supply mix within each supply type changes over time, from present to 2050. The bottom row shows the resulting change in carbon intensity of the delivered energy. The top row shows the demand composition of supply—the amount and relative share that each final demand type consumes of each supply type—at present and in 2050. Demand includes the use of electricity to produce hydrogen and SNG.

Figure 52 shows the low carbon transition for the Mixed Case. The carbon intensity of electricity is reduced by a factor of more than 30 over time despite a near doubling of generation as new electric loads are brought on in buildings, transportation, and industry, plus production of hydrogen and SNG as fuels for load balancing. The steady carbon intensity decline is the result of phasing out uncontrolled fossil fuel generation at it retires while increasing the shares of renewable, nuclear, and CCS generation, a process that is accelerated after 2030. Pipeline gas is decarbonized by an order of magnitude over time, with almost all biomass resources turned into bio-SNG and added to the pipeline, in combination with SNG and hydrogen produced from electricity. Overall pipeline gas demand decreases slightly over time, as most building gas and a portion of industrial gas use are eliminated by electrification, and the primary new gas loads are in heavy duty transportation (in the from of CNG and LNG). In liquid fuels petroleum use declines by about three-quarters as a consequence of vehicle efficiency improvements in combination with fuel switching to electricity for light duty vehicles and pipeline gas for heavy duty vehicles. Some transportation fuel demand is met by hydrogen, which is trucked in liquid form from supply to fueling stations, and therefore included in the liquid fuels category. The overall energy intensity of liquid fuels decreases modestly over time, as the hydrogen share grows, but petroleum remains the principal liquid fuel.

Figure 53 the low carbon transition in the High Renewables Case. It resembles the pattern of the Mixed Case in many regards, with the exception of no CCS in generation, which is replaced by a higher share of renewable generation, with a steep ramp in wind generation beginning around 2030. Generation carbon intensity is again reduced more than 30 fold. The production of hydrogen and SNG from electricity is higher than in the Mixed Case, as a result of higher balancing requirements from variable generation, and the resulting share of these fuels in the pipeline gas mix is higher. The overall quantity of pipeline gas remains constant over time, with reduced building gas use offset by higher transportation gas use than in the mixed case. The proportion of natural gas remains somewhat higher within the pipeline mix, and consequently the carbon intensity decrease is somewhat less over time. Petroleum, on the other hand, decreases more rapidly, with an especially steep decline in the 2030s, as electricity replaces more gasoline in light duty transportation and CNG/LNG replaces more diesel in heavy duty transportation. Hydrogen plays a smaller role in transportation for a similar reason, and again the carbon intensity of liquid fuels overall is only modestly reduced as petroleum remains the dominant residual liquid fuel, albeit in much reduced quantity.

Figure 52. Energy Supply Sector Low Carbon Transition in Mixed Case

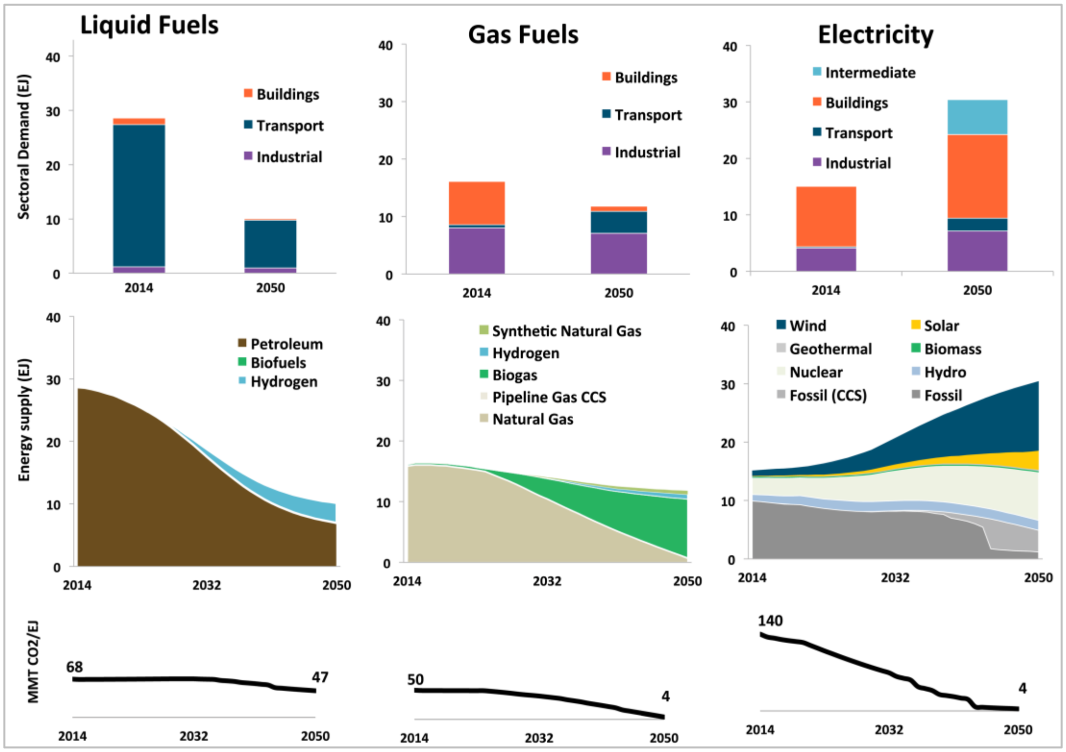


Figure 53. Energy Supply Sector Low Carbon Transition in High Renewables Case

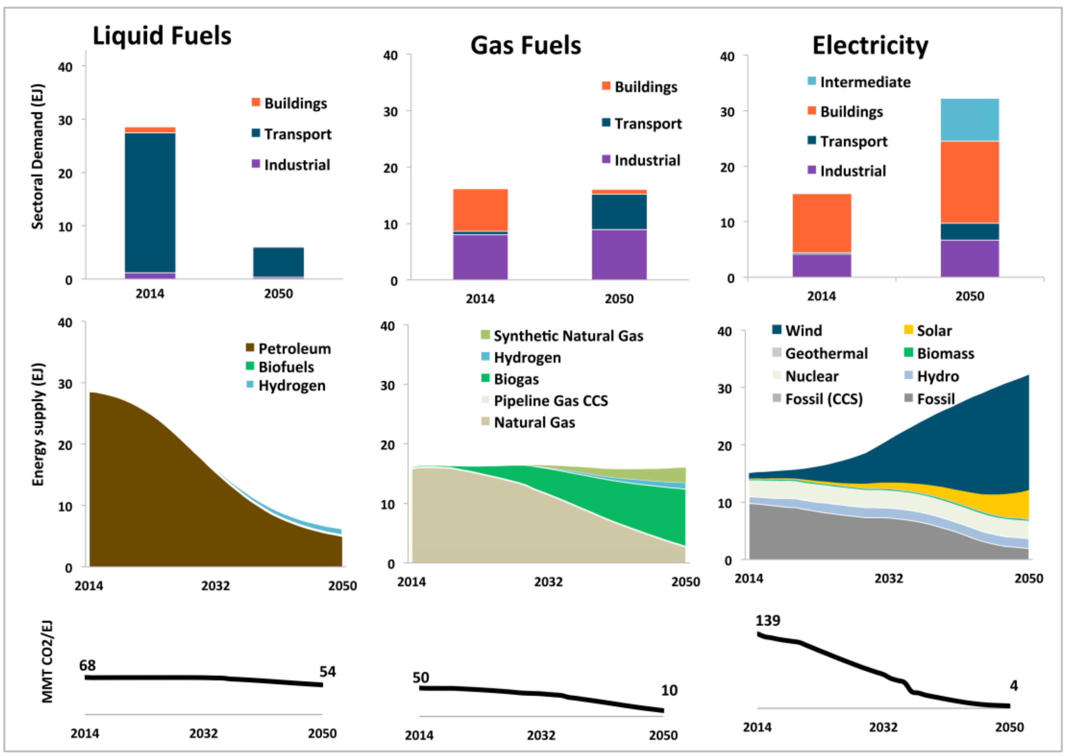


Figure 54. Energy Supply Sector Low Carbon Transition in High Nuclear Case

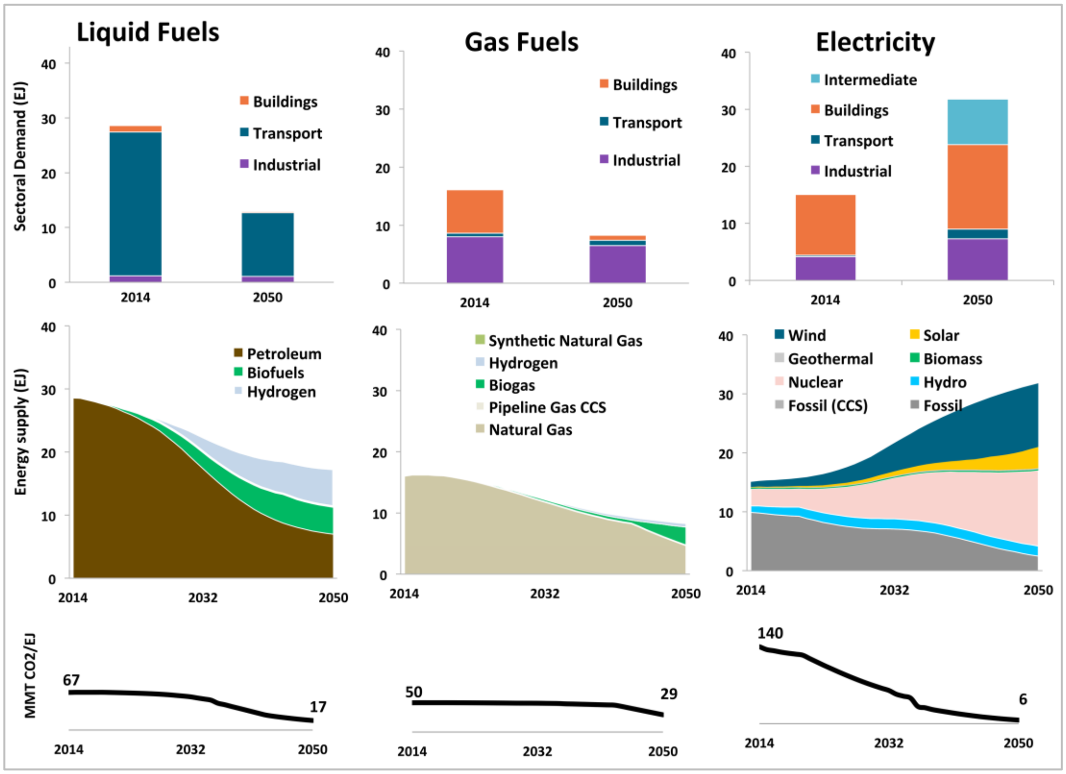


Figure 55. Energy Supply Sector Low Carbon Transition in High CCS Case

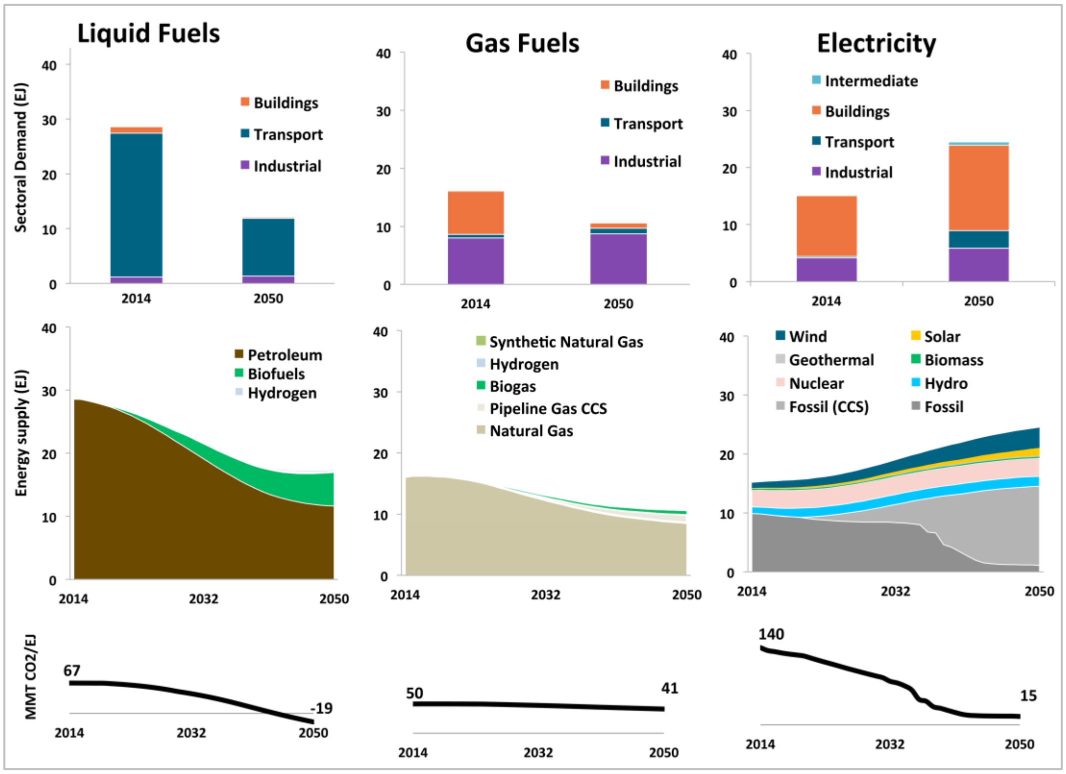


Figure 54 shows the low carbon transition in the High Nuclear Case. The decrease in electricity carbon intensity is similar to the previous cases, and the increase in total generation and renewables, along with the level of residual fossil generation, being similar to that in the Mixed Case. Without CCS, nuclear power expands rapidly after about 2020 to take over the remaining share of retired fossil generation. The strategies for gas and liquid fuels are different from the Mixed and High Renewables Cases, which is a consequence of pursuing a very different strategy for transportation fuels. In the High Nuclear Case, biomass is used primarily for the production of liquid fuels (mostly renewable diesel), and electricity-produced hydrogen is mostly allocated to use in transportation fuel cells. Because of the growth in biofuels and hydrogen, the quantity of liquid fuels declines only modestly over time, as the combined carbon intensity decreases by a factor of more than three. Pipeline gas supply declines more in quantity than in the earlier cases, while the pipeline fuel mix remains dominated by natural gas. As a consequence, the reduction in pipeline gas carbon intensity over time is modest, especially before the 2040s when more gasified biomass is introduced to the pipeline.

Figure 55 shows the low carbon transition in the High CCS Case. Since substantial fossil fuel use remains in this scenario, with carbon emissions being captured, it is the case most similar in pattern to the existing energy system, including the continued use of coal in generation. The presence of CCS to capture emissions elsewhere in the economy allows for a less steep drop in electricity carbon intensity than in other cases, though it still declines by order of magnitude below present. Renewables increase modestly and nuclear is kept at current levels, while the overall increase in generation is less than in other cases. Pipeline gas declines only modestly in quantity and remains dominated by natural gas, since CCS is assumed to capture some combustion emissions in industry. As a consequence the decline in carbon intensity of pipeline gas is even less than in the High Nuclear Case. The High CCS Case also has the lowest decline in petroleum use, though still about half relative to present. However, the carbon intensity of liquid fuels overall decrease dramatically, to a negative emissions level. This is due to the application of CCS to the refining of biomass to produce biodiesel. This is the only application of BECCS in the four scenarios. The High CCS Case is also unique among the scenarios in not using electric fuels to balance non-dispatchable generation.

11.4. Demand Sector Transition

The figures below show the low carbon transition in energy end use over time for the Mixed Case, illustrating energy efficiency and fuel switching strategies. Starting with changes in the physical stock, they show the magnitude and rate of demand-side infrastructure turnover needed to meet the 2050 emissions target.

The figures describe five key demand subsectors: light duty vehicles, heavy duty vehicles, residential space heating, commercial lighting, and iron and steel. While not covering all of the demand subsectors modeled in this study, the five subsectors chosen are both very important for overall energy and emissions, and indicative of the transition within their respective sectors. Each figure shows six kinds of indicators as they evolve over the period from 2014 to 2050: from top to bottom these are total service demand, new stock by fuel type, total stock by fuel type (includes retirements, not shown separately in this figure), service demand decomposed by fuel type, final energy by fuel type, and emissions by fuel type.

Figure 56 shows the low carbon transition in light duty vehicles. Total vehicle miles traveled increase over time, following the trend in the *AEO* Reference Case. Between the mid-2020s and mid-2030s, sales of fuel cell, battery electric, and plug-in hybrid electric vehicles rise from a small share to the majority share of new LDVs, and by the 2040s they constitute all new LDV sales, about one-third of each type. Total vehicle stock composition shows a time lag of approximately one decade in reflecting new vehicle sales. Reflecting the change in stocks, VMT by fuel shows electricity and hydrogen growing from a small share in 2030 to the dominant share in 2040. Final energy by fuel declines much sooner than the uptake of non-ICE vehicles, as fuel economy in conventional gasoline vehicles improves, starting with current federal standards. Emissions from LDVs decline more or less linearly from the present to 2050, reflecting the sequence of developments described above, in combination with the declining carbon intensities of electricity and hydrogen production, which reach negligible levels by 2050 in the Mixed Case.

Figure 56. Light Duty Vehicle Low Carbon Transition in Mixed Case

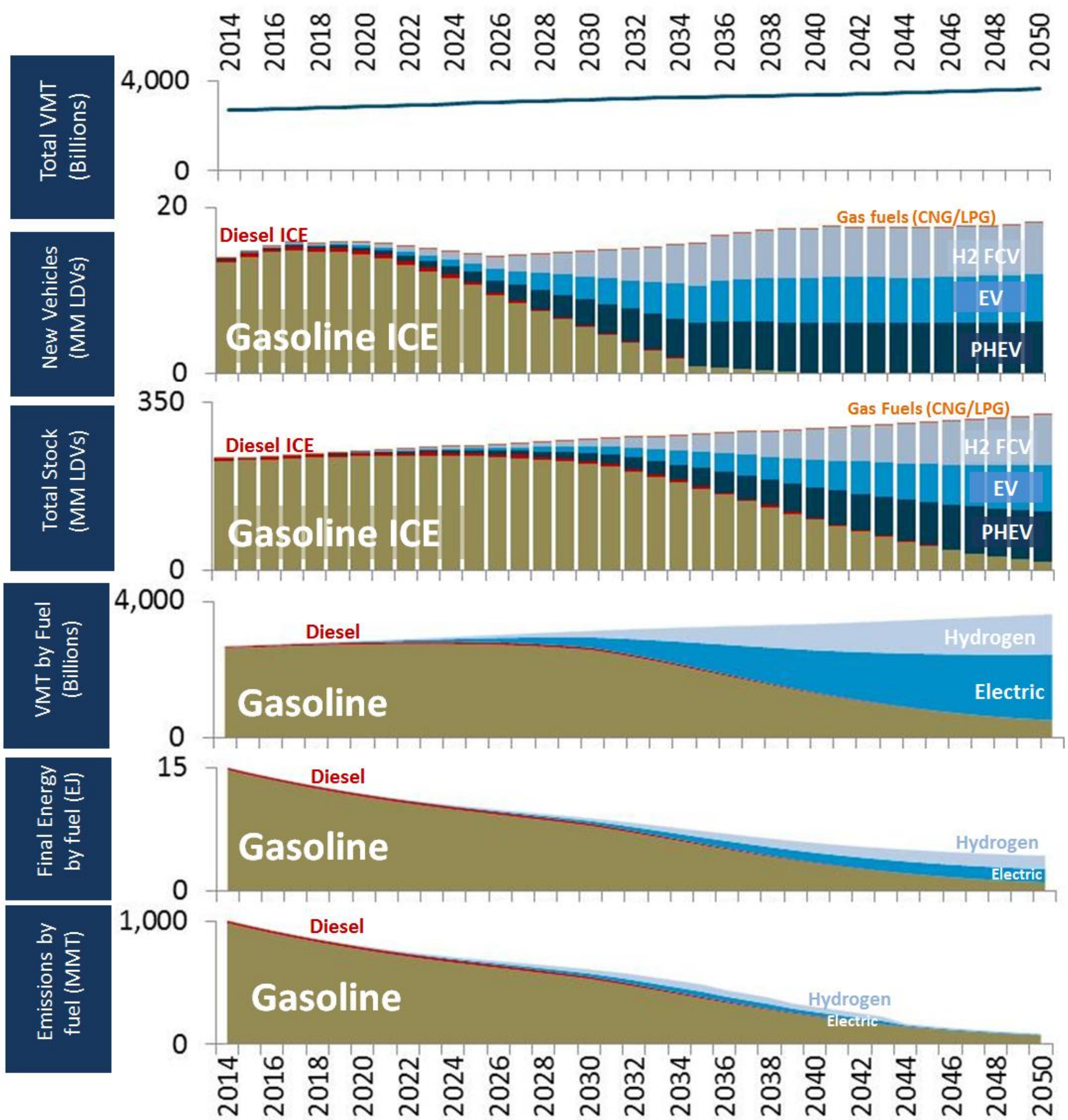


Figure 57 shows the low carbon transition in heavy duty vehicles. HDV miles nearly double over time, following the trend in the *AEO* Reference Case. CNG/LNG and hydrogen fuel cell HDVs are introduced in the 2020s and rise in share to the majority of new vehicle sales by the early 2030s, and the majority of stocks and VMT by fuel by the late 2040s. Final energy rises with increasing mileage to the mid-2020s, then levels out, reflecting efficiency improvements in both conventional diesel and non-diesel alternative vehicles. Emissions from HDVs peak in the 2020s and decline thereafter, despite the plateau in final energy, as the carbon intensity of both pipeline gas supply and hydrogen production fall in the mixed case.

Figure 57. Heavy Duty Vehicle Low Carbon Transition in Mixed Case

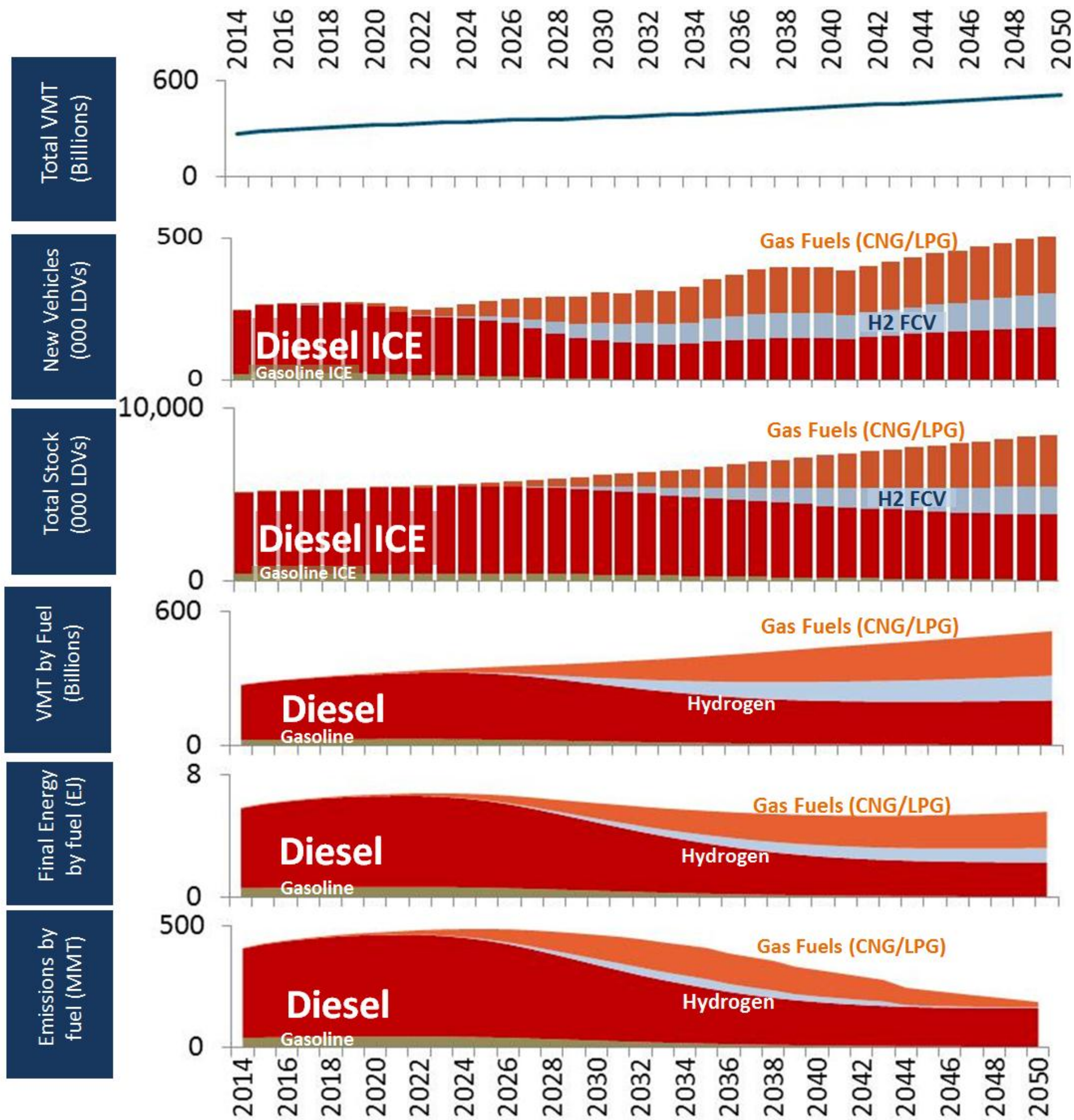


Figure 58 shows the low carbon transition in residential space heating. Both residential housing units and residential floor space increase by almost half over time, following the trend in the *AEO* Reference Case. The principal strategy employed is fuel switching from natural gas furnaces and radiators to electric radiators and heat pumps. This is a rapid and relatively near term transition, as electric heat constitutes the majority of new heating sales by 2020, and of total residential heating stock and final energy use by the 2030s, with almost all heating from electricity by 2050. Reflecting the carbon intensity trajectory of generation in the Mixed Case, both direct and indirect emissions from residential space heating become negligible after the mid-2040s. The bottom chart in Figure 58 shows space heating's share of total residential emissions over time, which shows a similar linear reduction path over the next three decades.

Figure 58. Residential Space Heat Low Carbon Transition in Mixed Case

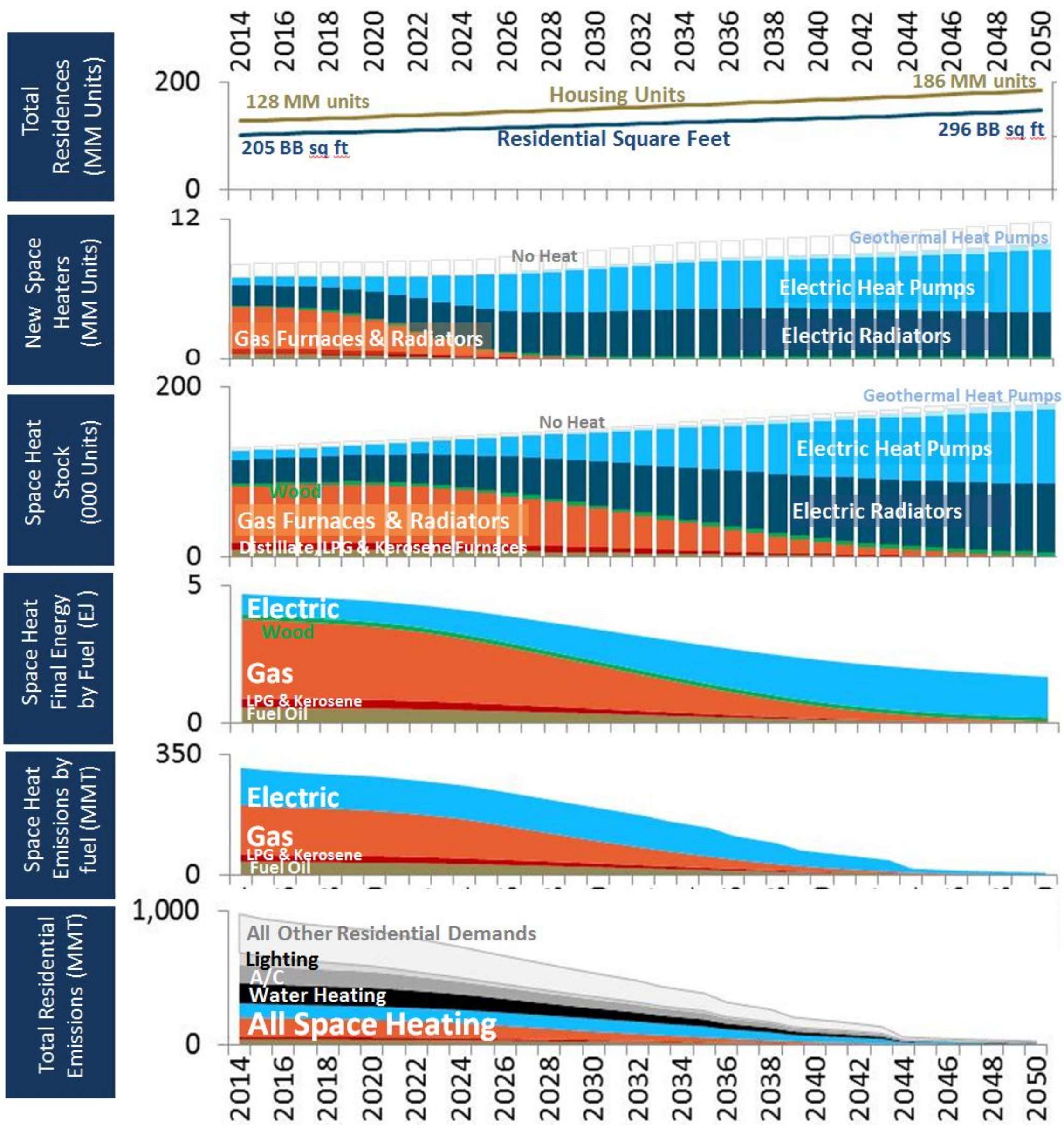


Figure 59 shows the low carbon transition in commercial lighting. Commercial lighting demand increases 40% by 2050, following the trend for commercial floor space in the AEO Reference Case. The strategy employed is replacement of existing lighting technologies with LEDs, which constitute all new lighting after the mid-2020s. The entire commercial lighting stock consists of LEDs by the early 2030s. Reflecting the carbon intensity trajectory of generation in the mixed case, indirect emissions from lighting become negligible by 2040. The bottom chart in Figure 59 shows lighting's contribution of total commercial emissions over time, a negligible share by 2040.

Figure 59. Commercial Lighting Low Carbon Transition in Mixed Case

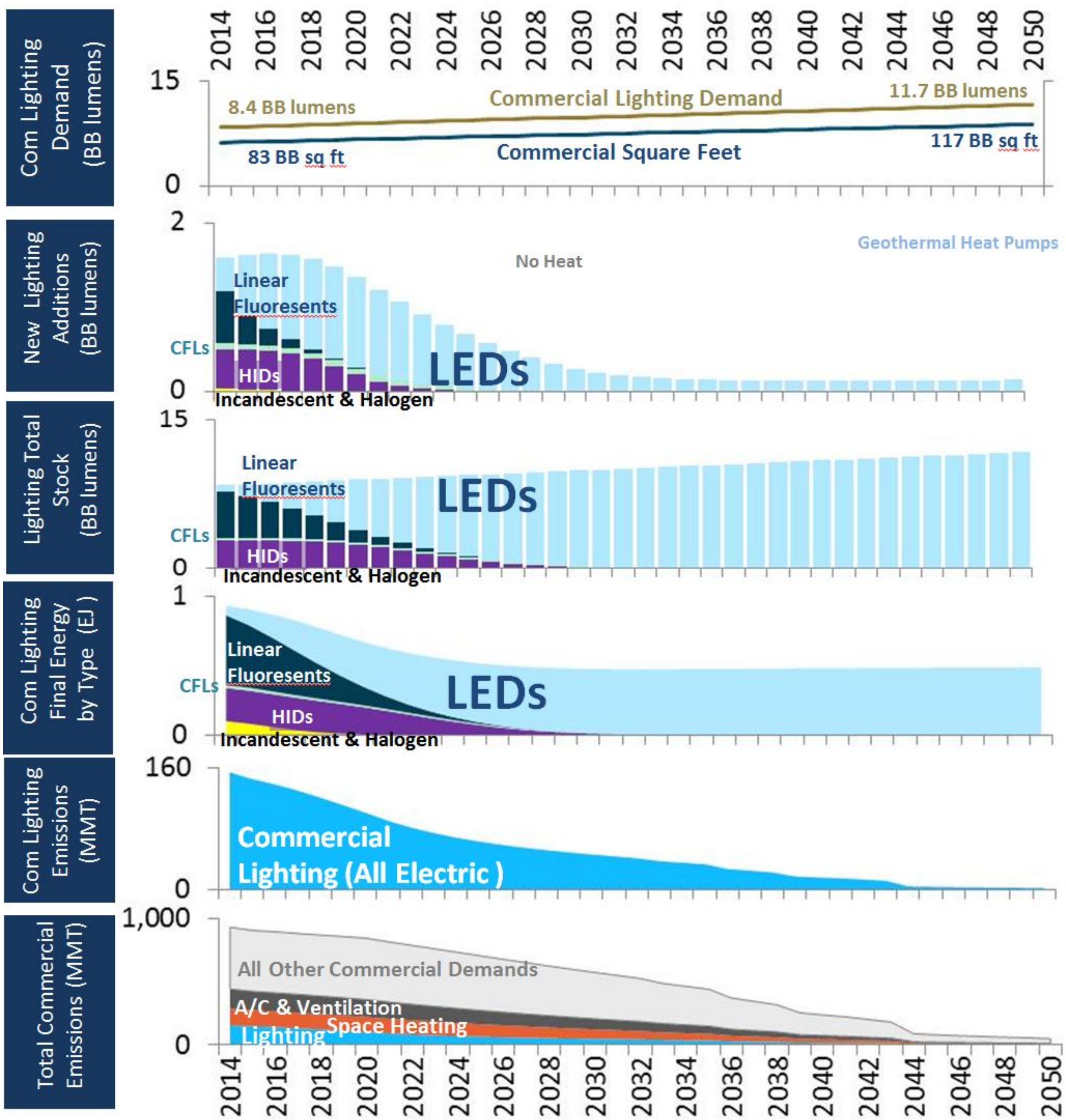
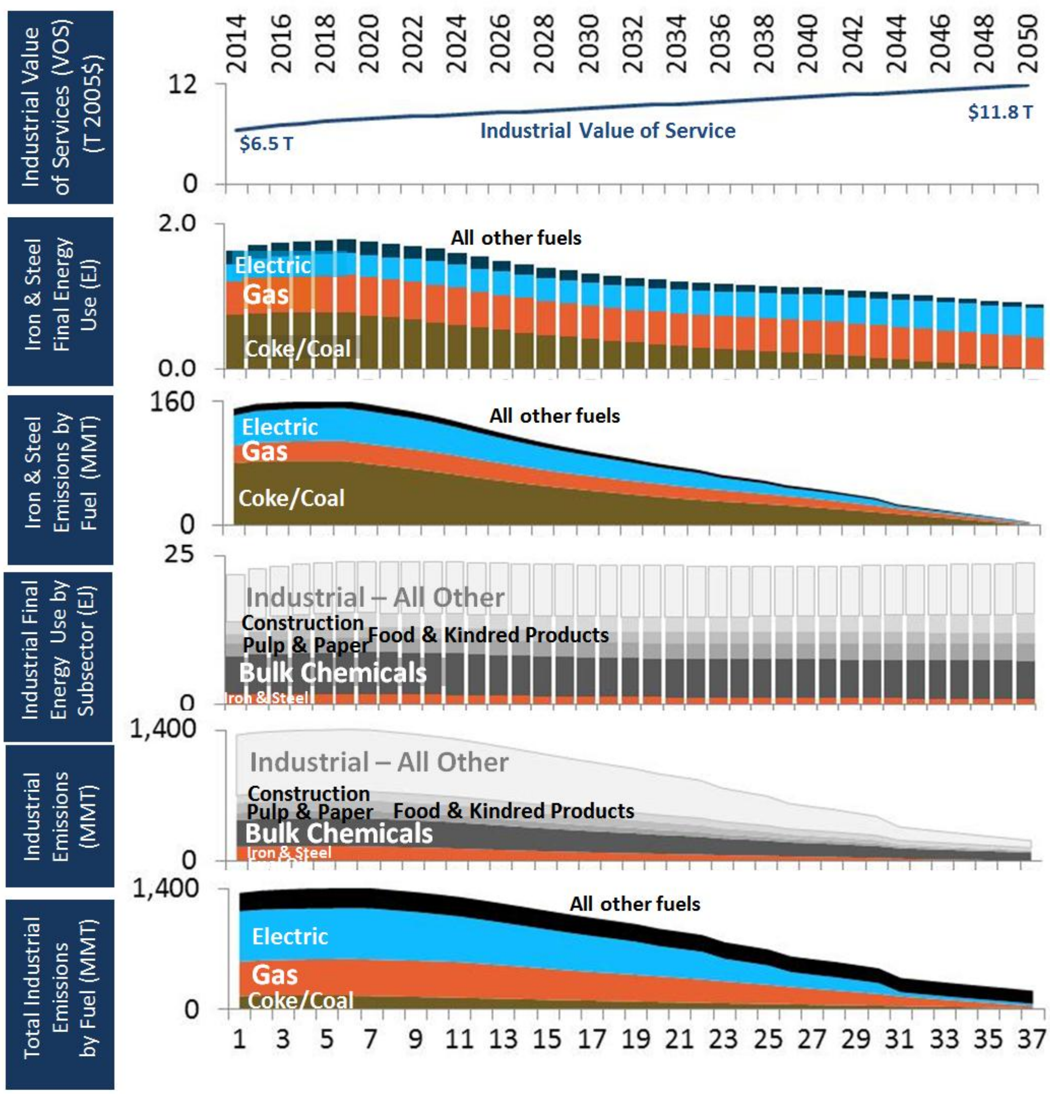


Figure 60 shows the low carbon transition in the iron and steel industry. By 2050, iron and steel value of shipments increase by 80% over current levels based on the *AEO* Reference Case. In all cases except for the High CCS Case, the main strategy for iron and steel is an acceleration of the reference case trend of converting basic oxygen furnaces (BOF) utilizing pig iron as a feedstock into electric arc furnaces (EAFs), which use scrap steel or direct reduced iron (DRI). The High CCS Case maintains the Reference Case production technology and utilizes CCS to capture combustion-related emissions, with an increase in final energy demand. In the Mixed Case and all other cases, final energy demand significantly decreases and coal and coke are phased out by 2050, with final energy supplies coming primarily from equal shares of electricity and pipeline gas. The lower three graphs of Figure 60 show the share of iron and steel in industrial energy use and emissions, and the share of industrial emissions by fuel type. Industrial final energy demand increases slightly over time while it declines in all other sectors, so that industry is responsible for nearly half (about 43-46% across scenarios) of all final energy use in the U.S. economy by 2050.

Figure 60. Iron and Steel Industry Low Carbon Transition in Mixed Case



12. Conclusions

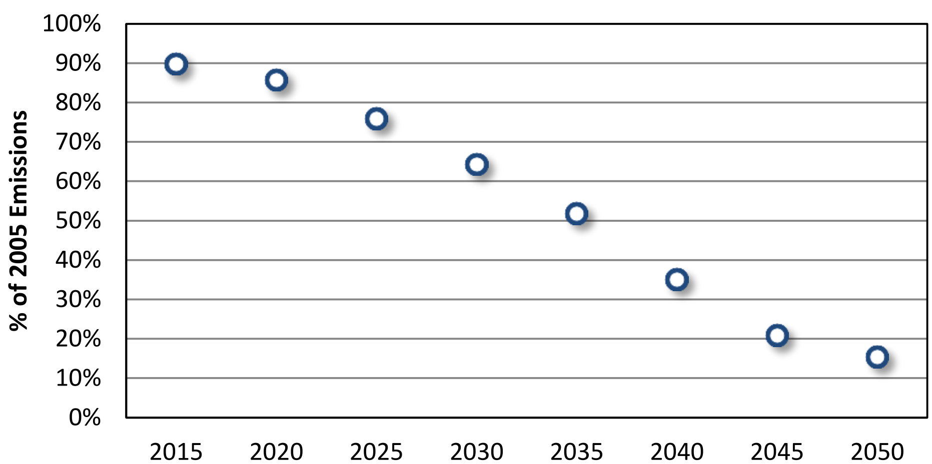
1. Is it technically feasible to reduce U.S. GHG emissions to 80% below 1990 levels by 2050, subject to realistic constraints?

This study finds that it is technically feasible for the U.S. to reduce GHG emissions 80% below 1990 levels by 2050 with overall net GHG emissions of no more than 1,080 MtCO_2e, and fossil fuel combustion emissions of no more than 750 MtCO_2. Meeting a 750 MtCO_2 target requires a transformation of the U.S. energy system, which was analyzed using PATHWAYS. The analysis employed conservative assumptions regarding technology availability and performance, infrastructure turnover, and resource limits. Four distinct scenarios employing substantially different decarbonization strategies —High Renewable, High Nuclear, High CCS, and Mixed Cases, which were named according to the different principal form of primary energy used in electricity generation, and also differed in other aspects of energy supply and demand—all met the target, demonstrating robustness by showing that redundant technology pathways to deep decarbonization exist.

Analysis using the GCAM model supports the technical feasibility of reducing net non-energy and non-CO_2 GHG emissions to no more than 330 Mt CO_2e by 2050, including land use carbon cycle impacts from biomass use and potential changes in the forest carbon sink.

The U.S. total emissions trajectory for the Mixed Case, assuming a constant terrestrial CO_2 sink, is shown in Figure 61.

Figure 61. U.S. Total GHG Emissions for the Years 2015-2050, as a Percentage of 2005 Emissions



2. What is the expected cost of achieving this level of reductions in GHG emissions?

Achieving this level of emissions reductions is expected to have an incremental cost to the energy system on the order of 1% of GDP, with a wide uncertainty range. This study uses incremental energy system costs—the cost of producing, distributing, and consuming energy in a decarbonized energy system relative to that of a reference case system based on the *AEO*—as a metric to assess the cost of deep reductions in energy-related CO_2 emissions. Based on an uncertainty analysis of key cost parameters in the four analyzed cases, the interquartile (25^{th} to 75^{th} percentile) range of these costs extends from negative $90 billion to $730 billion (2012 $) in 2050, with a median value of just over $300 billion. To put these estimates in context, levels of energy service demand in this analysis are consistent with a U.S. GDP of $40 trillion in 2050. By this metric, the median estimate of net energy system costs is 0.8% of GDP in 2050, with 50% probability of falling between -0.2% to +1.8%. GCAM analysis indicates that the complementary reductions in non-energy and non-CO_2 GHGs needed to meet the 80% target are achievable at low additional cost.

These cost estimates are uncertain because they depend on assumptions about consumption levels, technology costs, and fossil fuel prices nearly 40 years into the future. To be conservative, energy service demands in this analysis were based on an economy and lifestyles that resemble the present day and on technology cost assumptions that reflect near-term expectations, with relatively flat cost trajectories for many technologies out to 2050. Even at the higher end of the probability distribution (the 75th percentile estimate of $730 billion), which assumes little to no technology innovation over the next four decades, the incremental energy system cost of a transition needed to meet the 750 $MtCO_2$ target is small relative to national income.

These incremental energy system costs did not include non-energy benefits, for example, the avoided human health and infrastructure costs of climate change and air pollution. Additionally, the majority of energy system costs in this analysis were incurred after 2030, as deployment of new low-carbon infrastructure expands. Technology improvements and market transformation over the next decade could significantly reduce expected costs in subsequent years.

3. What changes in energy system infrastructure and technology are required to meet this level of GHG reduction?

Deep decarbonization requires three fundamental changes in the U.S. energy system: (1) highly efficient end use of energy in buildings, transportation, and industry; (2) decarbonization of electricity and other fuels; and (3) fuel switching of end uses to electricity and other low-carbon supplies*.* All of these changes are needed, across all sectors of the economy, to meet the target of an 80% GHG reduction below 1990 levels by 2050.

The transformation of the U.S. energy system, while gradual, entails major changes in energy supply and end use technology and infrastructure. With commercial or near-commercial technologies and limits on biomass availability and carbon capture and storage (CCS) deployment, it is difficult to decarbonize both gas and liquid fuel supplies. For this reason, meeting the 2050 target requires almost fully decarbonizing electricity supply and switching a large share of end uses from direct combustion of fossil fuels to electricity (e.g., electric vehicles), or fuels produced from electricity (e.g., hydrogen from electrolysis). In our four decarbonization cases, the use of electricity and fuels produced from electricity increases from around 20% at present to more than 50% by 2050.

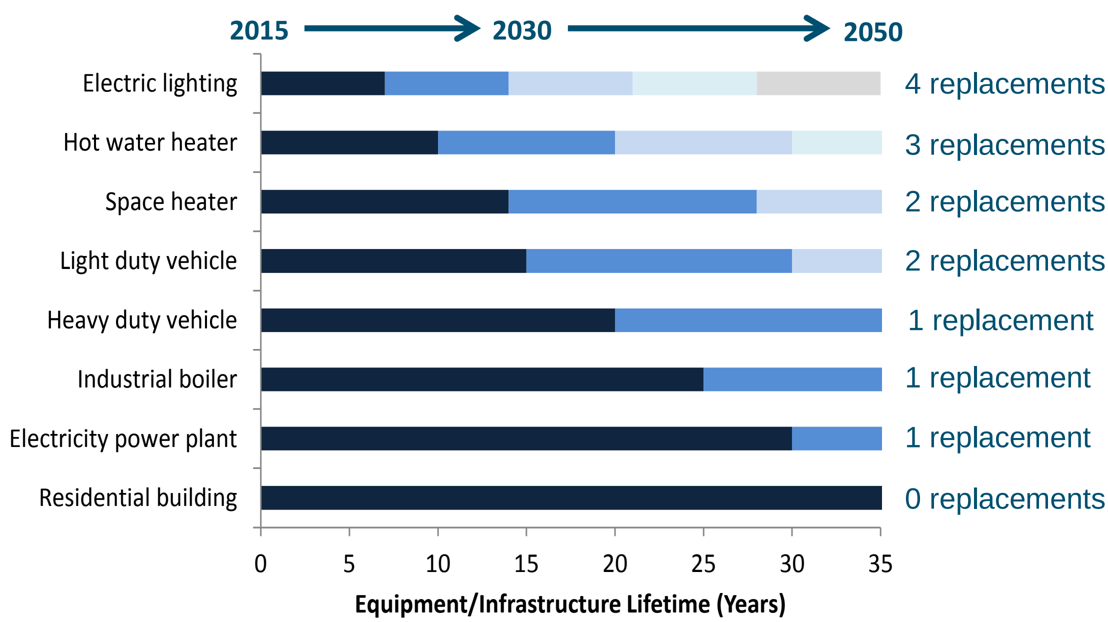
As a result, electricity generation would need to approximately double (an increase of 60-110% across scenarios) by 2050 while its carbon intensity is reduced to 3-10% of its current level. Concretely, this would require the deployment of roughly 2,500 gigawatts (GW) of wind and solar generation (30 times present capacity) in a high renewables scenario, 700 GW of fossil generation with CCS (nearly the present capacity of non-CCS fossil generation) in a high CCS scenario, or more than 400 GW of nuclear (four times present capacity) in a high nuclear scenario.

Similar levels of transformation would be required in other sectors. For example, light duty vehicles (LDVs) would need to become more efficient and switch to low carbon fuels. The average fleet fuel economy of LDVs would need to exceed 100 miles per gallon gasoline equivalent in 2050, while shifting 80-95% of miles driven from gasoline to alternative fuels such as electricity and hydrogen. This would require the deployment of roughly 300 million alternative fuel vehicles by 2050.

4. What are the implications of these technology and infrastructure changes for the energy economy and policy?

There is still sufficient time for the U.S. to achieve 80% GHG reductions by 2050 relying on natural infrastructure turnover. However, to achieve emissions goals and avoid the costs of early retirement, it is critical to account for economic and operating lifetimes in investment decisions. The figure below illustrates the limited number of opportunities between now and 2050 for replacement or addition of infrastructure based on natural stock rollover for different types of equipment.

Figure 62. Stock Lifetimes and Replacement Opportunities



For some important kinds of long-lived infrastructure—for instance, power plants—there is likely to be only one opportunity for replacement in this time period. Adding new high carbon generation (e.g., coal plants) creates infrastructure inertia that either makes the 2050 target more difficult to reach, requires expensive retrofits, or puts investments at risk. Reflecting full lifecycle carbon costs up-front in investment decisions for long-lived infrastructure would reduce these risks. Transitions that involve shorter-lived equipment—for example, LDVs—raise other considerations. This analysis shows that adoption rates for alternative LDVs can initially ramp up slowly, constituting only a small share of the LDV fleet by 2030, but that they must comprise the bulk of new sales shortly thereafter in order to ensure that only a small share of conventional gasoline vehicles remain in the stock by 2050. This suggests that current barriers to adoption of low carbon LDV technologies need to be addressed well before 2030. One key barrier is upfront costs, which can be reduced by timely R&D, market transformation programs, and financial innovation. Anticipating and addressing such barriers in advance is essential to meeting emissions targets at low overall cost.

A deeply decarbonized energy economy would be dominated by fixed cost investments in power generation and in efficient and low-carbon end-use equipment and infrastructure, while fossil fuel prices would play a smaller role. Petroleum consumption is reduced by 76–91% by 2050 across all scenarios in this study, declining both in absolute terms and as a share of final energy. Meanwhile, incremental investment requirements in electricity generation alone rise to $30–70 billion per year above the reference case by the 2040s. The overall cost of deeply decarbonizing the energy system is dominated by the incremental capital cost of low carbon technologies in power generation, light and heavy duty vehicles, building energy systems, and industrial equipment. This change in the energy economy places a premium on reducing capital and financing costs through R&D, market transformation, and creative financing mechanisms. The new cost structure of the energy system reduces the exposure to volatile energy commodity prices set on global markets, while also suggesting a critical role for investment in domestic energy infrastructure.

The recent U.S. government commitment to reduce U.S. total GHG emissions by 26–28% below 2005 levels by 2025 is consistent with the results of this report. Figure ES-1 shows the reduction in total GHG emissions over time relative to 2005 for the Mixed Case in this study, assuming a constant terrestrial carbon sink. In this scenario, U.S. total GHG emissions (net CO_2e) were reduced by 25% in 2025 relative to 2005.

In its announcement, the U.S. government also reaffirmed the goal of "economy-wide reductions on the order of 80% by 2050." Since the U.S. commitment level for 2025 lies on the same trajectory as the deep decarbonization pathways in this analysis, this suggests that successfully achieving the 2025 target would put the U.S. on the road to 80% reductions by 2050. From the perspective of this study, there are different ways that the U.S. can achieve the 2025 target, some of which would lay the necessary groundwork for deeper reductions to follow, and others that might meet the target but tend to produce flat, rather than declining, emissions in the long term. This indicates the importance of evaluating near-term approaches in the light of deep decarbonization analysis. For example, proposals to prevent the construction of new coal power generation unless it is equipped with CCS are consistent with this report's finding that long-lived infrastructure additions must be low-carbon if the 2050 target is to be met while avoiding stranded assets. Other measures, such as increasing the stringency of vehicle fuel economy and appliance efficiency standards, are effective low-cost measures for reaching the 2025 goal, but to continue along the deep decarbonization trajectory after 2025 will require complementary efforts in policy, technology development, and market transformation to enable deeper decarbonization measures (e.g. deeper generation decarbonization, extensive switching of end uses to electricity and low carbon fuels) later on.

This study did not find any major technical or economic barriers to maintaining the U.S. long-term commitment to reducing GHG emissions consistent with limiting global warming to less than 2°C. In terms of technical feasibility and cost, this study finds no evidence to suggest that relaxing the 80% by

2050 emissions target or abandoning the 2°C limit is justified. In addition, the 2°C goal plays a critical role as a guide for near-term mitigation efforts, providing a benchmark for the necessary scale and speed of infrastructure change, technical innovation, and coordination across sectors that must be achieved in order to stay on an efficient path to climate stabilization.

Energy system changes on the scale described in this analysis imply significant opportunities for technology innovation and investment in all areas of the U.S. energy economy. Establishing regulatory and market institutions that can support this innovation and investment is critical. Both areas—technology innovation and institutional development—are U.S. strengths, and place the U.S. in a strong leadership and competitive position in a low carbon world.

Fossil fuel use not controlled by CCS would be greatly reduced and limited to a smaller number of sources. Decarbonized energy systems of 2050 would look fundamentally different from those of today. Historically, U.S. primary energy supply has been dominated by fossil fuels, which have accounted for well over 80% of primary energy use throughout the past 60 years. By contrast, meeting a 750 Mt CO_2 target would require reducing uncontrolled combustion of fossil fuels to at least 80% below current levels, a 10-fold decrease in carbon emissions per capita and a 15-fold decrease in carbon emissions per dollar of GDP. Residual fossil fuel combustion would be concentrated in a smaller number of emissions sources than at present due to fuel switching to electricity in transportation and buildings. This implies a very different kind of energy system, as more than one-third of current U.S. CO_2 emissions are from mobile sources in the transportation sector alone.

The majority of final energy would be delivered in a form that is currently delivered by network providers today (e.g. the utilities that operate the electricity grid and gas pipeline system). Across the scenarios in this study, 58-71% of final energy is delivered to end users in 2050 in the form of either electricity or pipeline gas, primarily as a consequence of reductions in liquid fuel demand due to energy efficiency and fuel switching. This implies a potentially significant role for electric and gas utilities in policy implementation, not only in decarbonization of electricity generation and pipeline gas, but also in demand side energy efficiency and fuel switching (such as electric vehicles), where the low financing costs of utilities might be leveraged for customers in ways that promote consumer adoption.

Deep emission reductions would depend on interactions across sectors and fuel types that today may not share the same markets or regulatory environments, suggesting a need for policy innovation. Interactions across sectors and fuel types—for example, electrification of LDVs while decarbonizing the electricity supply, or switching to pipeline gas for HDVs while decarbonizing the gas supply—become increasingly important sources of CO_2 emission reductions over time in all of our cases, in comparison to same-sector or same-fuel measures (e.g., improving internal combustion engine efficiency). For an energy sector that has historically been relatively insular across energy sources and end uses (e.g., a transportation sector powered predominantly by petroleum-based liquid fuels), this greater integration creates unprecedented but, if anticipated, eminently soluble regulatory and planning challenges.

Further research is needed in many areas. This study identifies five pathway determinants, or key elements of a low carbon energy system in which technology choices or resource endowments disproportionately enable or constrain technology options elsewhere in the system: (1) the availability of CCS and where it is applied, (2) the amount of biomass judged to be sustainable for bioenergy use and how it is applied, (3) the dominant form of primary energy in the electricity generation mix, (4) the approach used to balance electricity generation and end use demand, especially with high penetrations of non-dispatchable (inflexible) generation, and (5) the extent of, and technologies used for, fuel switching and end use efficiency. These five areas are potential focal points for research, innovation, policy, and regulation.

Additional areas identified in the analysis as requiring further research include a better understanding of land use emissions and the terrestrial sink; low-carbon HDV technologies; hydrogen and synthetic natural gas production; and industrial emission reduction potential associated with new product design, materials, and production processes. For the modeling approach used in the PATHWAYS analysis, frontier research areas include downscaling the analysis to the sub-national level, and also internationalizing it through cooperative efforts like the DDPP, in order to develop a more granular understanding of decarbonization challenges and opportunities across jurisdictions and potentially identify new opportunities for joint R&D, trade, market development, and policy collaboration.

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Appendix A. Acronyms

AEO: Annual Energy Outlook, report issued by U.S. Energy Information Administration

BECCS: Bio-Energy with Carbon Capture and Storage

BOF: Basic oxygen furnaces

BTS2: U.S. DOE Billion Ton Study Update

CCS: Carbon capture and storage (or Carbon capture and sequestration)

CDIAC: Carbon Dioxide Information Analysis Center

CHP: Combined heat and power

CNG: Compressed Natural Gas

DDPP: Deep Decarbonization Pathways Project

DOE: U.S. Department of Energy

DRI: Direct reduced iron

EAF: Electric arc furnace

EDGAR: Emission Database for Global Atmospheric Research

EIA: U.S. Energy Information Administration

EMF21: Energy Modeling Forum Study 21

EMF24: Energy Modeling Forum Study 24

EPA: U.S. Environmental Protection Agency

EV: Electric vehicle

F-T: Fischer-Tropsch

GCAM: global integrated assessment model

GDE: Gallon diesel equivalent

GDP: Gross Domestic Product

GGE: Gallon gasoline equivalent

GHG: Greenhouse gas

HDV: Heavy-duty vehicle

HFCV: Hydrogen fuel cell vehicle

HVAC: Heating, Ventilation, Air Conditioning

ICE: Internal combustion engine

IDDRI: Institute for Sustainable Development and International Relations

ILUC: Indirect land use change

LDV: Light-duty vehicle

LED: Light Emitting Diode; high efficiency lighting

LNG: Liquefied Natural Gas

LPG: Liquefied propane gas

LULUCF: Land Use, Land Use Change and Forestry

MACs: Marginal abatement cost curves

NEMS: U.S. National Energy Modeling System

P2G: Power-to-Gas

PATHWAYS: bottom-up stock rollover model of the U.S. energy system

PHEV: Plug-in hybrid electric vehicle

R&D: Research and Development

RCP: Representative Concentration Pathway

RFS: Renewable Fuel Standard

SDSN: Sustainable Development Solutions Network

SNG: Synthetic natural gas

VMT: Vehicle miles traveled

VOS: Value of service

Appendix B. Data Sources

Table 11. Data Sources for PATHWAYS Model Inputs and Cases

Sector	Subdivisions	Categories	Data Types	Data sources[1]
Macro-economy	Population GDP	Nationwide Census division Value added	Current Growth forecasts	EIA 2013
Residential	Single family Multi-family Other	Heating Cooling Lighting Water Heating Other	Stocks Lifetimes Capital costs Fuel types Efficiencies	EIA 2013 DOE 2010 DOE 2012
Commercial	Buildings Utilities Other	Heating Cooling Lighting Water Heating Other	Stocks Lifetimes Capital costs Fuel types Efficiencies	EIA 2013 DOE 2010 DOE 2012
Transportation	Passenger Freight Military Other	Vehicles Rail Air Shipping Other	Stocks Lifetimes Capital costs Fuel types Efficiencies	EIA 2013 NRC 2010 NRC 2013 FHA 2010 FHA 2011
Industry	Iron and steel Cement Refining Chemicals Other	Heat/steam CCS Other	Stocks Lifetimes Capital costs Fuel types Efficiencies	EIA 2013 EIA 2010 Kuramochi 2012
Electricity Supply	Generation Transmission Distribution	Fossil Renewable CCS Nuclear Other	Efficiencies Capital cost Operating cost Other	EIA 2013 EIA 2014b,c B&V 2013 NREL 2012 NREL 2013a NREL 2014a,b, c EPA 2014b CARB 2012 CARB 2014
Fossil Fuel Supply	Petroleum Natural Gas Coal	Gasoline Diesel Jet fuel LNG Other	Efficiencies Capital cost Operating cost Emission factors Other	EIA 2013 EPA 2014a
Biomass	Feedstock Conversion	Purpose grown Crop waste Forestry waste Committed uses Other	Efficiencies Capital cost Operating cost Other	DOE 2011 Gassner 2009 Tuna 2014 Liu 2011 Swanson 2010
Others	Fuels Produced from Electricity	Hydrogen Synthetic Natural Gas	Efficiencies Capital cost Operating cost Other	SGC 2013 NREL 2009

[1]Primary Data Sources for Table 11

(B&V 2012) = Black and Veatch (2012), *Cost and Performance Data for Power Generation Technologies*
(CARB 2012) = California Air Resources Board (2012), *Vision for Clean Air: A Framework for Air Quality and Climate Planning*
(CARB 2014) = California Air Resources Board (2014), *EMFAC Model* and *EMFAC Database*
(DOE 2010) = Department of Energy (2010), *Lighting Market Characterization Report*
(DOE 2011) = Department of Energy (2011), *Billion Ton Update*
(DOE 2012) = Department of Energy (2012), *Energy Savings Potential of Solid-State Lighting in General Illumination Applications*
(EIA 2010) = Energy Information Administration (2010), *Manufacturing Energy Consumption Survey Data 2010*
(EIA 2013) = Energy Information Administration (2013), *Annual Energy Outlook 2013*, *Assumptions to the Annual Energy Outlook 2013,* and supporting data files from National Energy Modeling System
(EIA 2014a) = Energy Information Administration (2014), *Annual Energy Outlook 2014,* and supporting data files from National Energy Modeling System
(EIA 2014b) = Energy Information Administration (2014), *Form EIA-860*
(EIA 2014c) = Energy Information Administration (2014), *Form EIA-923*
(EPA 2014a) = Environmental Protection Agency (2014), *Emissions Factors for Greenhouse Gas Inventories*
(EPA 2014b) = Environmental Protection Agency (2014), *Power Sector Modeling Platform v.5.13*
(FERC 2014) = Federal Energy Regulatory Commission (2014), *FERC Form No. 714*
(FHA 2010) = Federal Highway Administration (2010), *Highways Statistics 2010*
(FHA 2011) = Federal Highway Administration (2011), *Highways Statistics 2011*
(NRC 2010) = National Research Council (2010), *Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles*
(NRC 2013) = National Research Council (2013), *Transitions to Alternative Vehicles and Fuels*
(NREL 2009) = National Renewable Energy Laboratory (2009), *Current State-of-the-Art Hydrogen Production Cost Estimates from Water Electrolysis*
(NREL 2012) = National Renewable Energy Laboratory (2012), *Renewable Electricity Futures Study*
(NREL 2013a) = National Renewable Energy Laboratory (2013), *Western Wind, Eastern Wind, and ERCOT datasets* by AWS Truepower
(NREL 2013b) = National Renewable Energy Laboratory (2013), *Potential for Energy Efficiency Beyond the Light-Duty Sector*
(NREL 2014a) = National Renewable Energy Laboratory (2014), *National Solar Radiation Database*
(NREL 2014b) = National Renewable Energy Laboratory (2014), *Solar Prospector*
(NREL 2014c) = National Renewable Energy Laboratory (2014), *System Advisor Model Version 2014.1.14*
(SGC 2013) = Svenskt Gastekniskt Center AB (2013), *Power-to-Gas – A technical review*

Appendix C. CO_2 Emissions by End Use

A limited number of energy end uses contribute to the bulk of U.S. CO_2 emissions from fossil fuel combustion. As shown, the top 15 emitting end uses contributed to an estimated 63% of emissions in 2010. This relatively high level of concentration of emissions among end uses is consistent with our sector-based, bottom-up modeling approach.

Table 12. CO_2 Emissions by Energy End Use in the U.S., 2010

Energy End Use	CO_2 Emissions ($MtCO_2$)	% Total Energy CO_2 Emissions
Light-Duty Vehicles	1,060	19%
Freight Trucks	351	6%
Commercial Space Heating	286	5%
Industrial Refining	262	5%
Bulk Chemicals Production	259	5%
Air travel	178	3%
Residential Lighting	170	3%
Commercial Space Cooling	162	3%
Commercial Water Heating	160	3%
Residential Space Heating	129	2%
Iron and Steel	118	2%
Commercial Lighting	116	2%
Residential Space Cooling	101	2%
Food Products Production	100	2%
Commercial Ventilation	87	2%
Total Above	**3,538**	**63%**
Total Energy CO_2 Emissions	**5,634**	

Source: EIA, Annual Energy Outlook, 2013

Appendix D. 2015 Technical Supplement

This technical supplement was prepared in order to show additional detail by case for key metrics of cost, GHG emissions, final energy demand, primary energy flows and investment from the Pathways analysis. The table of contents below shows the figures available in this supplement. In addition, a series of output spreadsheets that show additional detail by region and subsector is available from E3.

Figure 1 Final Energy Demand by Final Energy, Year, and Case

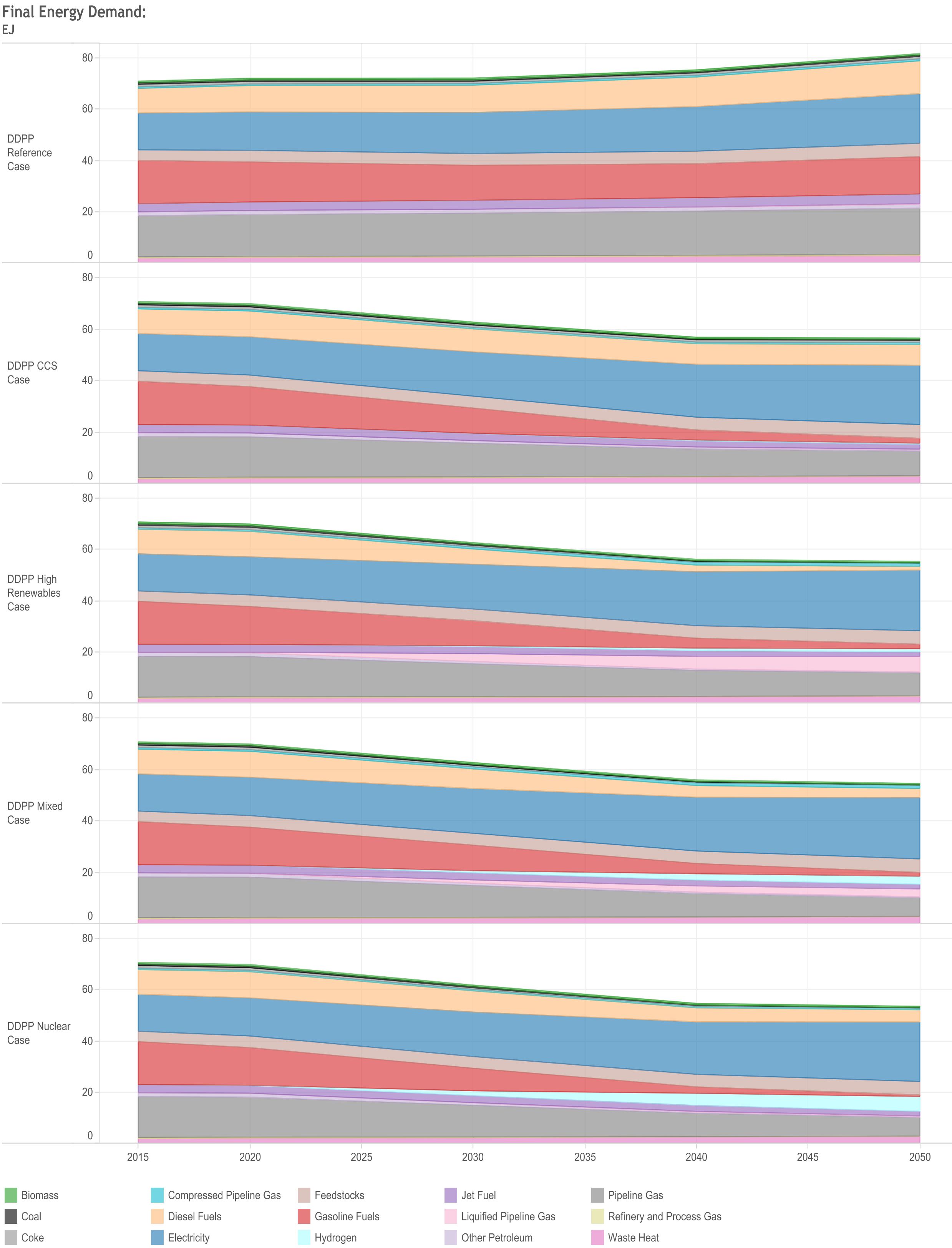


Figure 2 GHG Emissions by Final Energy, Year, and Case

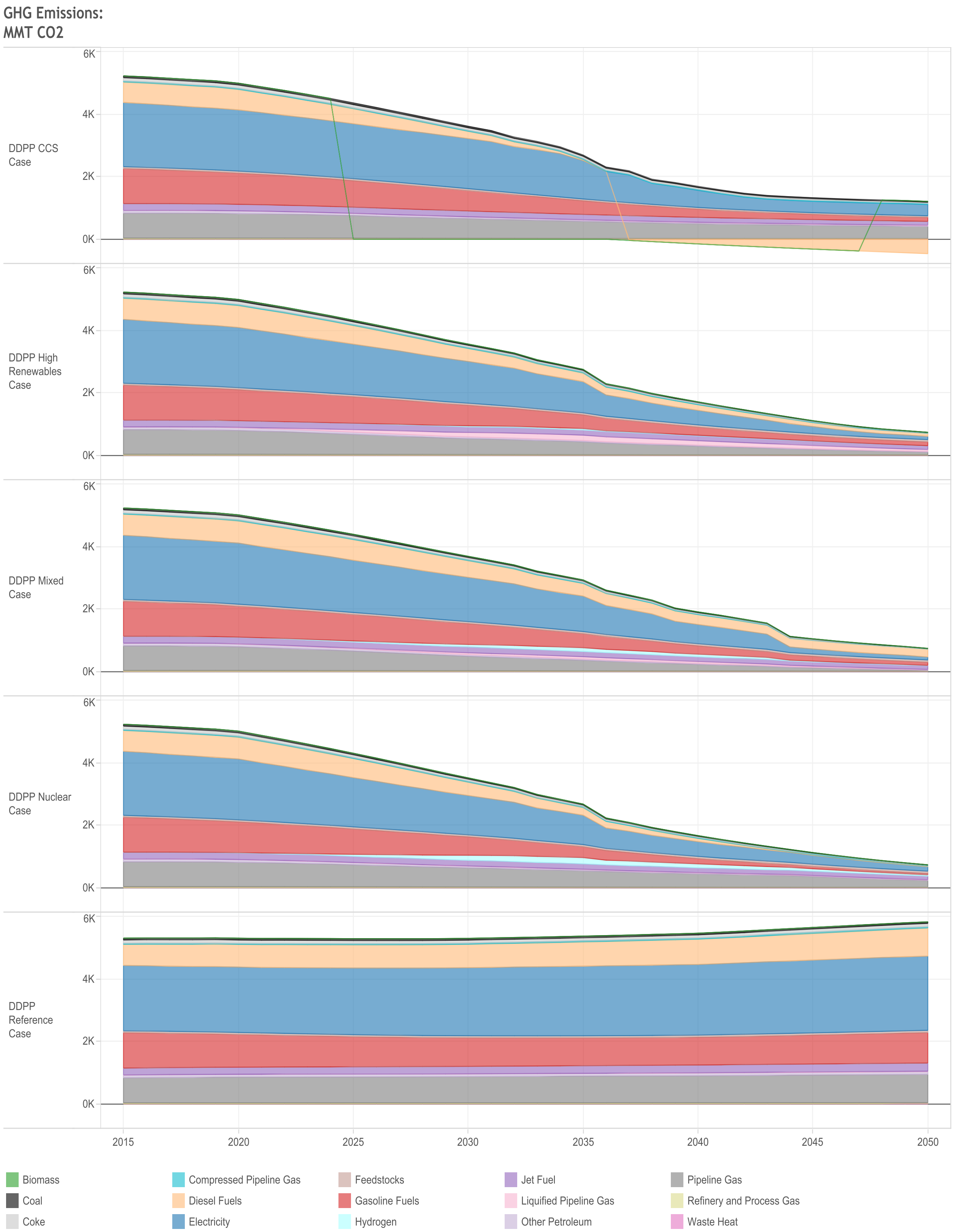


Figure 3 Incremental Costs ($2012B), by Cost Category, Year, and Case

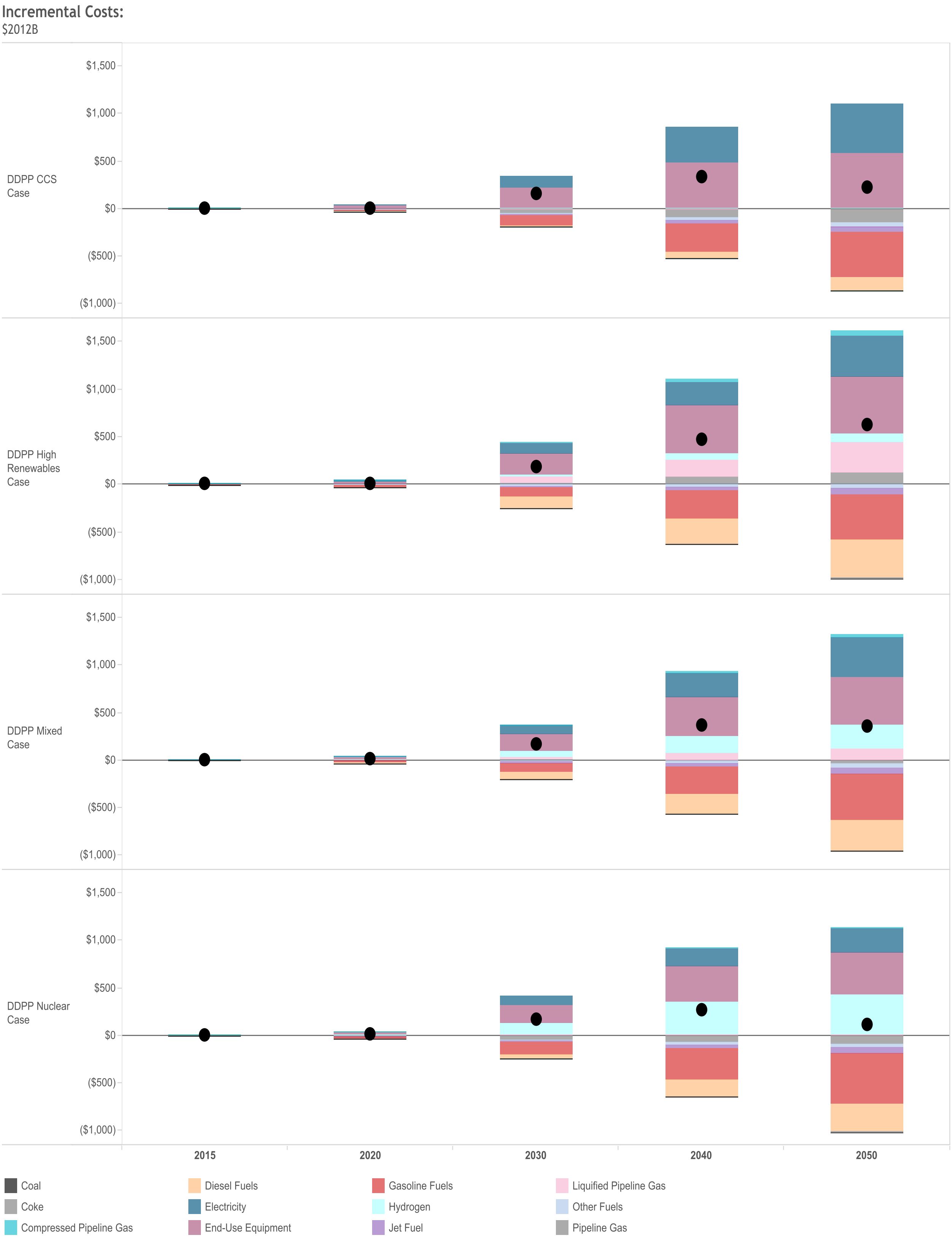


Figure 4 Incremental Cost by Uncertainty Run, Year, and Case

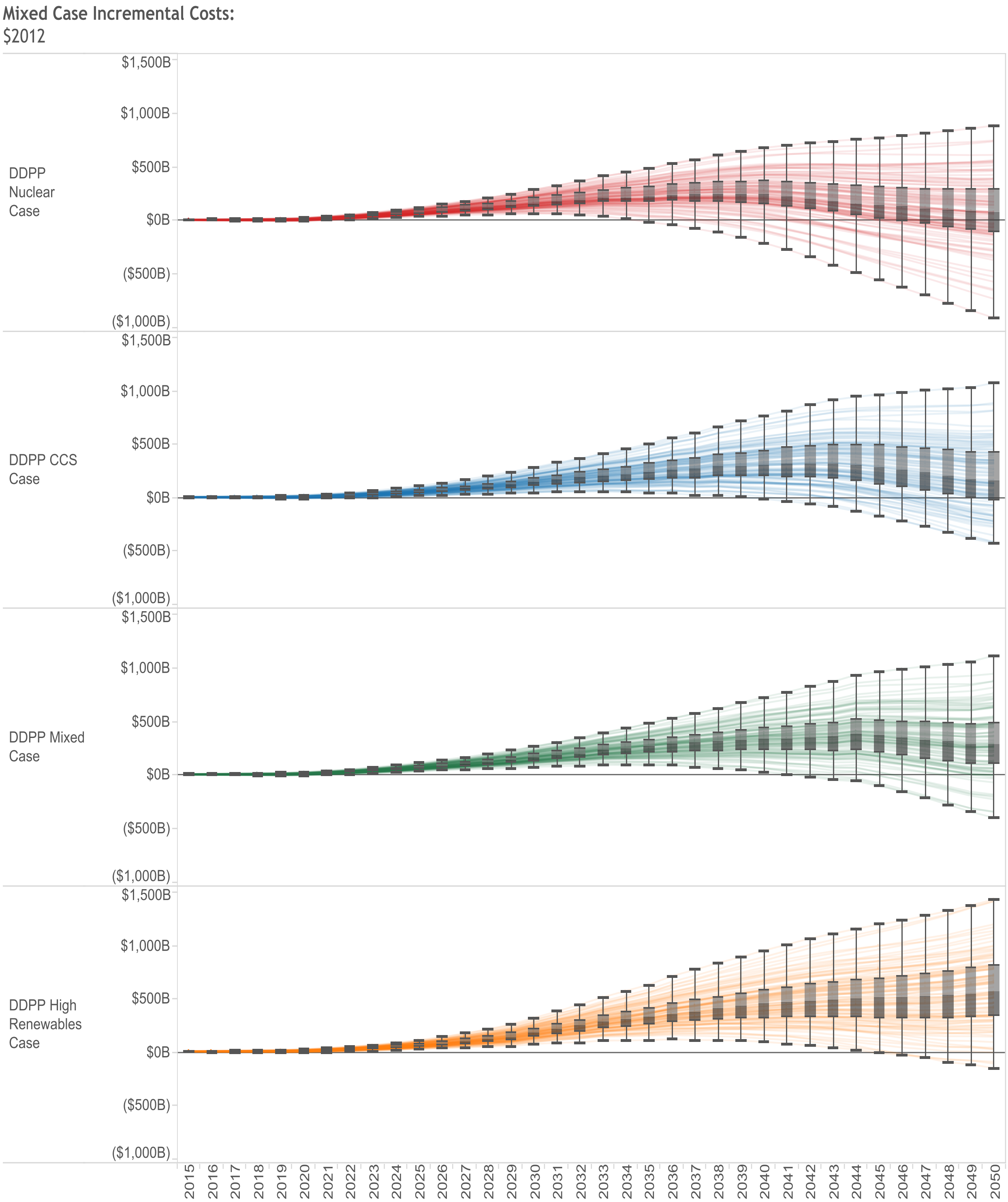


Figure 5 Low-Carbon Technology Investment by Technology Type, Year, and Case

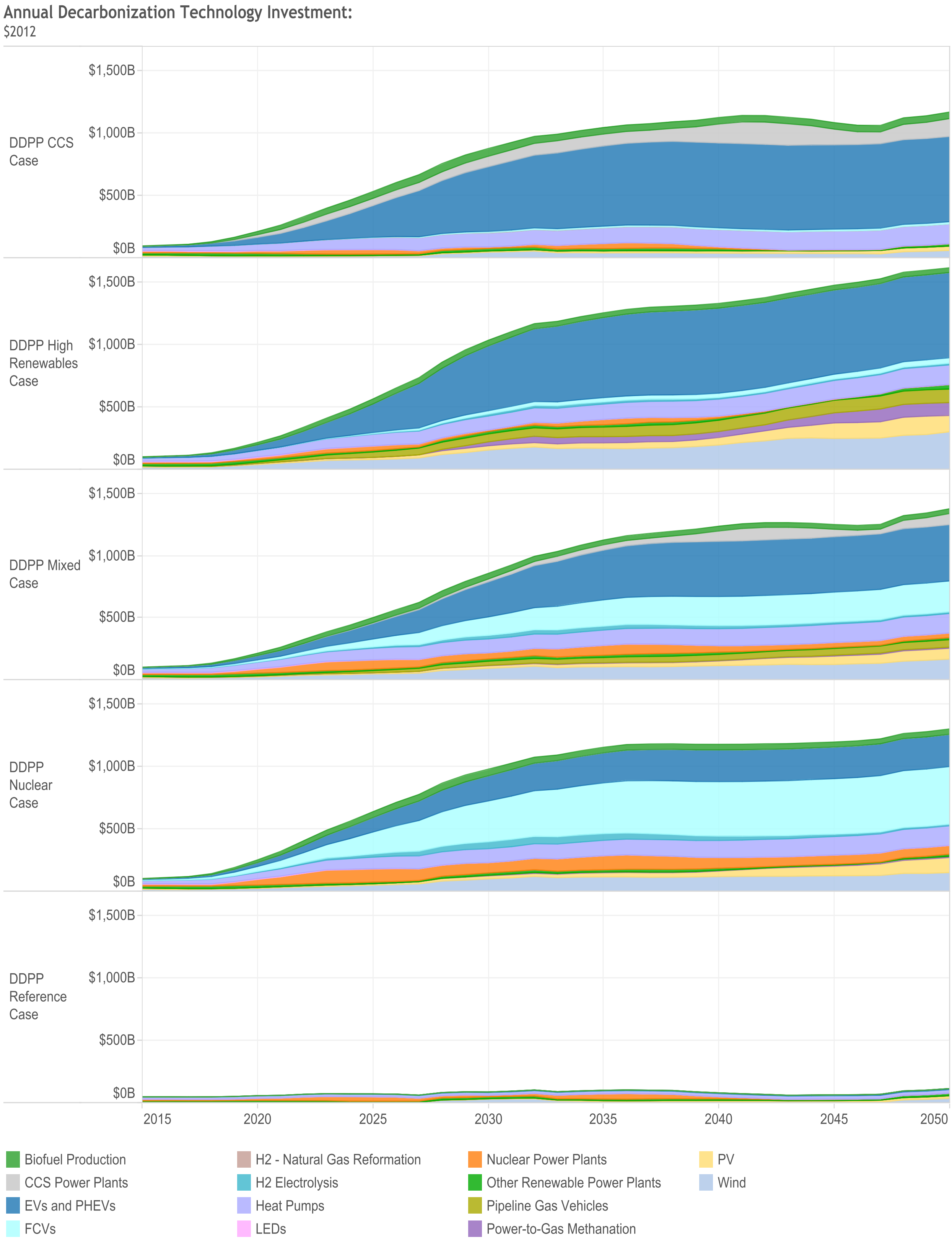


Figure 6 Generation Investment by Region, Technology, Year, and Case

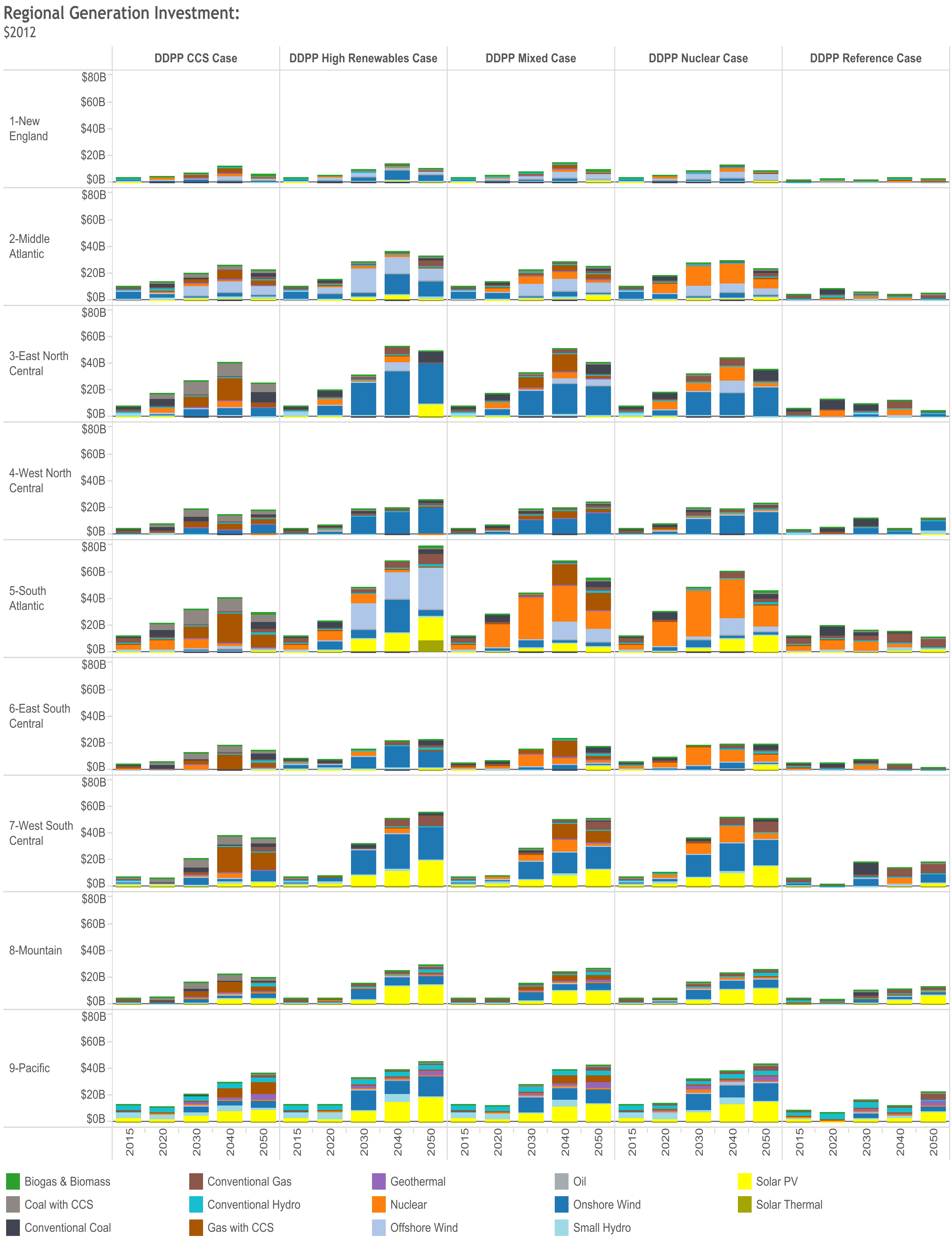
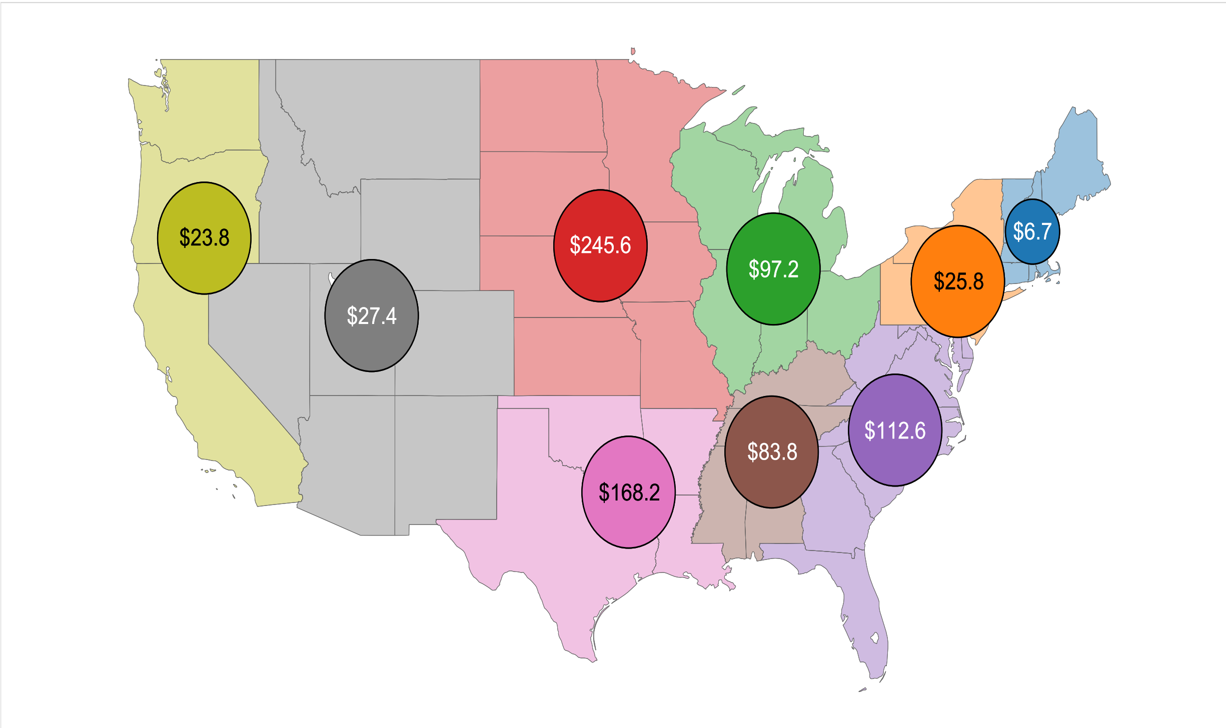


Figure 7 Cumulative Biomass Economy Investments by Region

Cumulate 2015-2050 Biomass Commodity Payments:
$2012B



Cumulative 2015-2050 Biofuel Production Investment:
$2012B

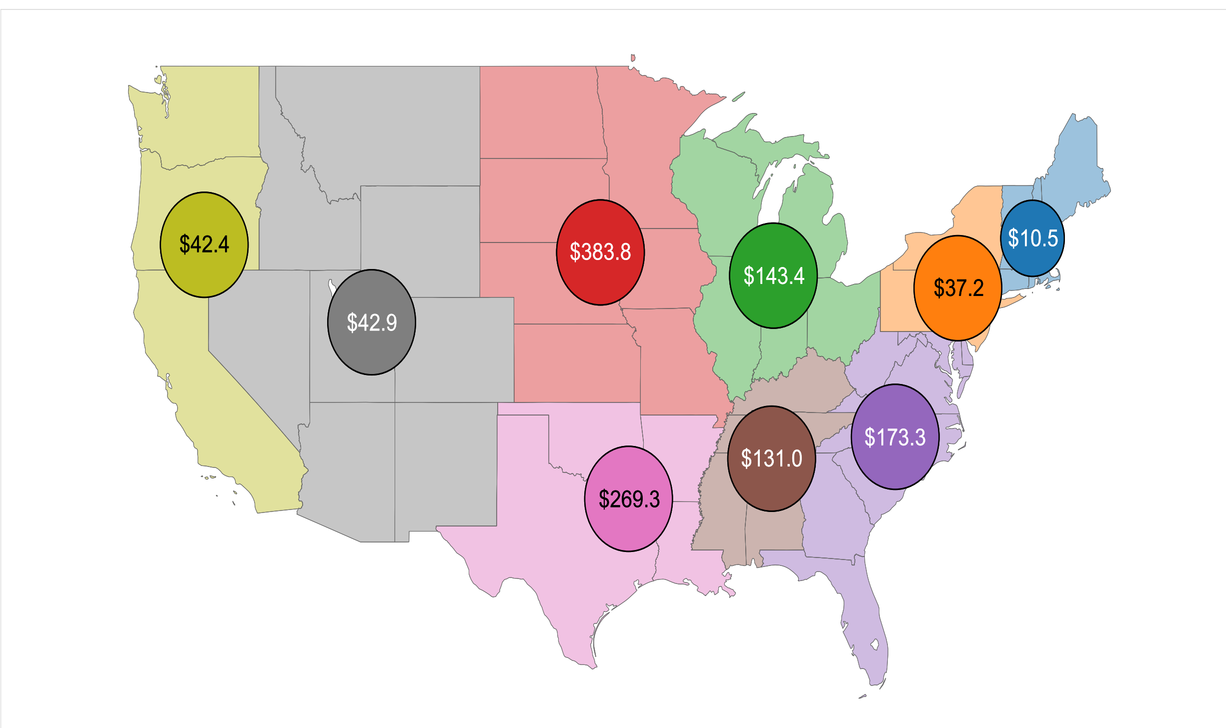


Figure 8 Emissions Reduction Wedges

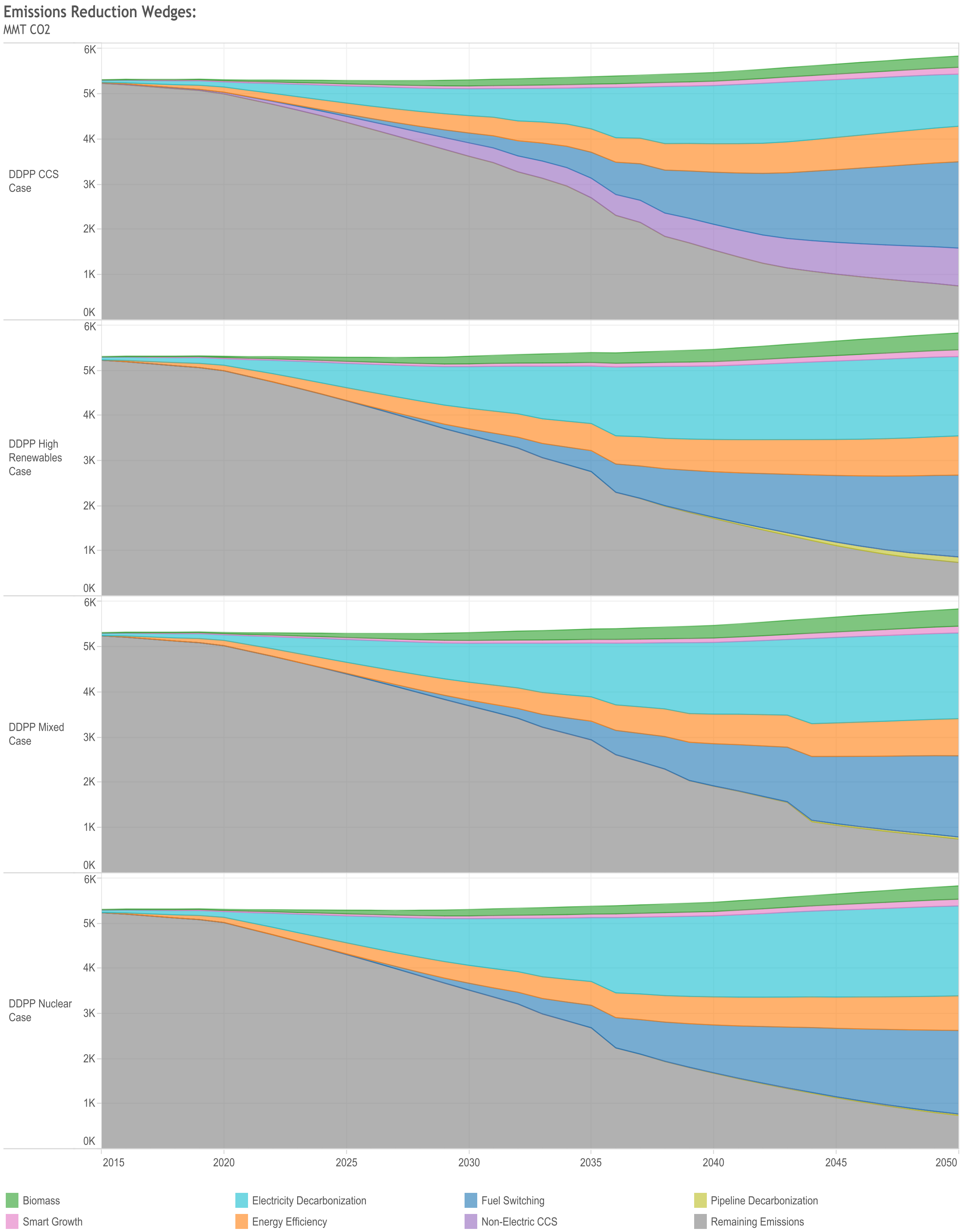


Figure 9 Reference Case Transition Chart

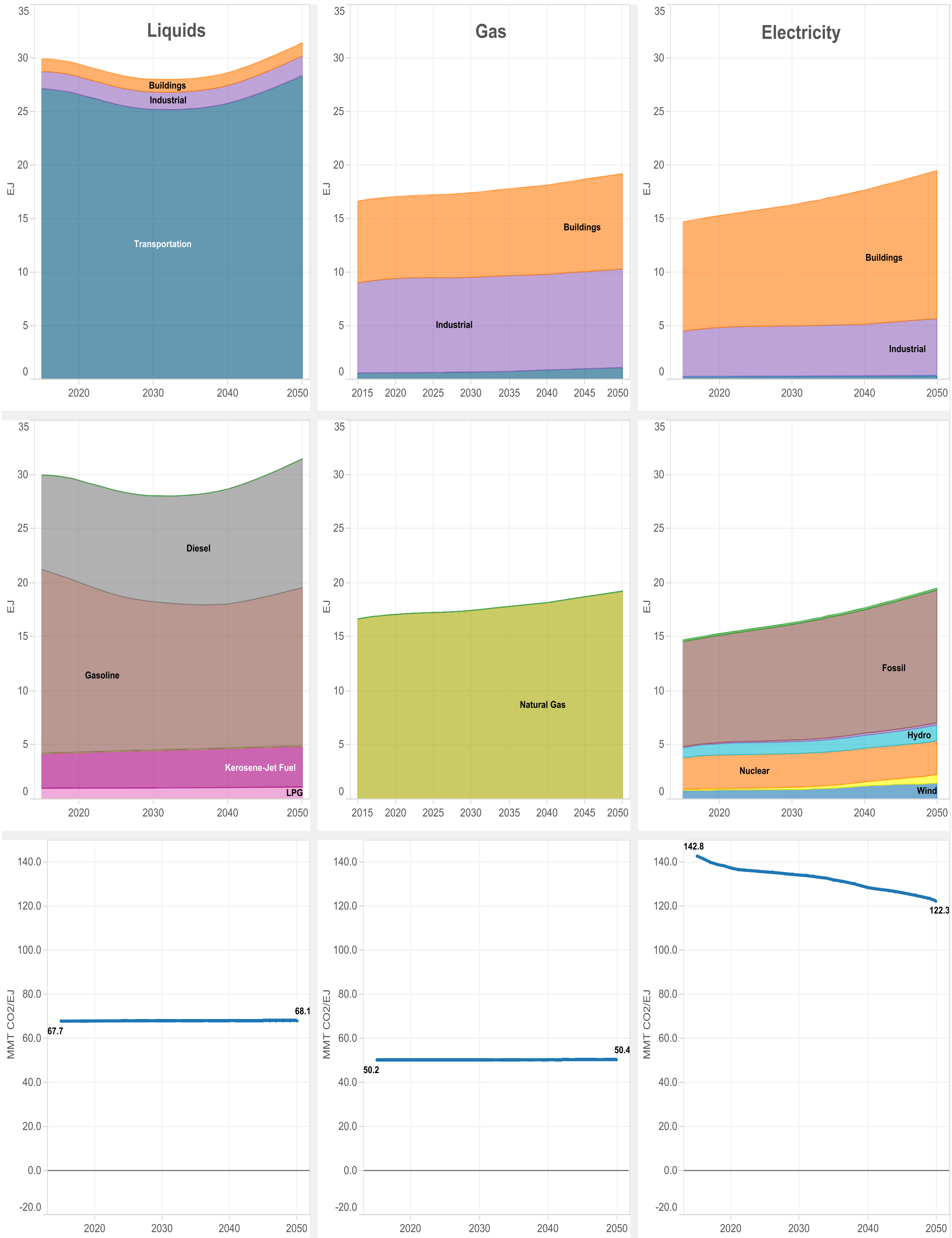


Figure 10 CCS Case Transition Chart

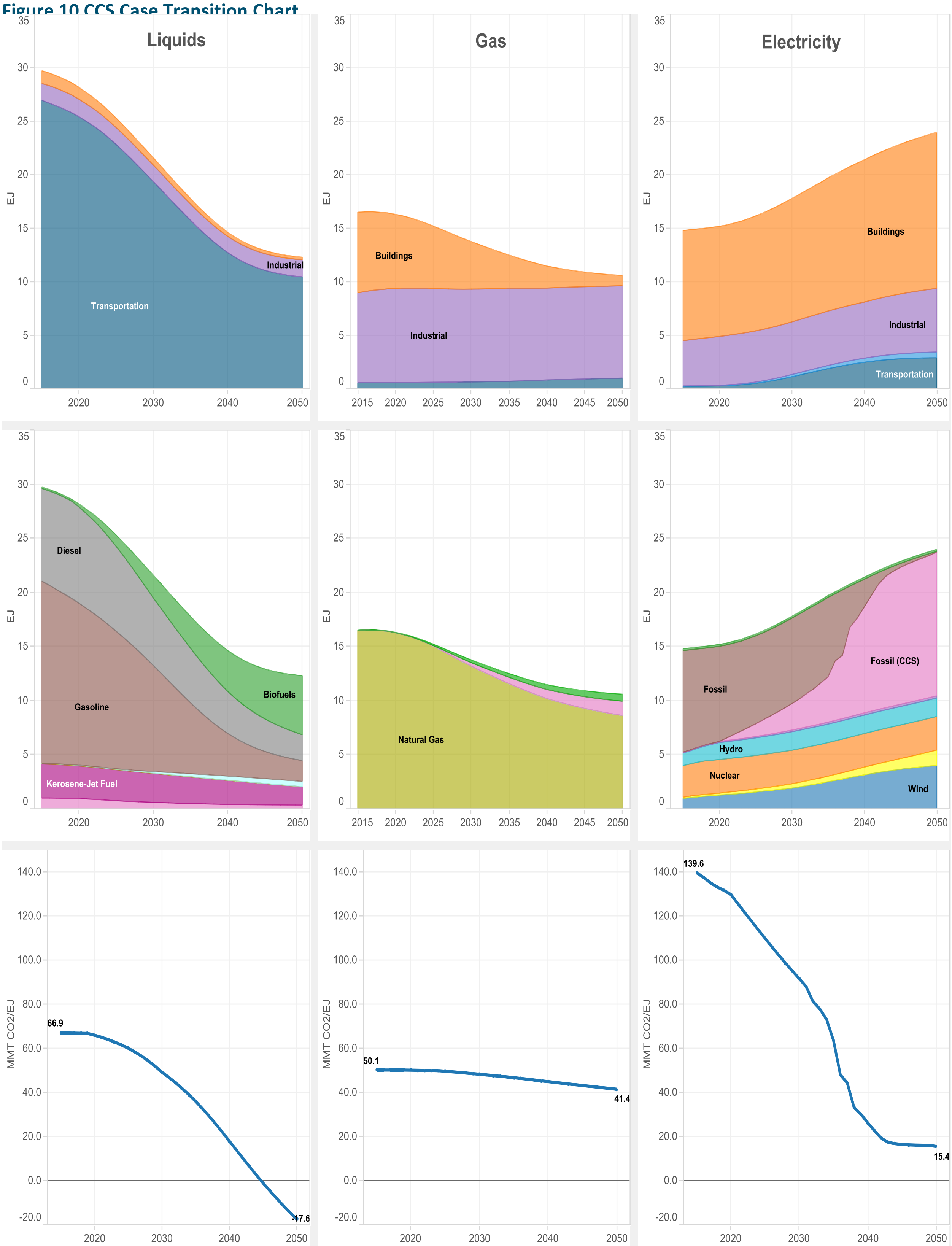


Exhibit D D112

Figure 11 High Renewables Case Transition Chart

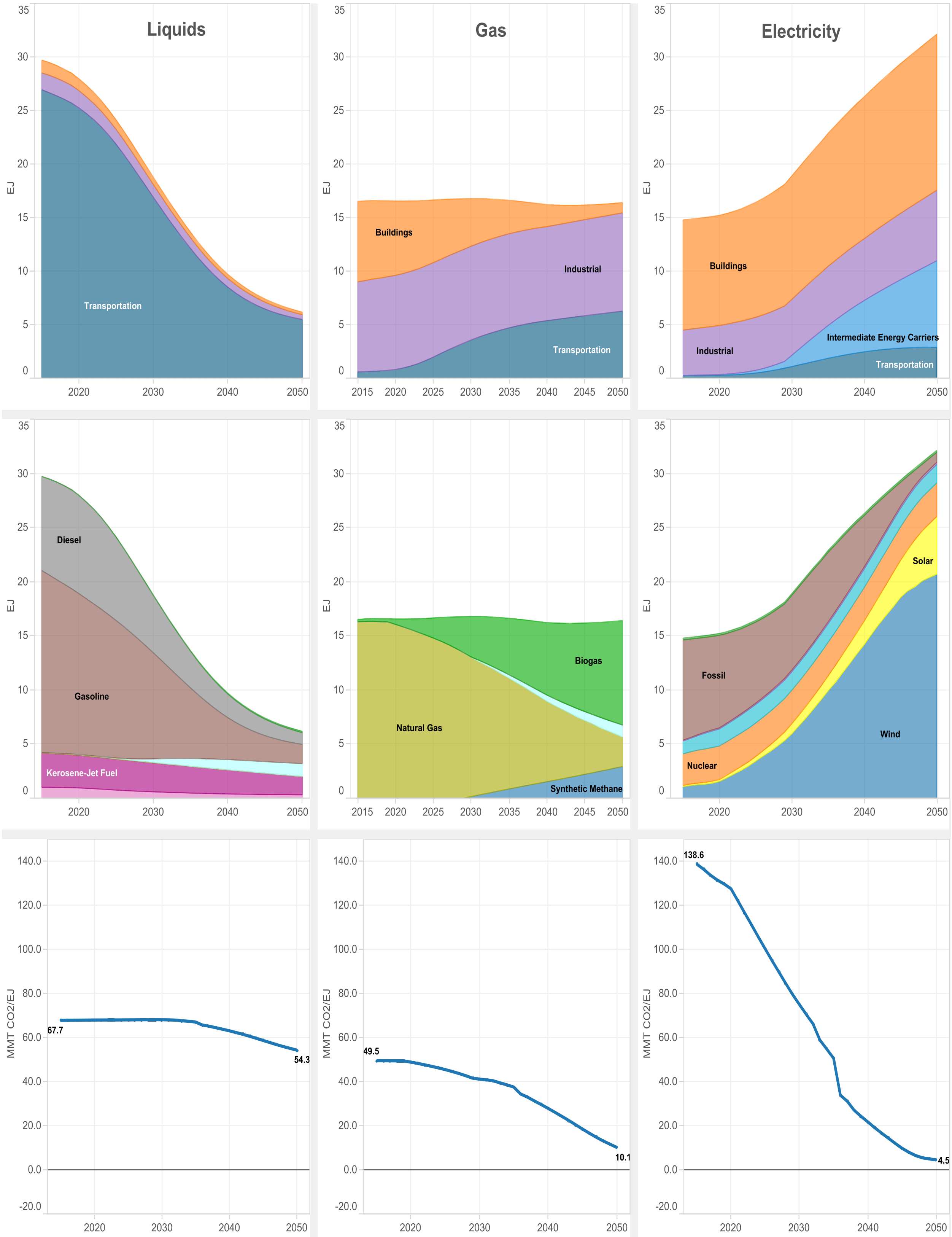


Exhibit D D113

Figure 12 Mixed Case Transition Chart

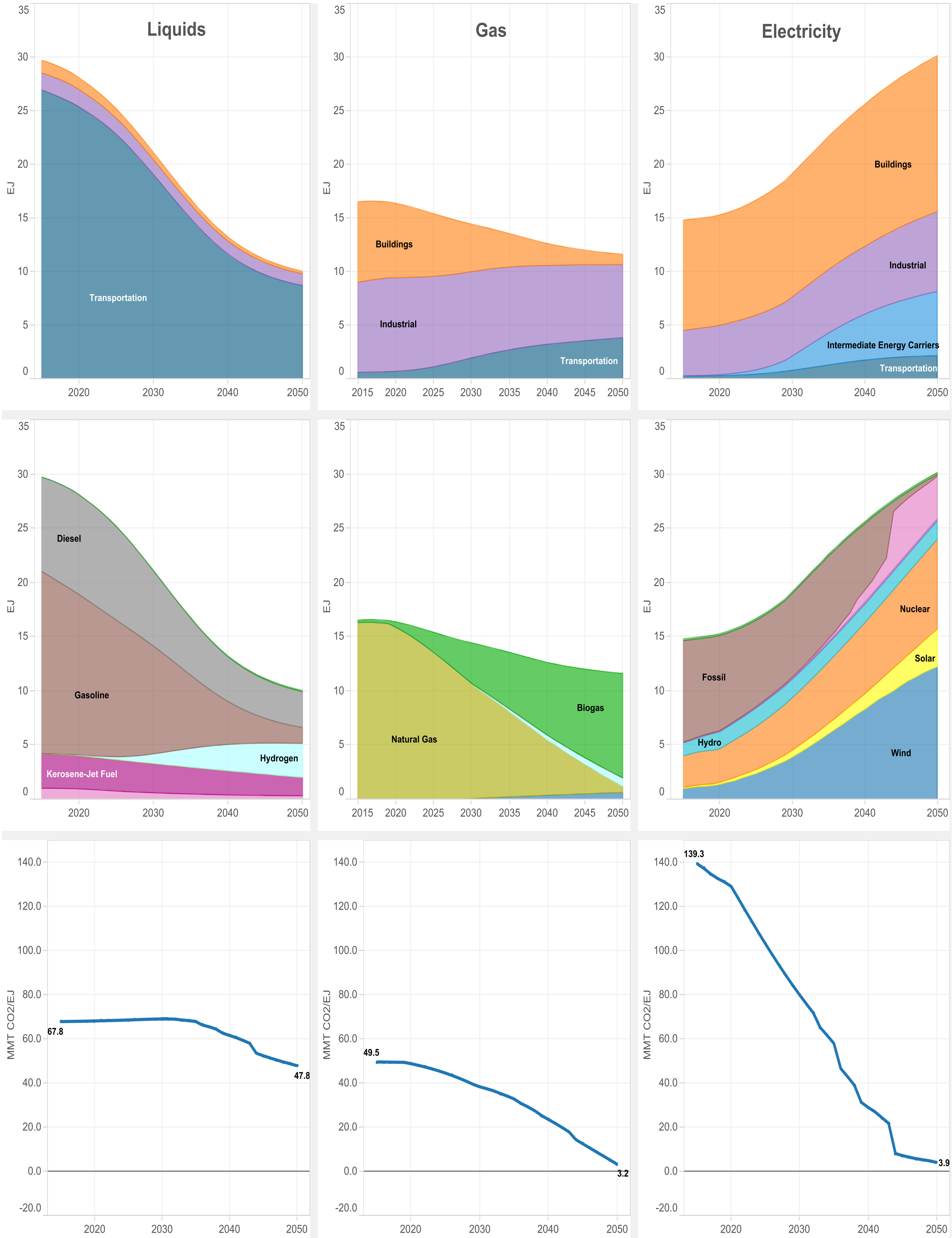


Figure 13 Nuclear Case Transition Chart

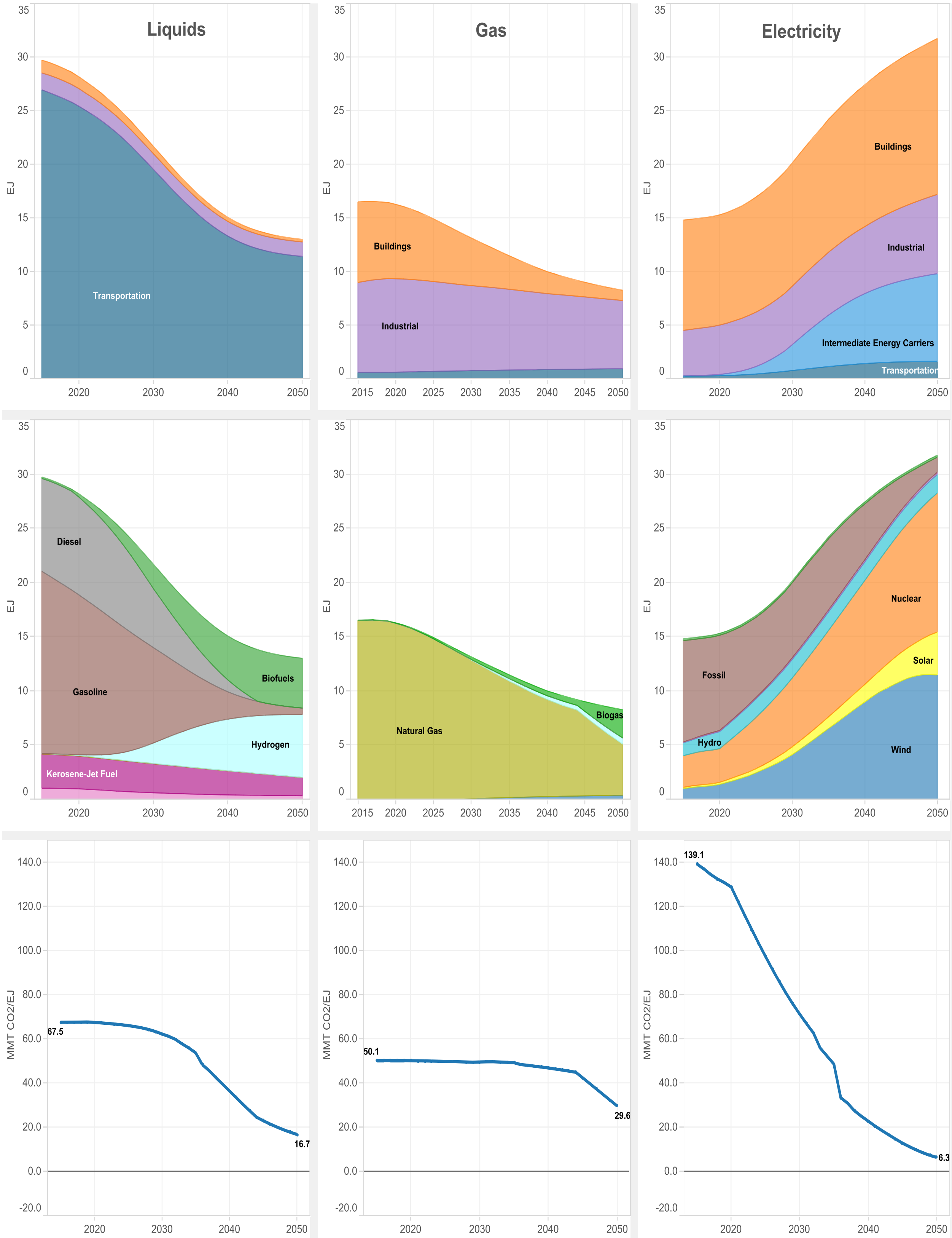


Exhibit D D115

Figure 14 CCS Sankey Diagram, 2050

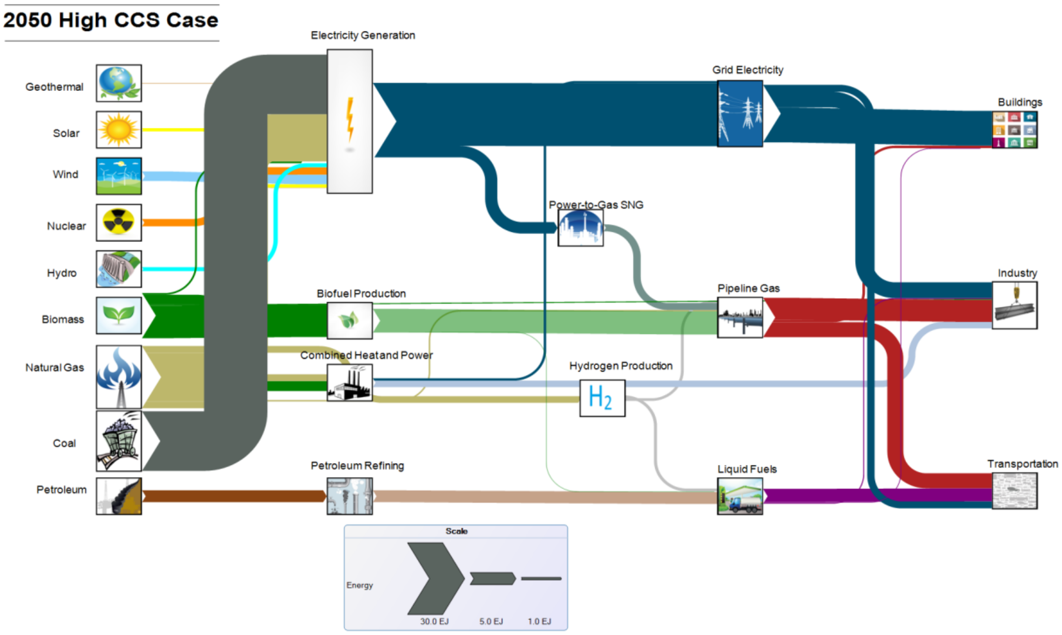


Figure 15 High Renewables Sankey Diagram, 2050

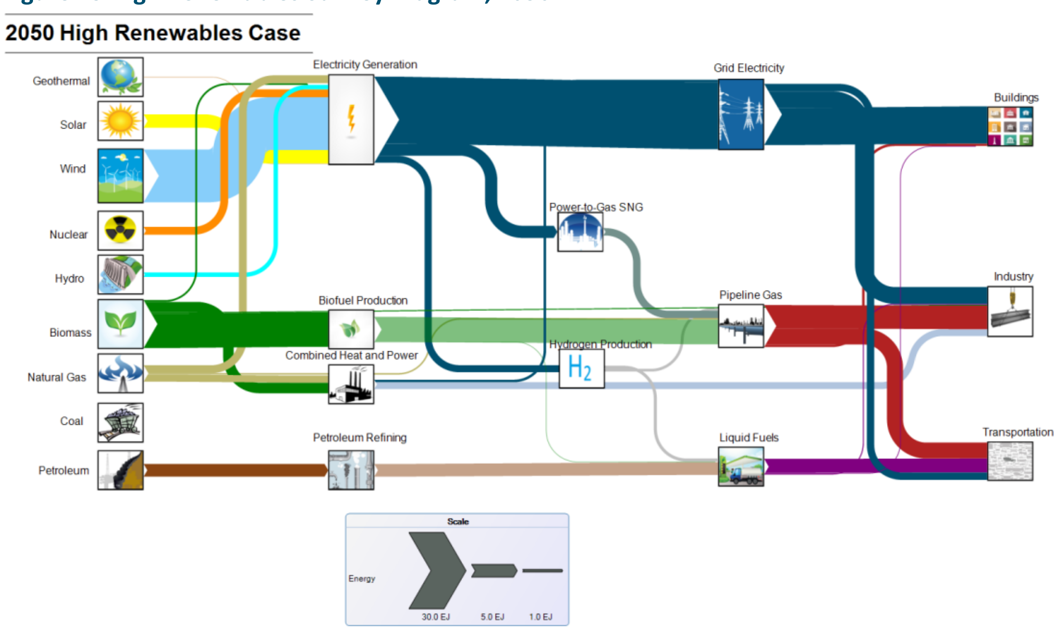


Figure 16 Mixed Case Sankey Diagram, 2050

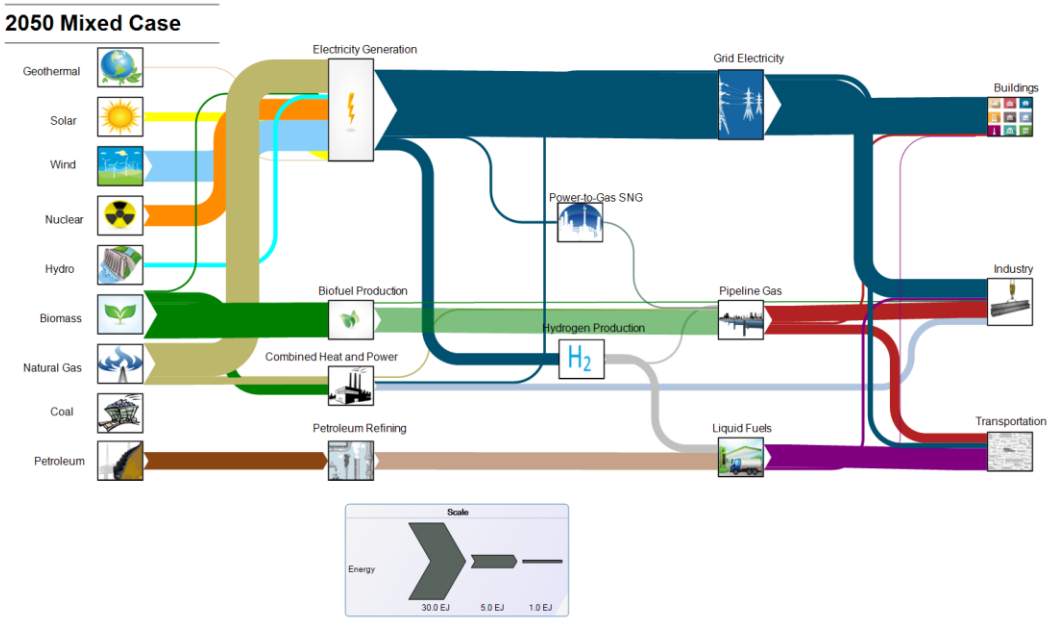


Figure 17 Nuclear Case Sankey Diagram, 2050

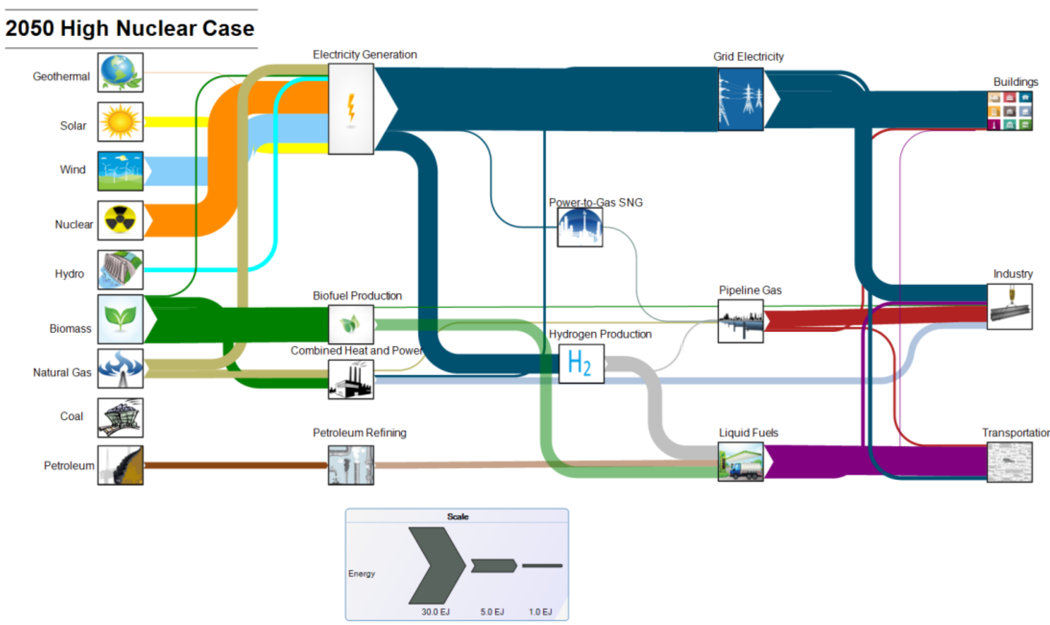


Exhibit D D117

Figure 18 Example Week Electric Generation by Case, Year, and Interconnection

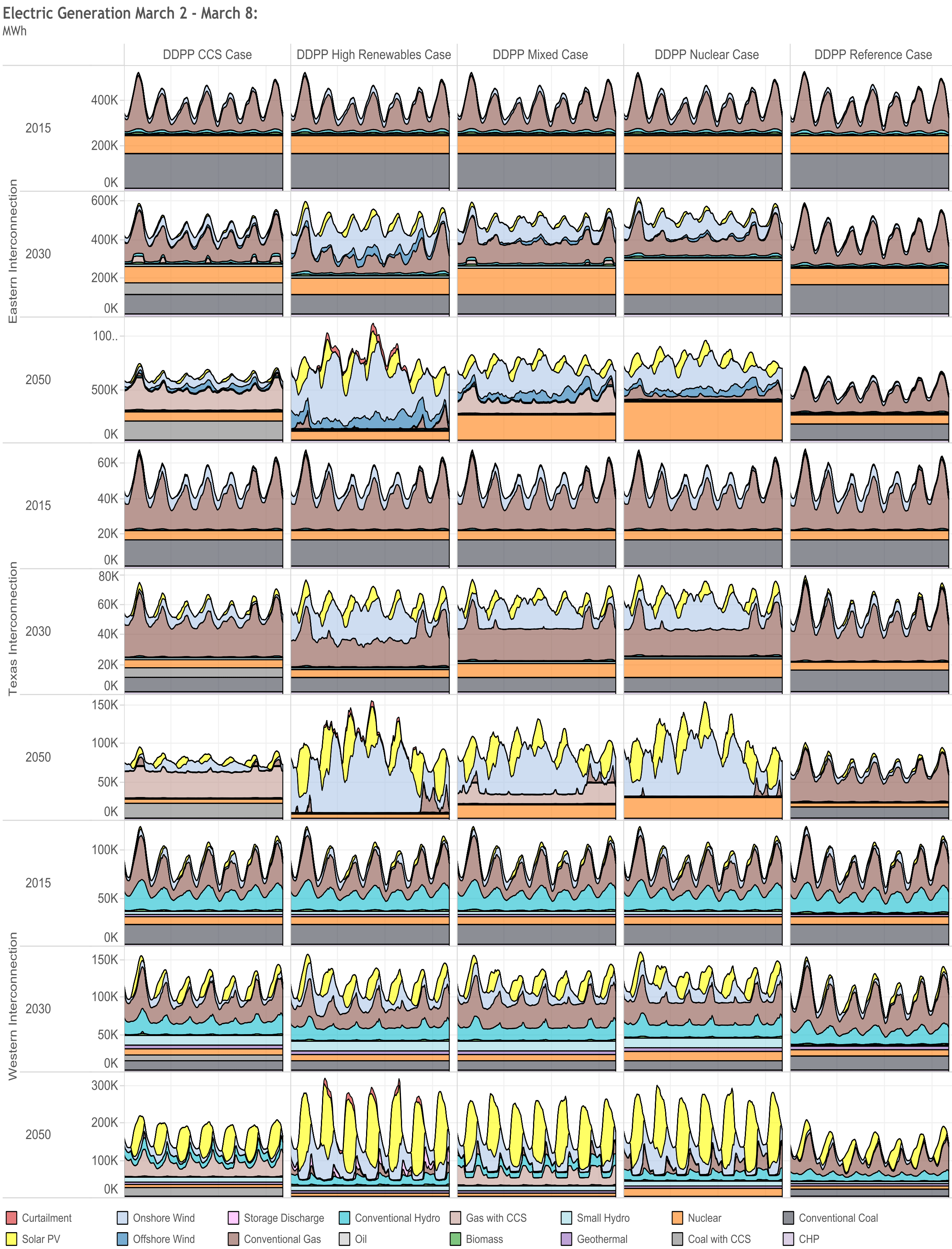


Figure 19 Example Week Electric Load by Case, Year, and Interconnection

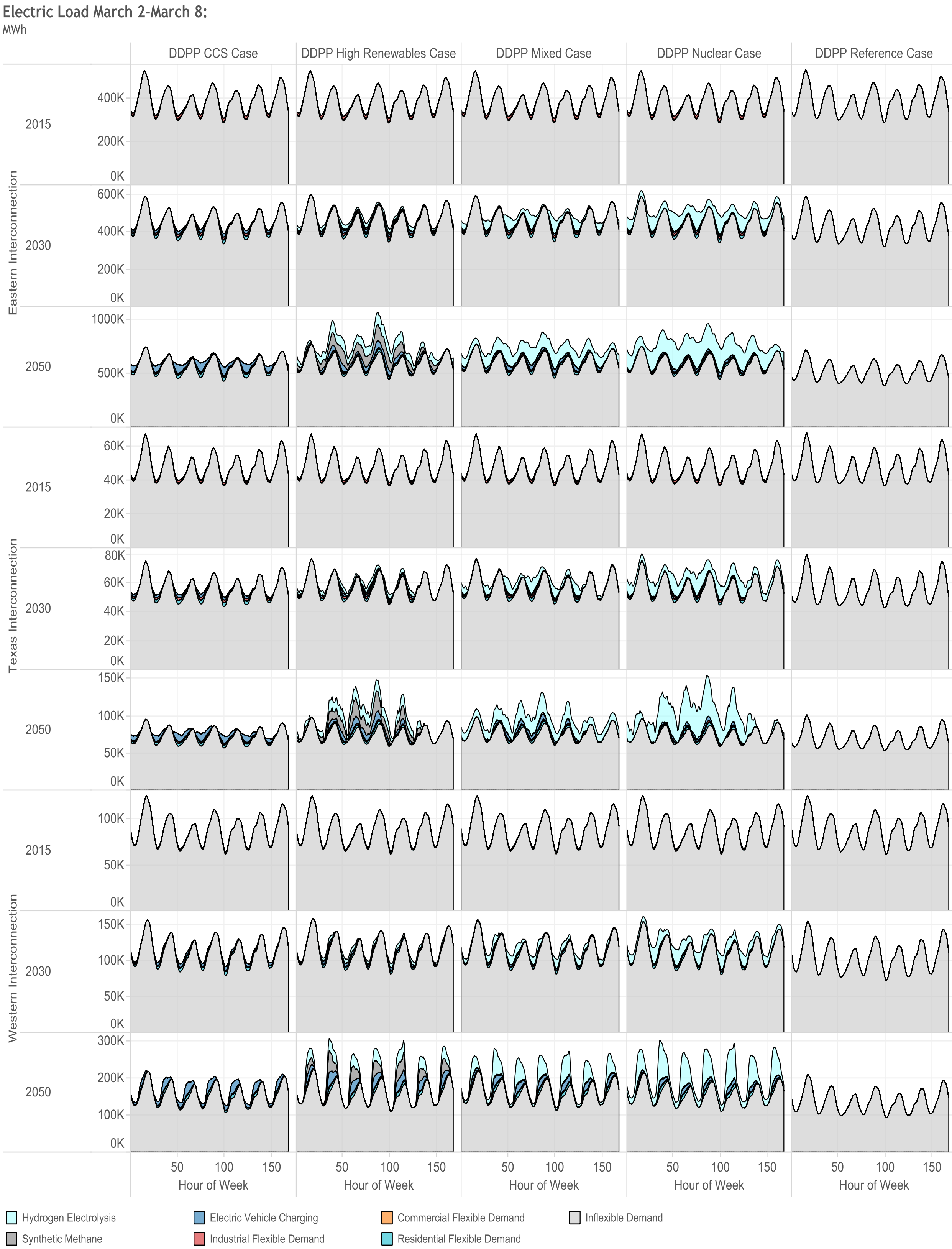
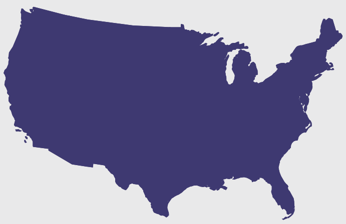


EXHIBIT E. RESEARCH REPORT: POLICY IMPLICATIONS OF DEEP DECARBONIZATION IN THE UNITED STATES

US 2050 Vol. 2
Policy Report

policy implications of deep decarbonization *in the United States*



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Policy Implications of Deep Decarbonization in the United States

Policy Implications of Deep Decarbonization in the United States is published by Energy and Environmental Economics, Inc. (E3) and the Deep Decarbonization Pathways Project (DDPP).

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Policy Implications of Deep Decarbonization in the United States

Energy and Environmental Economics, Inc. (E3)
Deep Decarbonization Pathways Project (DDPP)

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The authors take full responsibility for the contents of this report.

Preface

Deep Decarbonization Pathways Project

The Deep Decarbonization Pathways Project (DDPP) is a collaborative global initiative to explore how individual countries can reduce greenhouse gas (GHG) emissions to levels consistent with limiting the anthropogenic increase in global mean surface temperature to less than 2 degrees Celsius (°C). Limiting warming to 2°C or less, an objective agreed upon by the international community, will require that global net GHG emissions approach zero by the second half of the 21st century.[1] This, in turn, will require steep reductions in energy-related CO_2 emissions through a transformation of energy systems, a transition referred to by the DDPP as "deep decarbonization."

The DDPP is led by the Sustainable Development Solutions Network (SDSN) and the Institute for Sustainable Development and International Relations (IDDRI). Currently, the DDPP includes 16 research teams from countries representing 75% of global GHG emissions: Australia, Brazil, Canada, China, France, Germany, India, Indonesia, Italy, Japan, Mexico, Russia, South Africa, South Korea, the United Kingdom, and the United States. The research teams are independent and do not necessarily reflect the positions of their national governments. Starting in the fall of 2013, the research teams have been developing potential high-level roadmaps, or "pathways," for deep decarbonization in their respective countries.

The initial results of this effort were published in September 2014 and officially presented as part of the *Economic Case for Action* session at the Climate Summit convened by UN Secretary-General Ban-Ki Moon in New York. A U.S.-specific report, *Pathways to Deep Decarbonization in the United States*, was published in November 2014. Other individual country studies were announced in September 2015, and all studies by DDPP country research teams including the United States, along with reports synthesizing results across the teams, are available for download at http://deepdecarbonization.org.

[1] Intergovernmental Panel on Climate Change, *5th Assessment Report*, http://www.ipcc.ch/report/ar5/

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Executive Summary

I. What is this report?

This report describes the economic and policy implications of deep decarbonization in the United States. "Deep decarbonization" refers to the reduction of greenhouse gas (GHG) emissions over time to a level consistent with limiting global warming to 2°C or less, based on the scientific consensus that higher levels of warming pose an unacceptable risk of dangerous climate change (IPCC, 2013). The analysis builds on results from an earlier report, *Pathways to Deep Decarbonization in the United States* (DDPP, 2014), conducted by Energy and Environmental Economics (E3) in collaboration with Lawrence Berkeley National Laboratory (LBNL) and Pacific Northwest National Laboratory (PNNL) for the Deep Decarbonization Pathways Project (DDPP), an international consortium of research teams studying pathways to deep decarbonization in sixteen of the world's highest-emitting countries.

The 2014 report assessed the technical feasibility and cost of different technology options for reducing net U.S. GHG emissions (CO_2e) 80% below the 1990 level by the year 2050, the long-term target set by the U.S. government (USG, 2009). While evaluating reductions in all types of GHG emissions, the main focus of the analysis was on the deep decarbonization of the U.S. energy system, defined as reducing CO_2 from fossil fuel combustion to 1.7 metric tons per capita in 2050, an order of magnitude below recent U.S. levels.

II. What is this report's intended contribution?

This report is based on a detailed year-by-year analysis of the changes in U.S. physical infrastructure required to achieve deep decarbonization by mid-century. The analysis was performed using PATHWAYS, an open-source tool developed by the authors for this purpose. PATHWAYS uses a bottom-up approach to represent the supply and demand sides of the energy system at a very granular level by economic subsector and geographic region, including a sophisticated model of the electricity grid. Using transparent and conservative assumptions, we built multiple technology scenarios – or "pathways" – to understand the technical requirements and costs of different alternatives for achieving the deep decarbonization goal.

The main objective of this report is to reorient the discussion of climate policy toward a practical focus on implementation. The analytical combination of physical stocks, high granularity, and long time horizon allows this study to make three contributions toward that end. First, it provides policy makers and businesses with a detailed understanding of what deep decarbonization will actually require in terms of scale and timing of investment, rates of technology adoption, distribution of costs and benefits, and risks associated with different options.

Second, this level of analytical detail allows the policy discussion to move beyond emissions targets to the required end state of an energy system that can meet those targets. Working backwards from that end state, the analysis maps out the physical and economic requirements of the transitional steps along the way. This provides unique insight into the challenges and opportunities of the transition across sectors, industries, jurisdictions, and levels of government, and concrete guidance for what policy must accomplish in all these areas.

Third, deep decarbonization provides a new lens on analytical approaches and policy prescriptions in the energy and climate domain, with the key question being whether and under what conditions they are effective in driving an energy system transformation. Some of the policy guidance in this report departs from current conventions, while highlighting new questions that are not yet on the policy radar.

III. What are the main characteristics of a deeply decarbonized energy system in the U.S.?

Our analysis shows that deep decarbonization in the U.S. is both technically feasible and economically affordable. There are multiple alternative pathways to achieving the 2050 emissions-reduction target using only existing commercial or near-commercial technologies, at a net cost equivalent to about 1% of GDP. The main characteristics of a deeply decarbonized energy system in the U.S. can be summarized in three seeming paradoxes:

Physical energy system. Deep decarbonization will profoundly transform the physical energy system of the U.S., with fossil fuel use decreasing by two-thirds from today while decarbonized energy supplies expand by a factor of five. However, this can be achieved while supporting all anticipated demand for energy services – for example, current or higher levels of driving, home heating and cooling, and use of appliances.

Energy economy. Deep decarbonization will profoundly transform the U.S. energy economy, in terms of what money is spent on and where investment will flow. In contrast to today's system in which more than 80% of energy costs go to fossil fuel purchases, in a deeply decarbonized system more than 80% of energy costs will go to fixed investments in low-carbon infrastructure such as wind generation and electric vehicles. However, the net change in consumer costs for energy services is likely to be small.

Macro-economy. Deep decarbonization will have a small net cost relative to U.S. GDP, as increased spending on low-carbon infrastructure and equipment is offset by reduced spending on fossil fuels. In all deep decarbonization scenarios, U.S. energy costs actually decrease as a share of GDP over time, from about 7% today to about 6% in 2050. While the overall impact on energy costs is modest, the transition to deep decarbonization nonetheless offers significant benefits for the U.S. macro-economy, such as insulation from oil price shocks, even without counting the potential economic benefits of avoiding severe climate change.

Some argue that deep decarbonization will entail disruptive lifestyle changes, reduced energy services, high costs, and worrisome risks to the U.S economy. Others assume that a low-carbon energy system will be much like the present one, but we will pay more for it. In fact, our analysis shows that the imperative to transform the energy system in response to climate change brings with it the opportunity to create a system that supports all the energy services that individuals and industries demand at very little difference in net cost and without many of the negative side effects that the current system brings to the economy, society, and the environment. The "paradox" indicated by our analysis is that people should have higher expectations of a decarbonized energy system, not lower ones.

IV. What does the transition from the current energy system to a deeply decarbonized energy system require?

While there are a number of plausible technology pathways for achieving deep decarbonization in the U.S. economy – four distinct pathways are demonstrated in our analysis – they all have certain key features in common.

Three pillars of decarbonization. Across all technology pathways there are "three pillars" that must all be in place in order to reach the 2050 decarbonization goal. It is already possible to establish performance metrics in each of these areas that apply to all scenarios independently of the technical details of how they are implemented:

- *Highly efficient end use of energy in buildings, transportation, and industry.* Energy intensity of GDP must decline by 70% from now to 2050, with final energy use reduced by 20% despite a forecast population increase of 40% and a 166% increase in GDP.

- *Nearly complete decarbonization of electricity, and reduced carbon in other kinds of fuels.* The carbon intensity of electricity must be reduced by at least 97%, from more than 500 g CO_2/kWh today to 15 g CO_2/kWh or less in 2050.

- *Electrification where possible and switching to lower-carbon fuels otherwise.* The share of end-use energy coming directly from electricity or fuels produced from electricity, such as hydrogen, must increase from less than 20% in 2010 to over 50% in 2050, displacing fossil fuel combustion.

Sustained transformation. Deep decarbonization in the U.S. requires the emissions intensity of the economy to decrease 8% per year, and per capita emissions to decrease 5.5% per year. These rates of change are ambitious, but not infeasible. They will, however, require a sustained long-term transformation of energy supply and demand infrastructure. Policies that produce incremental changes without facilitating transformation can lead to technology lock-in and emissions reduction dead ends that make deep decarbonization by mid-century unattainable. “Solutions” can quickly evolve into problems. Examples include policies that focus on internal combustion engine fuel economy and ethanol-gasoline blends without widespread deployment of electric or fuel cell vehicles, and those that focus on a coal-to-natural gas transition in power generation without an accompanying build-out of renewable, nuclear, or carbon capture and storage (CCS) generation.

Timely replacement. Deep decarbonization can be achieved in the U.S. without retiring existing equipment and infrastructure before the end of its economic lifetime**,** which reduces the expected cost of the transition. However, because these lifetimes are typically long, there is only one natural replacement cycle before mid-century for some of the most important infrastructure, such as electric power plants, buildings, and industrial boilers. When replacement time arrives, the new equipment must be consistent with the low-carbon transition path. Failure to replace retiring infrastructure with efficient and low-carbon successors will either lead to failure to meet emission-reduction targets or require early retirement of the replacement equipment.

Technical progress*.* Deep decarbonization can be achieved in the U.S. using existing commercial and near-commercial technologies, and does not require deployment of technologies that are currently in an early stage of development including Gen IV nuclear, deep offshore wind, advanced geothermal, advanced cellulosic ethanol, advanced biodiesel, or CCS with greater than 90% capture rate. While these could help facilitate the transition, they are not necessary conditions for it. What *is* required is steady progress in current technologies that leads to rapid and widespread consumer adoption, high volume production, and corresponding price declines.

Cross-sector coordination. The interaction between energy supplies and end-use equipment becomes increasingly important over time in determining overall carbon intensities. For example, the emissions benefits of electric vehicles (EVs) grow in proportion to electricity decarbonization. EVs that charge on an average U.S. power grid today have one-third lower emissions per mile than fuel-efficient conventional vehicles, but as grid electricity approaches full decarbonization, EV emission intensities become 30 times lower. Achieving the full emissions benefit of parallel investments in supply side carbon intensity reduction and demand side fuel switching requires well-coordinated timing of deployment, for example in ensuring the readiness of charging infrastructure for EVs. This indicates a need for joint planning and coordinated policy and market signals across economic sectors that traditionally have little in common, such as power generation and transportation.

Network supply. In a deeply decarbonized system, two-thirds of final energy will be delivered through the electricity grid and natural gas pipeline. This energy is supplied by network providers, typically either regulated or publicly-owned utilities. The role of network providers in a low-carbon transition is crucial, since they constitute one of the main institutional vehicles for acquiring long-lived, high capital-cost equipment and infrastructure. Policy makers must ensure that regulatory signals to network providers related to procurement, rate-making, and cost allocation are consistent with deep decarbonization, and support a sustainable business model in the face of new challenges such as high levels of distributed generation.

V. What are the main benefits of deep decarbonization for the U.S.?

Stable climate and clean environment. Domestic deep decarbonization is the most important action the U.S. can take to protect the climate, providing leadership to the rest of the world by reducing by two-thirds or more U.S. consumption of the remaining global CO_2 budget for keeping anthropogenic warming below 2°C and avoiding the worst impacts of climate change. These impacts include increased severity of hurricanes, drought, heat waves, and flooding, and the damages these inflict on infrastructure, agriculture, and human well-being (IPCC, 2014). Deep decarbonization will also dramatically reduce air pollutants such as fine particulate matter, nitrogen oxides, and sulfur dioxide, and the resulting health impacts.

Macroeconomic and energy security. The predominance of fixed costs in a deeply decarbonized energy system will create a stable environment for investors and predictable energy costs for consumers. At the same time, deep reductions in fossil fuel consumption will dramatically reduce U.S. exposure to energy-related economic and security risks. By 2050, oil consumption would decrease to pre-1950 levels and oil's share of the economy to less than 1% of GDP. This will strongly limit the potential impact of oil price volatility on the U.S. economy, where it has historically triggered recessions, as well as the problems arising from insecurity over strategic resource availability and excessive engagement with unstable oil-producing regions.

Widespread economic benefits. Many U.S. industries and regions will benefit economically from the transition to a deeply decarbonized energy system. The shift from fossil fuel to low-carbon energy will mean vastly increased investment in efficient building technologies, decarbonized power generation and fuels, and alternative vehicles, together reaching more than $1 trillion annually by 2050. This investment will be widely distributed across regions, industries, and energy types. Revenues that are currently concentrated in a few industries and regions involved in supplying fossil fuels will decline, but the gradual timeline of the transition will provide opportunities for a successful shift to a low-carbon business model.

Modernization, competitiveness, and jobs. A deeply decarbonized energy system will necessarily be built on a sophisticated scientific and technological foundation, which plays to U.S. strengths in areas such as information technology, biotechnology, and nanotechnology, and provides a major competitive advantage in global markets for low-carbon energy. While deep decarbonization is likely to have a relatively small net impact on employment, building an efficient, high-tech 21st century energy system can work hand in hand with modernizing American infrastructure and fostering "re-industrialization," with the potential to generate many attractive science and engineering, manufacturing, and building trades jobs.

VI. What must policy accomplish to enable deep decarbonization?

Policy design must begin with an understanding of what policy actually needs to accomplish, namely the physical, financial, and institutional outcomes required by deep decarbonization. Key requirements indicated by our analysis include:

***Anticipate investment needs and build a suitable investment environment*.** The annual investment requirement for low carbon and efficient technologies rises from under $100 billion today to over $1 trillion in a span of about 20 years. Financial markets can supply this level of capital if investment needs are anticipated and a policy framework is constructed that limits risk and ensures adequate returns.

***Incorporate future carbon consequences in current purchasing decisions*.** Deep decarbonization in the U.S. can be achieved by replacing existing equipment and infrastructure at the end of its economic lifetime, but for a natural replacement strategy to succeed, current purchasing decisions must incorporate future carbon consequences through pricing, technology mandates, or emission standards.

***Create stable drivers for sustained long-term transitions*.** Timely replacement of infrastructure and equipment with efficient and low-carbon substitutes must be sustained over decades. This requires stable policy and a predictable investment environment. Deferring all responsibility to a carbon market or relying on *ad hoc* decision-making and inconsistent incentives will not produce a sustained transition.

***Develop institutional structures for coordination across sectors*.** Cross-sector interactions (for example, electricity and transportation) will grow increasingly important in a low-carbon transition. Anticipatory development of shared institutional structures, both market and regulatory, is needed for efficient coordination of operations, planning, investment, and research.

***Integrate supply- and demand-side planning and procurement*.** Maintaining reliability in an electricity system with high levels of wind, solar, and/or baseload nuclear will require corresponding levels of flexible demand, such as EV charging and hydrogen production. A system that matches supply and demand resources at the required spatial and time scales requires integrated planning and procurement.

***Create the right kinds of competition*.** Competition is potentially an important tool for driving innovation and reducing costs, but poorly informed policies can lead to unproductive competition, such as biofuels competing with gasoline. Long-term pathways analysis will help policy makers and investors understand what types of competition have value.

***Enable the required rates of consumer adoption*.** Achieving necessary rates of consumer adoption of equipment ranging from heat pumps to alternative vehicles will require a combination of incentives, financing, market strategies, and supporting infrastructure. This requires a high level of public-private cooperation, for example among government agencies, auto manufacturers, and utilities in rapidly expanding alternative vehicle markets in tandem with fueling infrastructure.

***Catalyze the needed cost reductions in key technologies*.** Policy makers can drive cost reductions in key technologies by helping to create large markets. High production volumes drive technological learning, efficient manufacturing, and lower prices. This effect - called "Moore's Law" in the computer industry - is already seen in wind and solar PV. Large markets can be built through technology standards, consumer incentives, coordinated research and demonstration, trade, and long-term policy certainty.

***Limit cost increases faced by consumers*.** Businesses, utilities, and policy makers have a mutual interest in limiting the level and rate of consumer cost increases during a low-carbon transition. Coordinating energy efficiency improvements with decarbonization of energy supplies limits increases in total consumer bills even if per unit energy prices increase. Long-term pathways planning facilitates financial strategies that spread the impact of large, lumpy costs.

***Minimize inequitable distributional effects*.** The sustainability of a low-carbon transition requires minimizing regressive cost impacts. A powerful tool in an energy system that depends on network suppliers is public utility commissions, which can mandate lower rates for low income customers through utility ratemaking. Distributional effects across regions, sectors, and industries are largely a function of technology strategies, which can be tailored to mitigate these effects.

VII. What are the keys to developing effective policy for an energy transformation?

The first key to developing effective policy for an energy transformation is understanding what policy needs to accomplish, as discussed in the previous section.

The second key is understanding the market and jurisdictional landscape in which the U.S. energy system operates. Some important characteristics of this landscape include:

- Energy markets are highly imperfect in ways that often require regulatory remedies, including natural monopolies, market power, underinvestment, geographic fragmentation, environmental externalities, and information asymmetries.

- Energy systems have strong geographic identities that can affect low-carbon strategies, including local resource endowments and associated industries, construction practices influenced by regional climate, and transportation choices driven by regional patterns of settlement.

- Energy policy is divided across federal, state, and local jurisdictions. In general, states have the strongest jurisdictional levers over the key infrastructure investment decisions underlying the “three pillars” of decarbonization: energy efficiency, decarbonized electricity, and electrification.

The third key is understanding the available policy toolkit and how best to fit the tools to the task.

- Common tools include pricing, emissions caps, consumer rebates, producer subsidies, performance standards, technology mandates, public-private partnerships, and (research, development, and demonstration) RD&D support.

- Sectoral characteristics largely determine the suitability of different policy instruments. For example, pricing and other market instruments are less likely to succeed in sectors that have short payback period requirements, limited access to information, unsophisticated market participants, a lack of substitute products, and an inability to mitigate regressive impacts.

The fourth key to effective policy is to begin policy discussions with questions, observations, and rigorous analysis that provides a foundation for well-tailored policies and avoids reliance on "silver bullet" solutions. Many commonly accepted policy prescriptions and analytical approaches have important limitations as they relate to deep decarbonization. Some key examples:

- Carbon prices have a role in the policy toolkit, but by themselves are unlikely to provide a sufficiently stable or large signal to drive the long-term investments required for deep decarbonization. The benefits of carbon prices tend to be taken for granted but their actual effects in specific contexts are often poorly understood.

- Marginal abatement cost, a staple of climate policy thinking, is a poorly suited guide to systemic change, and if applied literally has the potential to lead to a low-hanging fruit strategy that results in emissions dead ends inconsistent with deep decarbonization by mid-century.

- Societal cost-benefit analysis is a problematic tool for evaluating policy options when society is already committed to deep decarbonization. An example is social cost of carbon, which limits the ambition of current mitigation efforts based on unknowable future damage costs.

- International climate negotiations have long revolved around a theoretical debate on how to allocate the costs of mitigation, which were often poorly understood by the negotiators. Pathways analysis suggests that countries should be less concerned with mitigation as a free-rider problem than with missing the bus on the benefits of an energy transformation.

VIII. How can current federal policies better support deep decarbonization?

Our analysis supports the following recommendations in four key areas of current U.S. federal energy policy:

Electricity decarbonization and the Clean Power Plan. Electricity policy must drive near-complete decarbonization, achieving emission intensities 30 times lower than present by 2050. Policies (including state-level) that drive a "natural gas transition" without also driving a major expansion of renewable, nuclear, or CCS generation will not achieve the required emission intensities. Beyond decarbonizing generation, policies are needed to encourage system changes such as regional integration, electrification, flexible loads, wholesale market redesign, and cross-sector coordination.

Fuel decarbonization and the Renewable Fuel Standard. Low-carbon fuel policy must be weaned away from production of corn-based ethanol, specifically, and gasoline substitutes more broadly. Policy going forward should encourage the development of fuels produced from electricity, redirect biomass resources toward high value uses such as freight transport and industry that are less amenable to electrification, and create a glide path for eliminating biofuels with marginal emissions benefits.

Transportation energy and CAFE standards. The priorities for transportation policy should be to focus Corporate Average Fuel Economy (CAFE) standards on the transition to alternative vehicles so that by 2030 the majority of new sales are electric, fuel cell, or plug-in hybrid vehicles. Other priorities include development of fueling/charging infrastructure, RD&D on low-carbon freight and air transport technologies, and promoting large global markets to bring down vehicle costs.

Building electrification and energy codes and standards. Energy policy for buildings and appliances must shift focus to carbon emissions rather primary energy use, and from traditional energy efficiency to fuel switching. Other priorities include rethinking cost-effectiveness and enabling better use of advanced meter data to target demand-side opportunities.

IX. Beyond this study, how is deep decarbonization pathways analysis contributing to policy and public understanding?

Deep decarbonization pathways (DDP) analysis has been embraced as a policy tool by the international community. For example, a key U.S.-China joint declaration on climate change cooperation in September 2015 emphasized "the importance of formulating and making available mid-century strategies for the transition to low-carbon economies" (USG, 2015). In the policy discussion in advance of COP 21, the pathways developed by DDPP research teams for sixteen high-emitting countries provide benchmarks for evaluating short-term national emission-reduction commitments and examples of how to increase their ambition over time.

California illustrates the value of DDPs as a subnational policy formation tool. California's leaders conducted a DDP analysis to inform the setting of the state's 2030 GHG reduction target announced in January 2015, and the process was used to elicit input from public and private sector stakeholders. DDPs also provide a conceptual map within which more detailed analysis can be situated. For example, two new areas of research – on coordination of land use planning with renewable energy procurement to maximize conservation value and minimize ratepayer costs (TNC 2015) and on integration of power system operations and planning among separate balancing authorities across the western United States – are grounded in long-term electricity scenarios from California DDP analysis (Williams, 2012; Wu, 2015), and are already incorporated in state agency planning and proceedings.

DDPs provide a concrete foundation for improving the U.S. climate policy discussion. For example, the U.S. DDPP report was the source of the scenarios used in a November 2015 study by ICF International of the macroeconomic effects of deep decarbonization in the U.S., including impacts on GDP, employment, and household disposable income (ICFI, 2015). This work may help improve the U.S. climate policy discussion by addressing concerns about the economic effects of a low-carbon transition at a more granular level.

X. What are the next steps for this research?

Vertical DDPs. This report is not intended to be the final word, but a basis for policy discussion and further research, and to provide a demonstration of concept that encourages the widespread use of DDPs in energy planning, policymaking, and business decisions. As a next step, the U.S. DDPP team is planning to develop a set of "vertical" pathways studies linking national, state, and city levels to provide a more detailed understanding of actions required at different jurisdictional levels and how public and private sectors can collaborate on deep decarbonization.

PATHWAYS model. The U.S. DPPP team has developed an open source version of the PATHWAYS modeling tool used in this study, adaptable for use in any geography. We expect it to be publicly released and freely available in the spring of 2016 (USDDPP, 2015). The goal of this effort is to enable DDP analysis around the world that is transparent, comparable, and state-of-the-art.

I. Introduction

The Goal: Reduce Emissions Consistent with the 2°C Limit

This report describes important political, economic, and policy implications of deep decarbonization in the United States. "Deep decarbonization" refers to the reduction of greenhouse gas (GHG) emissions over time to a level consistent with limiting global warming to 2°C or less, based on the scientific consensus that higher levels of warming pose an unacceptably high risk of dangerous anthropogenic interference with the climate system (IPCC, 2013). This report draws primarily on the research conducted for a previous report *"Pathways to Deep Decarbonization in the United States"* (DDPP, 2014) by Energy and Environmental Economics (E3), Lawrence Berkeley National Laboratory (LBNL), and Pacific Northwest National Laboratory (PNNL) for the Deep Decarbonization Pathways Project (DDPP). The DDPP is a collaboration among research teams from sixteen of the world's highest-emitting countries, each of which are developing blueprints for emission reductions within their own national boundaries consistent with the 2°C limit. The U.S. analysis for the DDPP assessed the technical feasibility and cost of different technology options for reducing net U.S. GHG emissions (CO_2e) 80% below the 1990 level by the year 2050, which is the long-term target established by the U.S. government (USG, 2009). As part of this assessment, the analysis also focused on the DDPP target of reducing CO_2 from fossil fuel combustion in each country to 1.7 tonnes per capita in 2050. For the U.S., this is about one order of magnitude below current levels. Historical emissions and the 2050 targets are shown in Table 1.

Table 1. U.S. Greenhouse Gas Emissions in 1990 and 2012, with 2050 Target

	1990	2012	2050 Target	1990 to 2050 change
	$MtCO2_e$	$MtCO2_e$	$MtCO2_e$	%
CO_2 from fossil fuel combustion	4745	5066	**750**	-84%
Fossil fuel CO_2 per capita	19.0	16.1	**1.7**	-91%
Gross other GHG emissions	1485	1435	1309	-12%
Land use and forestry sink	-831	-979	-979	18%
Net GHG emissions	5399	5522	**1080**	-80%

Data source for 1990 and 2012 emissions: (US EPA, 2014)

This report aims to reorient the climate policy discussion in the U.S. toward practical implementation. It uses the technical and cost results of the U.S. 2050 study, plus additional data from a revised version of study containing a new technical supplement (DDPP, 2015A), from the cross-national synthesis report of the DDPP (DDPP, 2015B) and from analysis conducted by E3 for the state of California (E3, 2015), to build a foundation for a robust policy strategy for deep decarbonization the U.S. It touches on all levels of political jurisdiction – international, federal, regional, state, and local – as action at all these levels will be required to accomplish a global low-carbon transition. It looks at both short- and long-term requirements, making the case that short-term policies must be consistent with long-term strategies for deep decarbonization to succeed. The report contains four sections (Figure 1):

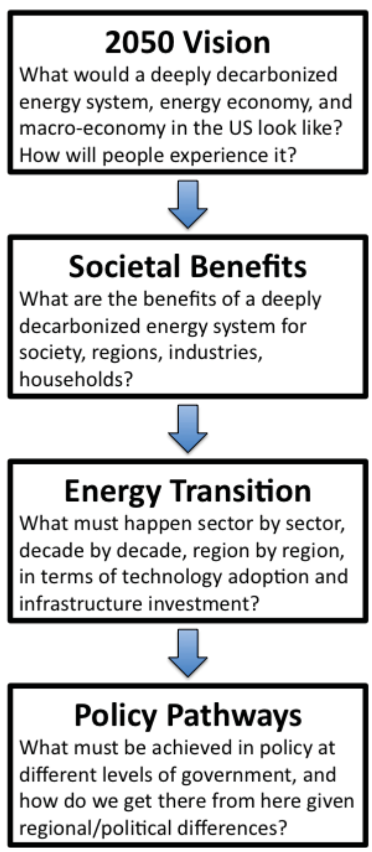
(1) **2050 vision**. This section describes key features of what deep decarbonization in the U.S. would look like from the physical energy system, energy economy, and macro-economy perspectives. It also describes how ordinary citizens might experience the changes in these areas.

(2) **Societal benefits**. This section describes the potential economic, health, and security benefits of deep decarbonization across regions, industries, households, and society as a whole. It also proposes a set of key themes for conveying these benefits to stakeholders and the general public, and provides supporting arguments and data.

(3) **Energy transition**. This section describes the main aspects of a low-carbon transition of the U.S. energy system, viewed sector by sector, region by region, and decade by decade. It describes what this transition will require over time in terms of technology deployment and infrastructure investment, and provides benchmark metrics that make these requirements concrete.

(4) **Policy pathways**. This section describes what policies must accomplish in both the short and long term at different levels of jurisdiction in order to achieve the low-carbon transition. It proposes specific policy approaches that take into account the realities of different economic interests and political environments across states and industries.

Figure 1. Sections in This Report



II. 2050 Vision

Three Aspects of Deep Decarbonization

A high level of commercial energy use, dominated by fossil fuels, is a fundamental feature of all modern societies. Current patterns of settlement, industrial production, and mobility have co-evolved with today's energy system. Achieving a deeply decarbonized global economy by mid-century will require profoundly changing this system while population and economic output continue to grow. At the most basic level, this entails two kinds of changes – making much more efficient use of energy to provide goods and services, and deeply reducing the carbon emitted in supplying that energy – without creating serious economic disruption.

The U.S. 2050 analysis found that this kind of transformation is both technically feasible and economically affordable. The vision of the resulting low-carbon economy and how it differs from the present system is described below from three perspectives, illustrated with results from the U.S. 2050 analysis and other relevant studies. The main findings can be summarized at a general level in the form of three seeming paradoxes:

1. **Deeply decarbonized energy system**: Deep decarbonization will profoundly transform the physical energy system of the U.S. However, the consumer experience of using energy goods and services is likely to be very similar to today.

2. **Deeply decarbonized energy economy**: Deep decarbonization will profoundly transform the U.S. energy economy, in terms of what money is spent on and where investment will flow. However, the change in consumer costs for energy goods and services is likely to be small.

3. **Deeply decarbonized macro-economy**: Deep decarbonization will have a small cost relative to GDP, but nonetheless offers significant benefits for the U.S. macro-economy, such as insulation from oil price shocks.

A. Deeply Decarbonized Energy System

Contrasting High and Low-Carbon Energy Systems

A high-level view of the differences between a deeply decarbonized U.S. energy system and the current U.S. system is shown in the Sankey diagrams below. Sankey diagrams use arrows to represent the major flows of energy from primary supply to end use, with the width of the arrows proportional to the magnitude of the flows. Figure 2 represents the current U.S. system, and Figure 3 represents a deeply decarbonized U.S. system in 2050 (the "mixed case" from the U.S. 2050 study). In both figures, primary energy supplies are shown on the left, conversion processes in the middle, and final energy consumption on the right. All final energy consumption is allocated to the three categories of buildings, transportation, and industry.

The consequences of the three main strategies of decarbonization – energy efficiency, low-carbon electricity generation, and fuel switching to electricity and other low-carbon fuels – are readily visible when comparing the two figures.

1. **Both primary and final energy use are steeply reduced** in the deeply decarbonized system of 2050 relative to today, despite rising energy service demand from growing GDP and population. Total final energy use is reduced more than 20%, per capita final energy use is reduced more than 40%, and final energy use per dollar of GDP is reduced more than 70%.

2. **Petroleum, coal, and natural gas play a much smaller role** in the primary energy supply than they do in the present system, especially petroleum and coal.

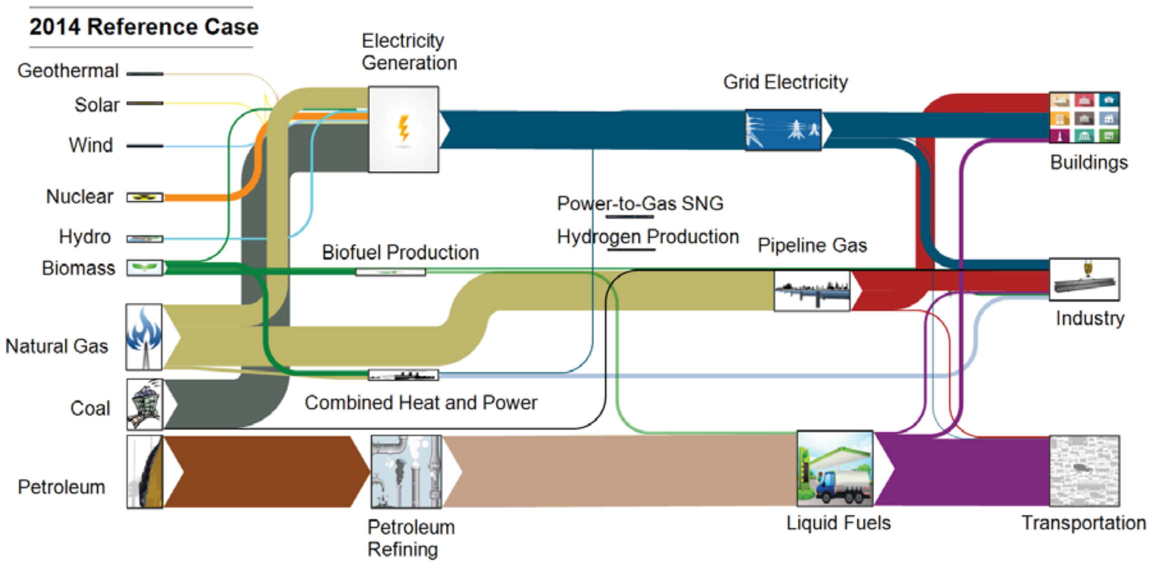
3. **Decarbonized forms of primary energy are dramatically increased,** as wind, solar, biomass, and nuclear become the dominant share of primary energy supply.

4. **Electricity becomes a much larger share of final energy**, due to fuel switching away from fossil fuels toward electricity, and also and electricity-derived fuels such as hydrogen and synthetic natural gas (SNG).

5. **Conversion processes that currently play a minimal role become much more important** in the decarbonized energy system. Biomass refining (for biogas and biodiesel, not ethanol) and the production of hydrogen and synthetic natural gas from electricity provide alternative low-carbon fuels for applications in which electrification is difficult.

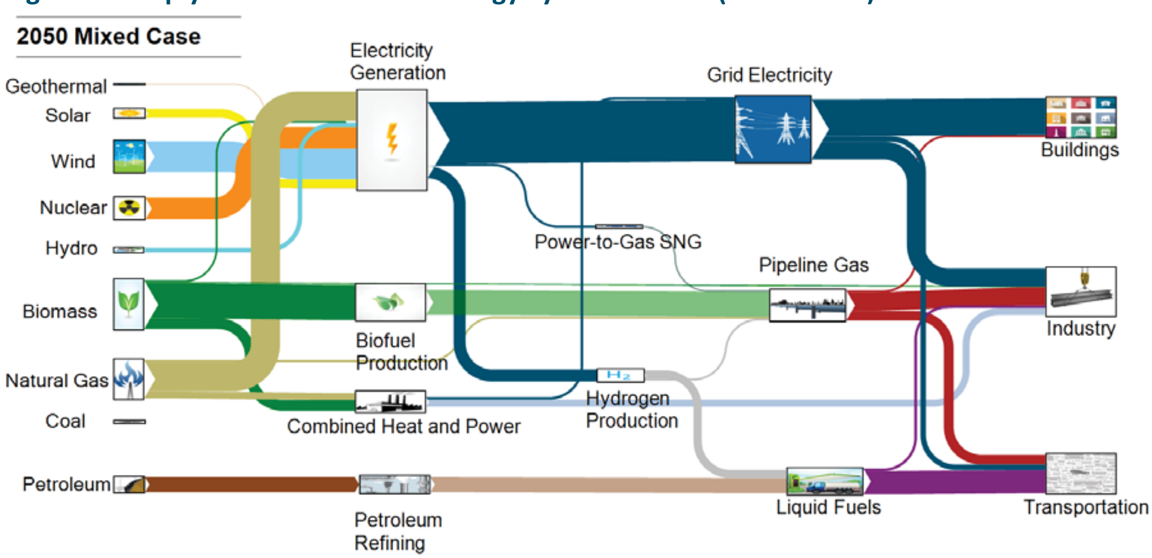
More detailed indicators of some key changes are shown in Figure 4 A-F.

Figure 2. U.S. Energy System in 2014



Source: (DOE, 2013)

Figure 3. Deeply Decarbonized U.S. Energy System in 2050 (Mixed Case)



Key Metrics of Deep Decarbonization

Fossil fuel use is reduced by two-thirds in a deeply decarbonized system in 2050 compared to today (Figure 4A). Much of the remaining fossil fuel is either used as a manufacturing feedstock or combusted in conjunction with carbon capture and storage (CCS) so that the CO_2 emissions are not released to the atmosphere.

Meanwhile, **non-fossil forms of primary energy increase by a factor of five** compared to today (Figure 4B). In the "mixed case" scenario, wind, solar, and nuclear electricity generation all show dramatic increases, and biomass becomes a major fuel source for non-electric end uses.

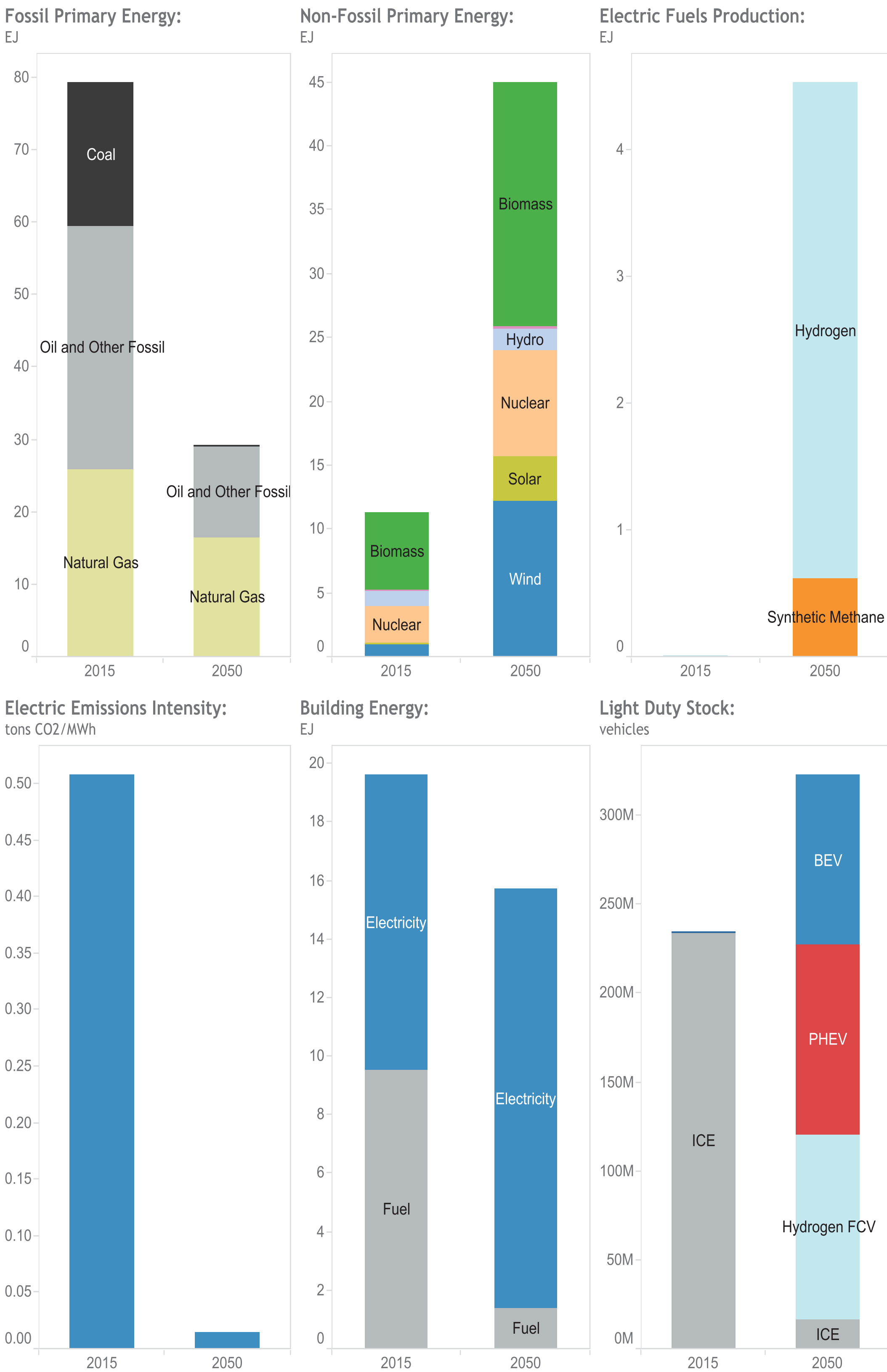
94% of light duty vehicles (LDV) are either battery electric, plug-in hybrid, or fuel cell vehicles. Overall, LDV stocks increase by a third by 2050, but LDVs with only conventional internal combustion engines and drive trains decrease to 6% of the total stock (Figure 4F).

In residential and commercial buildings, final energy is over 90% electricity, compared to about 50% today, despite increasing floor space due to population and GDP growth (Figure 4E). This results primarily from fuel switching of space and water heating from fuel oil and natural gas combustion to decarbonized electricity. This **fuel switching is responsible for most of the 20% decrease in total building final energy use**, as electric appliances are more thermodynamically efficient than combustion alternatives for space heating, water heating, and cooking.

The carbon emissions intensity of electricity in the deeply decarbonized system is reduced to less than 0.02 tonnes CO_2e per megawatt-hour, through a combination of reducing fossil generation and adding renewable, nuclear, and CCS power generation. In the current U.S. energy system, dominated by coal and natural gas, the intensity is greater than 0.5 tonnes CO_2e per megawatt-hour (Figure 4D).

Electric fuels produced from low-carbon electricity grow from virtually zero today to about 7% of the total final energy supply (>4 EJ) in the 2050 decarbonized system (Figure 4C). This includes hydrogen obtained from electrolysis of water, and SNG produced from hydrogen. Hydrogen is used in fuel cell vehicles, and both hydrogen and SNG are injected into the gas pipeline to provide a combustion fuel for transportation and industry with a lower lifecycle carbon intensity than fossil natural gas.

Figure 4. Comparisons of Current Energy System to Deeply Decarbonized System



A Decarbonized System Can Support Current Lifestyles

How will deep decarbonization affect people's daily lives? The seeming paradox is that while it entails a major physical transformation of the energy supply system, **the day to day interaction of most people with using energy goods and services will change very little**. In the U.S. analysis, the deeply decarbonized system was required to provide the same level of energy services as the reference case (business as usual) developed by the U.S. Department of Energy in their *Annual Energy Outlook*, in order to examine the feasibility of maintaining current lifestyles with a decarbonized system. The *AEO* reflects a growing population and economy demanding energy service levels equivalent to or greater than today's. Some typical examples of these service levels are shown in Figure 5.

- **Driving of personal vehicles is virtually unchanged from the present**, as measured by light duty vehicle miles traveled (VMT) per capita (around 8,000 miles per person per year). The *AEO* forecasts an increase of nearly 20% in 2050 VMT, but this projected increase is offset by urban design and transit measures in the deep decarbonization case.

- **Dishwashers are used just as much** as at present, as measured by average annual dishwashing cycles per household (around 150 cycles per year, a little less than every other day).

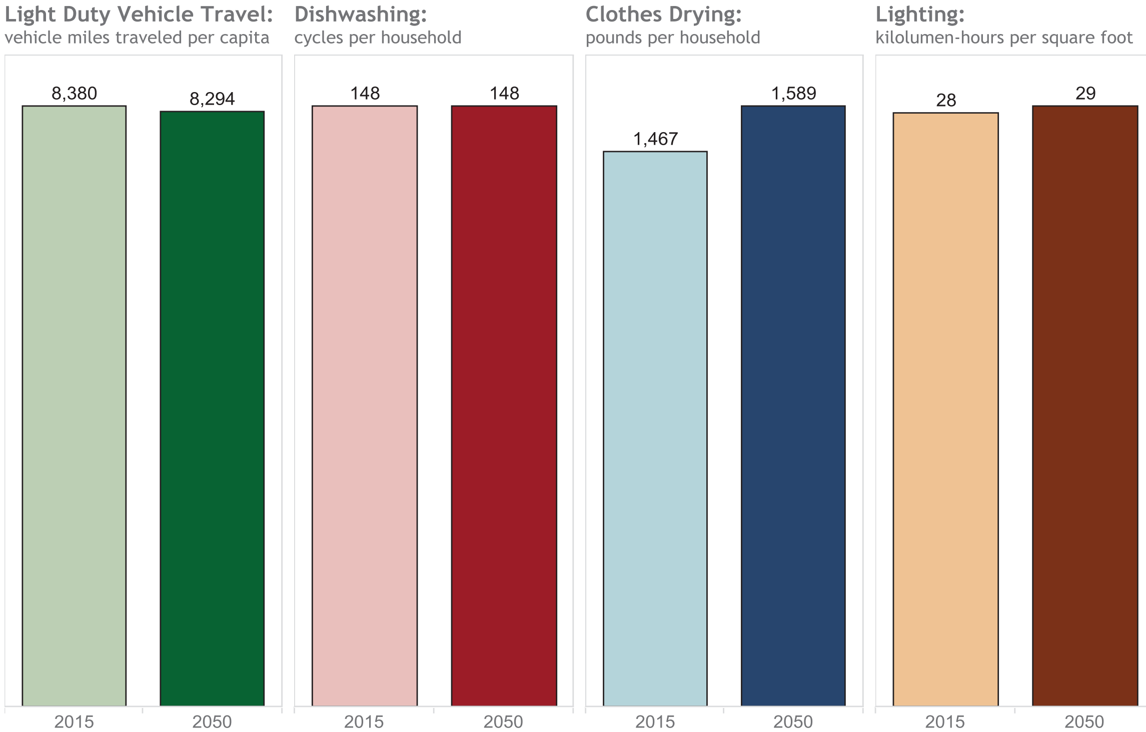
- **Residential lighting intensity increases slightly** (29 kilo-lumens per square foot of floor area). Overall lighting service demand increases, reflecting both an increase in intensity and an increase in floor area. The same is true for commercial lighting.

- **Clothes drying increases slightly**, as measured by annual average pounds of clothes put in the dryer per household (around 1,600 pounds per year, or about 30 pounds per week). This reflects an increasing penetration of residential clothes dryers in U.S. households.

Lifestyle changes, such as use of bicycles in lieu of cars, vegetarian diets, and wearing sweaters to reduce home heating loads, are not required, though by lowering energy service demand these measures could reduce the amount of low-carbon technology that must be deployed, and potentially lower costs.

As the service levels in Figure 5 indicate, the impact of deep decarbonization on daily life in 2050 is likely to be barely perceptible to most people. Electricity will still be reliable: a person will flip a switch or trigger an occupancy sensor and a light will come on. The heat will come on when the temperature reaches the thermostat stetting, and hot water will run from the tap when the faucet is turned on. Most people will be barely aware of the difference between an electric heat pump in their basement and their current oil or natural gas furnace. Cars will still be cars, and will have fueling networks similar to those today. Whether they drive an electric or fuel cell car, just as today most people won't often think about what's under the hood.

Figure 5. Deeply Decarbonized System Can Support Current Level of Energy Services



Source: (DOE, 2013)

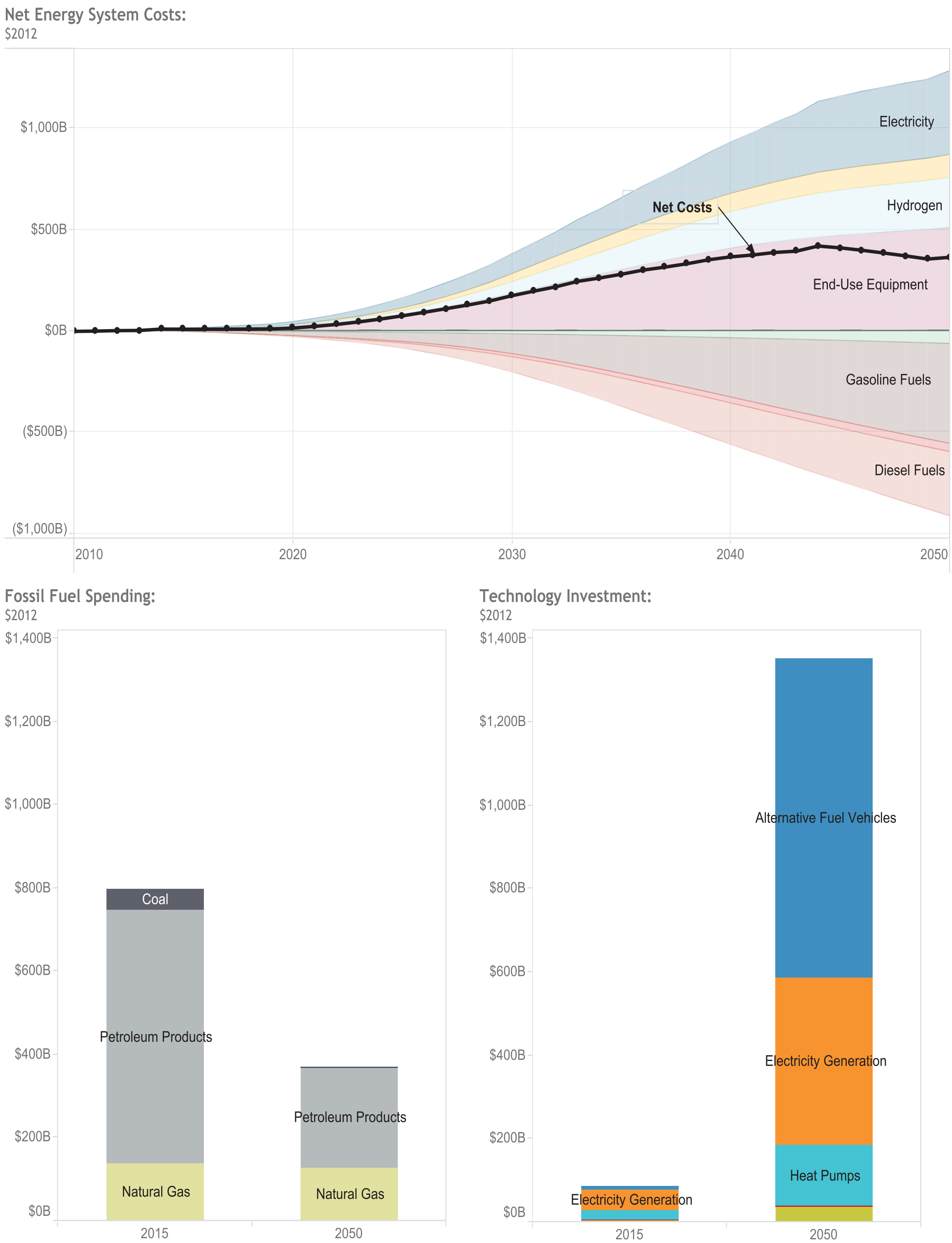
B. Deeply Decarbonized Energy Economy

Spending More on Technology and Less on Fuel

The deeply decarbonized energy economy is dominated by fixed capital costs for energy efficient and low-carbon technologies, consistent with the physical changes required. Deep decarbonization results in large increases in spending on low-carbon equipment and infrastructure, offset by large savings in fossil fuel purchases. For the "mixed case" low-carbon scenario in 2050, the analysis of net energy system cost shows incremental spending of $1,250 billion on end-use equipment and low-carbon energy production, minus savings from avoided fuel purchases, mostly for petroleum products, of $900 billion, resulting in a net cost of $350 billion in 2050 (Figure 6A). The uncertainty around these estimates, the scale of these costs in comparison to GDP, and their implications for the U.S. macro-economy are considered in the next section.

The change in the scale and direction of financial flows in the deeply decarbonized energy economy relative to that of today is dramatic. In the mixed case, which includes some use of CCS and therefore fossil fuels, **fossil fuel spending decreases from $800 billion today to below $400 billion in 2050** (Figure 6B) even as GDP, population, energy service demand, and the price of energy increase. Petroleum use falls by 60% relative to today, with a large share of the remaining petroleum being consumed as a feedstock for manufactured products, rather than consumed as a transportation fuel. In the high renewables case, the decrease in fossil fuel usage and spending is even greater. Meanwhile, spending on technologies increases from $100 billion today to $1,600 billion in 2050. **Most of the technology spending falls into three main categories – alternative fuel vehicles, electricity generation, and electric heat pumps** for space and water heating (Figure 6C).

Figure 6. Energy System Costs and Savings by Component

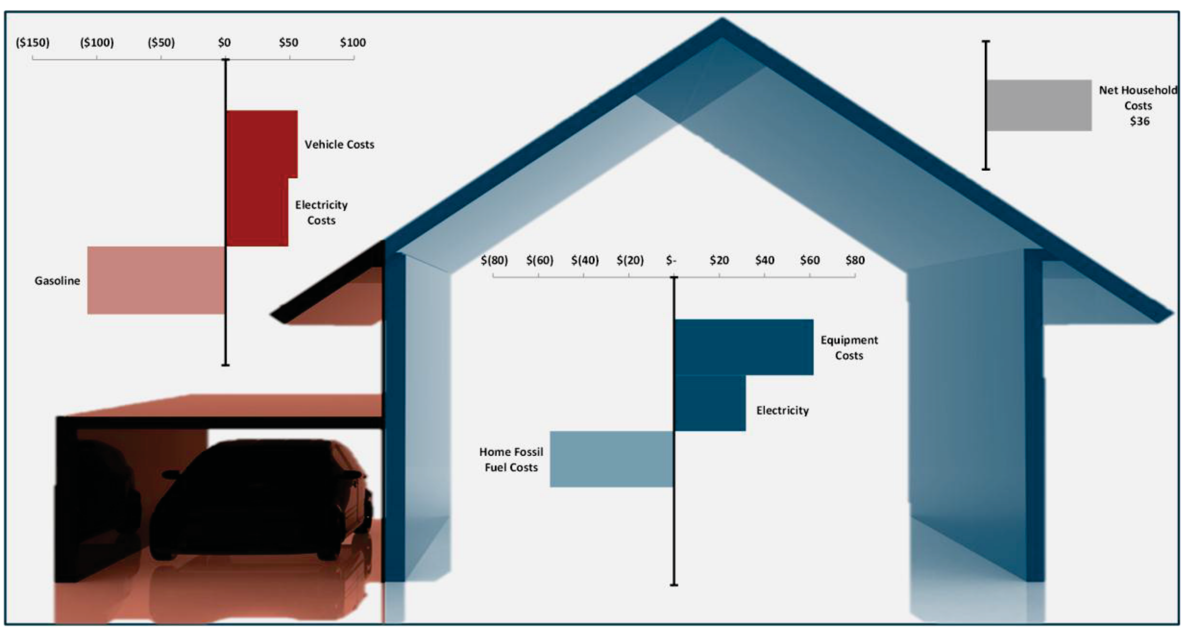


Small Change in Direct Consumer Spending for Energy

Despite the dramatic overall changes in the low-carbon energy economy, impacts on direct consumer costs are small. The U.S. 2050 analysis estimates the change in household spending on energy goods and services as a **$35 per month net increase** relative to the reference case (Figure 7). This small net increase in costs mirrors that for the country as a whole, being the result of increased spending on energy efficient and low-carbon equipment such as alternative vehicles, heat pumps, and LED lights, minus savings from reduced purchases of gasoline, diesel, natural gas, and fuel oil enabled by this equipment. Bringing these costs down over time to reduce the level of consumer up-front spending required on their homes and vehicles is the key to keeping net household costs low, or even producing a net savings.

The $35 per month net increase can be divided into spending on energy in the home and spending for transportation. Inside the home, average monthly costs for equipment (potentially lumpy up-front costs have been levelized to represent them as a monthly cash flow) increase by $60, and the cost of decarbonized electricity, which is powering a higher share of household end uses, increases by $30 per month. This is offset by a reduction in the cost of fuels avoided due to electrification, primarily natural gas, of $55 per month. Household transportation costs include an increase of $60 per month for the incremental cost of alternative vehicles, plus $50 per month for the increased cost of electricity, minus $100 per month in savings from avoided gasoline purchases.

Figure 7. Average Household Spending for Energy Goods and Services, 2050 Mixed Case



With electricity becoming the dominant form of energy directly used by households, for both transportation and in-home use, retail electricity rates become more important. The U.S. analysis shows that **average retail electricity rates are only modestly higher** (14%) in the mixed case than the reference case in 2050 (Figure 8). Overall household spending on electicity averages about $20 per month more than the reference cases, from a combination of higher average rates and higher usage.

Figure 8. Average Retail Electricity Rates in 2050, with Cost Components, Reference Case and Deep Decarbonization Cases

Average Electric Rate:
2012 cents/kWh

	Distribution	Transmission	Renewables	Variable and Fuel	Conventional Fixed	**Total**
DDPP Reference Case	3.9c	2.0c	2.7c	4.3c	3.9c	16.7c
DDPP Mixed Case	2.8c	2.6c	6.6c	1.8c	5.2c	19.1c
DDPP CCS Case	3.7c	2.0c	3.9c	4.6c	7.6c	21.8c
DDPP High Renewables Case	2.8c	4.5c	10.0c	0.4c	2.0c	19.5c
DDPP Nuclear Case	2.6c	2.6c	6.7c	0.8c	4.7c	17.4c

C. Deeply Decarbonized Macro-Economy

The Cost of Deep Decarbonization to the U.S. Economy is Small

The cost of deep decarbonization is small compared to GDP. The U.S. study estimates the cost of deep decarbonization across the four scenarios analyzed at $320 billion in 2050, or about 0.8% of forecast 2050 GDP of $40 trillion (Figure 9A). This is the "net energy system cost," which is the net cost of supplying and using energy in a low-carbon scenario compared to the reference case based on the *AEO*. Put another way, the net energy system cost is the additional cost of investment in efficient and low-carbon equipment and infrastructure minus the savings achieved from avoiding fossil fuel purchases, all compared to what would have occurred in the reference case.

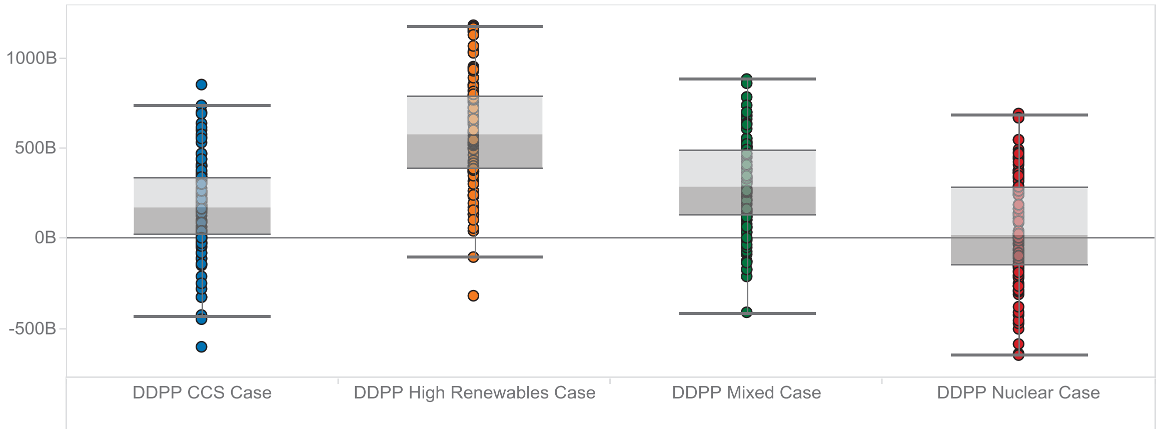
Even under unfavorable assumptions about future prices, the cost of deep decarbonization is small. Because of the long time period between the present and 2050, there is great uncertainty about future fuel prices and technologies. Using a wide range of estimates for these costs, the uncertainty analysis indicates a 50% likelihood that net energy system costs will range somewhere between a net savings of $90 billion (-0.2% of GDP) and a net cost of $730 billion (1.8% of GDP) in 2050 (Figure 9A).

Cost uncertainties are smaller in the short term and greater in the future, meaning that there will be time for course corrections if a particular pathway or policy turns out to be more expensive than anticipated. With multiple feasible technology options, cost uncertainty is not an adequate reason not to pursue deep decarbonization. The net energy system cost trajectory over time, including uncertainty bounds, is shown for the mixed case in Figure 9B. For this case, the expected net energy system cost is $350 billion in 2050 (0.9% of GDP), with a 50% likelihood of falling between $120 billion (0.3%) and $480 billion (1.2%).

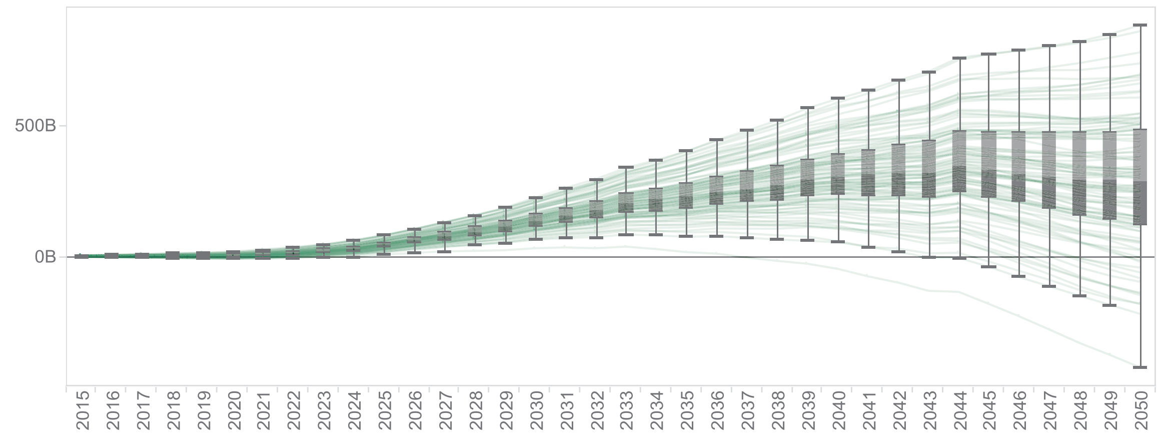
Regional costs of deep decarbonization are similar as a share of regional GDP to U.S.-wide costs, with some variation. At a regional level, mixed case net energy system costs in 2050 are shown for the nine U.S. census divisions range are shown in Figure 9C. The highest central cost estimate, and the largest uncertainty range, are in the South Atlantic region. The lowest central estimate and smallest uncertainty range are in New England.

Figure 9. Net Energy System Cost of Low-Carbon Scenarios Relative to Reference Case

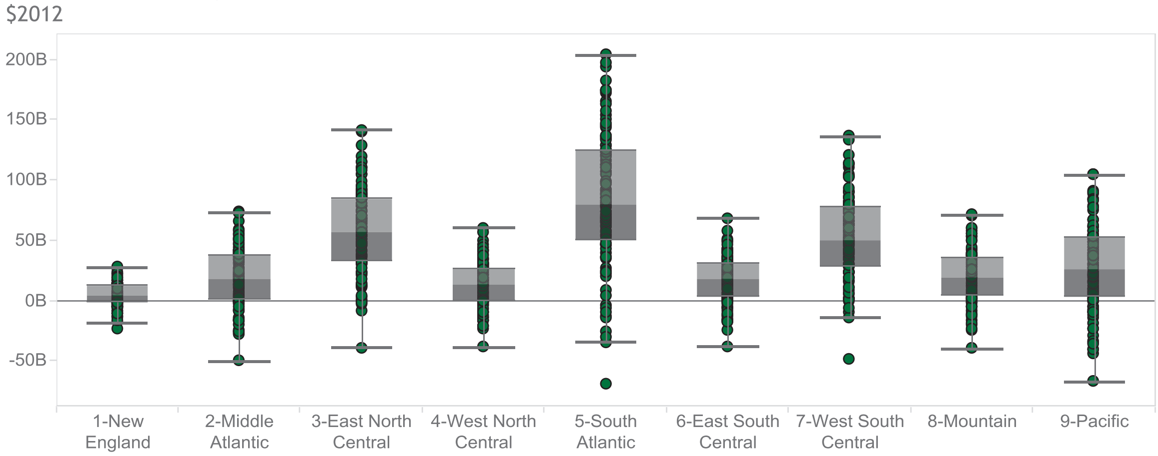
2050 Incremental Costs:
$2012



Mixed Case Incremental Costs:
$2012



2050 Mixed Case Regional Incremental Costs:
$2012

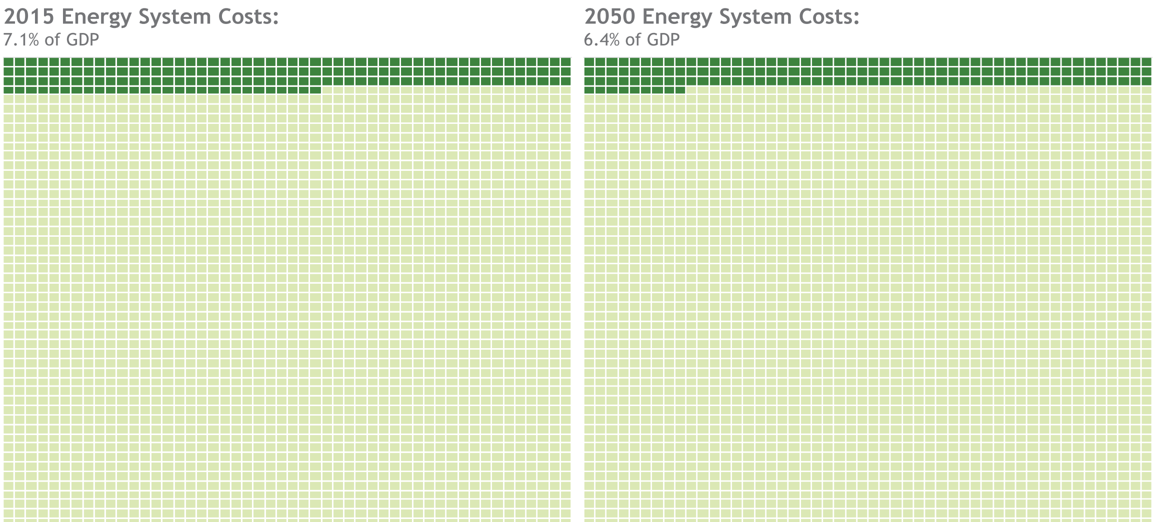


Putting Decarbonization Cost in Perspective

The incremental cost of deep decarbonization is small compared to overall spending on energy. In 2012, EIA figures show that total spending on energy supply in the U.S. was $1.36 trillion, or 8.6% of GDP ($15.8 trillion). This spending included $995 billion on primary energy for all purposes other than electricity generation. Almost all of the non-generation spending was for fossil fuels, dominated by $884 billion (66% of all energy spending) for petroleum. Retail electricity spending was $361 billion (27% of all energy spending). Of this, $82 billion was spent on primary energy for electricity generation, almost all on natural gas and coal. Total spending on fossil fuels for all purposes was $1.06 trillion (78% of all energy spending) or 6.7% of GDP. Over the 50 years from 1962 to 2012, energy spending in the U.S. as a percentage of GDP ranged from a low of 6% to a high of 13%. For comparison, in recent years spending on health care has hovered around 17% of GDP.

Total U.S. spending on energy declines as a percentage of GDP under deep decarbonization. Figure 10 shows an estimate of U.S. total energy system costs from the PATHWAYS model in 2015 at 7.1% of GDP, reflecting a decline in fossil fuel prices. From the U.S. deep decarbonization analysis, the total energy system cost of the mixed case in 2050 is estimated at 6.4% of GDP, a decrease in the energy share of GDP from the present.

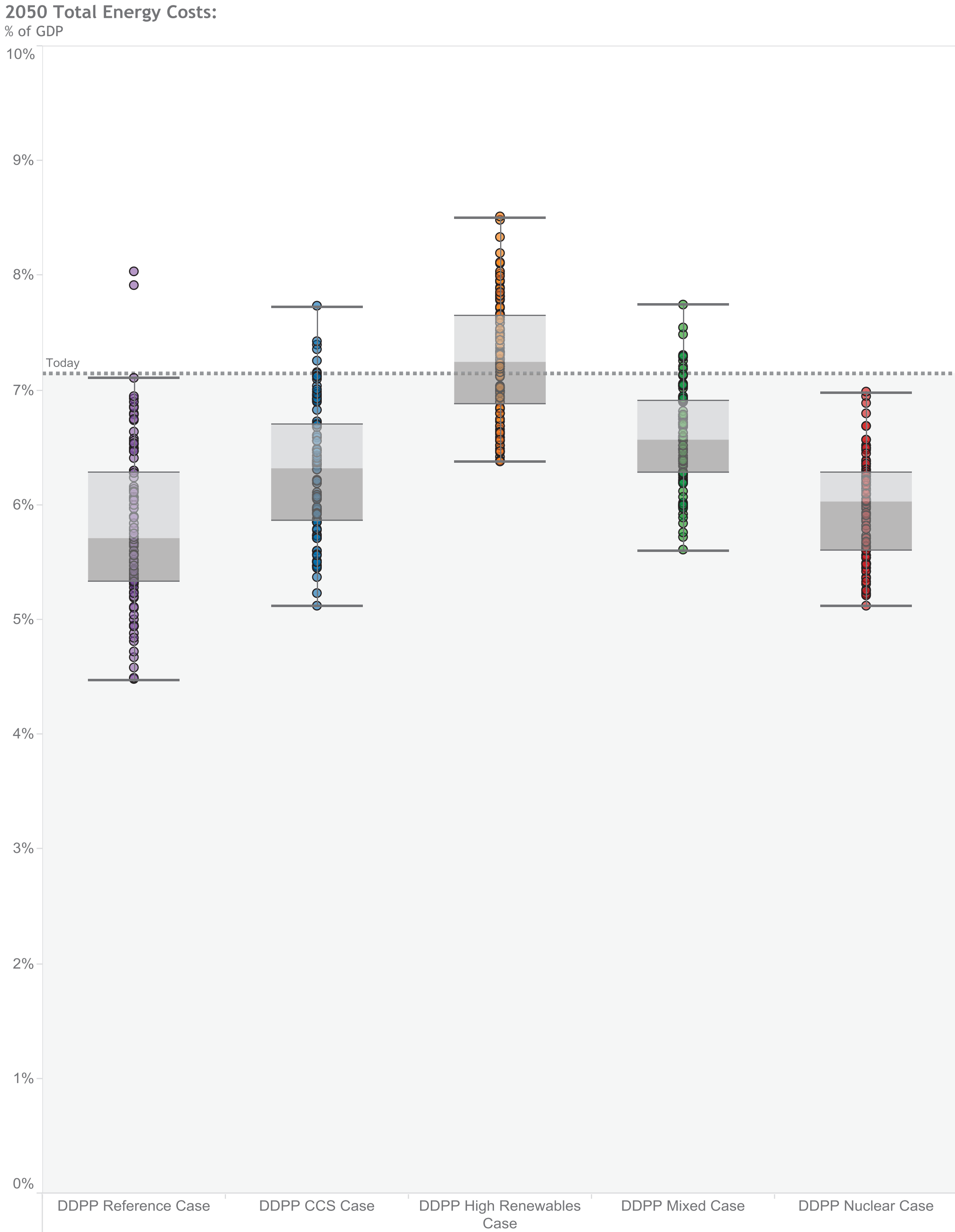
Figure 10. Energy Costs as a Share of U.S. GDP, Current and 2050 Deep Decarbonization Cases



Business as Usual Energy System Has Uncertain Costs

Future energy cost uncertainty is as large or larger for a fossil fuel based system as for a deeply decarbonized system (Figure 11). Under many scenarios of fuel price and technology cost in 2050, deep decarbonization cases have lower total cost than the reference case. Even under the most unfavorable assumptions, for the highest cost deep decarbonization case (high renewables case), energy cost as a share of GDP would lower than it was in 2012.

Figure 11. Total Energy Cost in 2050 as a Share of GDP, Including Uncertainty Ranges, for Reference Case and All Deep Decarbonization Scenarios



II. Societal Benefits

Four Essential Themes

The storyline of deep decarbonization is the economic, energy security, environmental, and public health benefits to society. There are four essential themes, all of which are supported by the findings of the U.S. 2050 study:

1. **Stable Climate and Clean Environment.** Deep decarbonization is the most important action that can be taken to protect the climate and the global environment. The necessary transformation of the energy system is feasible and affordable, and provides many other non-climate benefits. A deeply decarbonized energy system lowers air pollution, improves public health, reduces fossil fuel-related disasters, and promotes environmental justice.

2. **Macroeconomic and Energy Security.** A deeply decarbonized energy system has much more predictable energy costs and a more stable investment environment than the current system. It greatly reduces impacts of oil price volatility on the U.S. economy, insecurity over strategic resource availability, and engagement with unstable oil-producing regions.

3. **Widespread Economic Benefits.** A deeply decarbonized energy system has many more potential economic winners than the current system, due to dramatically increased and widely distributed investment across regions, technologies, energy types, and industries. Meanwhile, the fossil fuel industry has sufficient time to shift its vast resources and know-how to a low-carbon business model.

4. **Modernization, Competitiveness, and Jobs.** A clean, flexible 21st century energy system is the cornerstone of a smart, efficient 21st century economy. U.S. strengths in information technology, biotechnology, and nanotechnology will provide a major competitive advantage in global markets for low-carbon energy. Deep decarbonization works hand in hand with upgrading American infrastructure and fosters "re-industrialization," with the potential to generate many attractive high tech, manufacturing, and building trades jobs.

A. Stable Climate and Clean Environment

The Most Important Action the U.S. Can Take

Deep decarbonization is the most important action the U.S. can take to protect the climate. It will provide an example for the world to follow in keeping global warming below 2°C and avoiding the worst impacts of climate change. U.S. deep decarbonization pathways reduce emissions 80% below 1990 levels by 2050 (Figure 12), and the energy system transformation required to reach this level sets the stage for reaching zero net emissions by 2070.

Scientists estimate that global cumulative emissions going forward can total no more than 1200 billion tonnes of CO_2 to have a better-than-even chance of limiting warming to 2°C or less. Assuming a continued reduction to zero net emissions by 2070, deep decarbonization will limit U.S. cumulative emissions to 120 million tonnes of CO_2, or about one-tenth of the global budget. The U.S. is currently responsible for about one-seventh of global CO_2 emissions. In the reference case, the U.S. by itself would emit over 300 billion tonnes by 2070.

Deep decarbonization will help avoid the worst weather extremes due to climate change, including increased severity of hurricanes, drought, heat waves, and flooding, and the damage these will inflict on infrastructure, agriculture, and human well-being. It will reduce the requirements for adaptation, and the suffering incurred when adaptation is not possible. It will limit climate change impacts on habitats and biodiversity, and the impacts of ocean acidification on sea life.

A deeply decarbonized energy system will greatly reduce air pollution such as fine particulate matter, nitrogen oxides, and sulfur dioxide, most of which comes from fossil fuel combustion (Figure 13). This will improve public health, reducing air pollution-related conditions such asthma and heart disease. By dramatically reducing the volume of fossil fuel flows, it will reduce the incidence of disasters related to the fossil fuel supply chain, such as the Deepwater Horizon oil spill, exploding train cars of crude oil, and toxic emissions from refineries. It will reduce water use and pollution associated with fossil fuel extraction and thermal power generation. **Because many of the side-effects of fossil fuel extraction, processing, and combustion fall disproportionately on the poor, deep decarbonization will improve environmental justice.**

Figure 12. CO_2 Emissions to 2050, Reference Versus Deep Decarbonization Scenarios

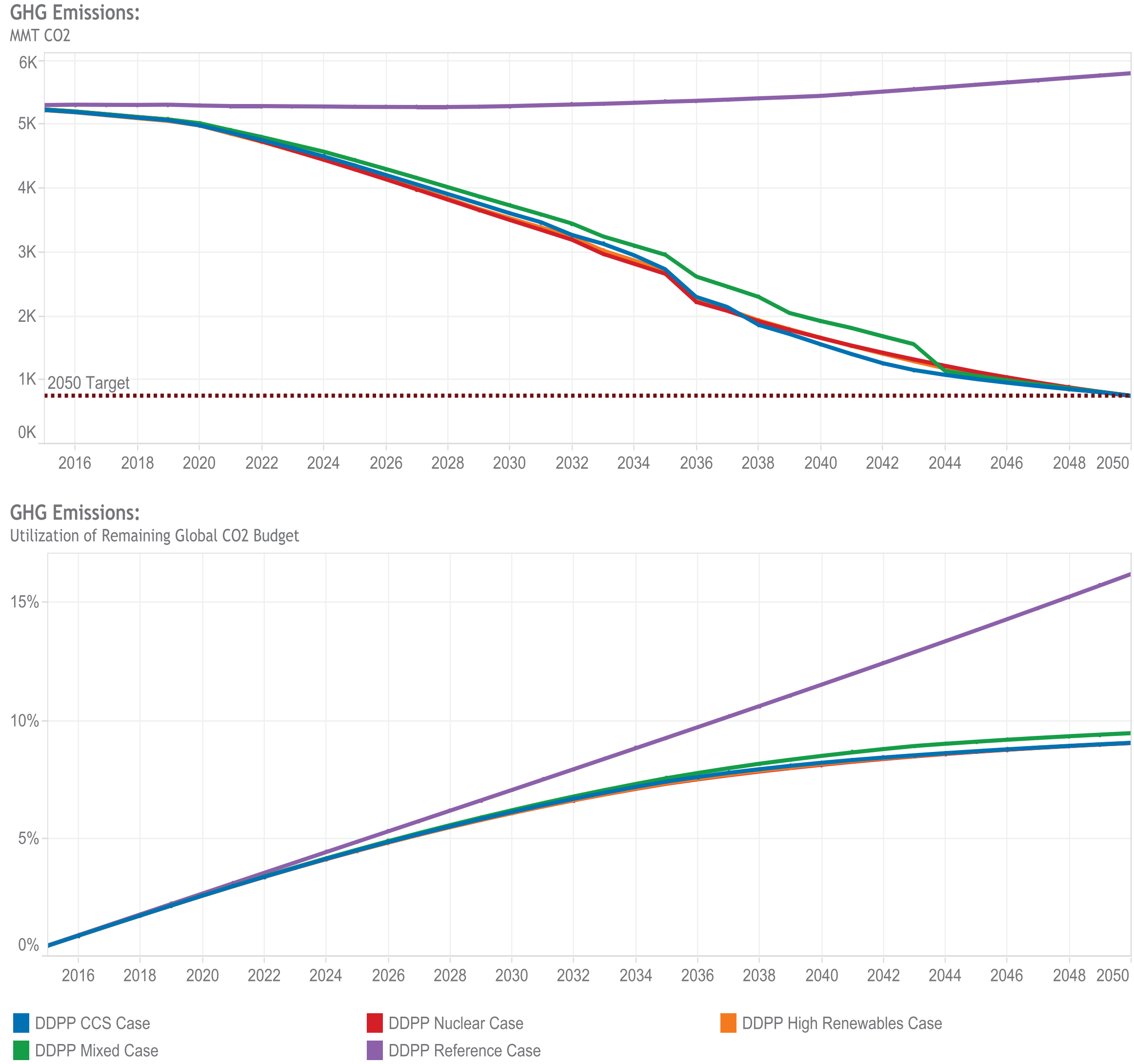
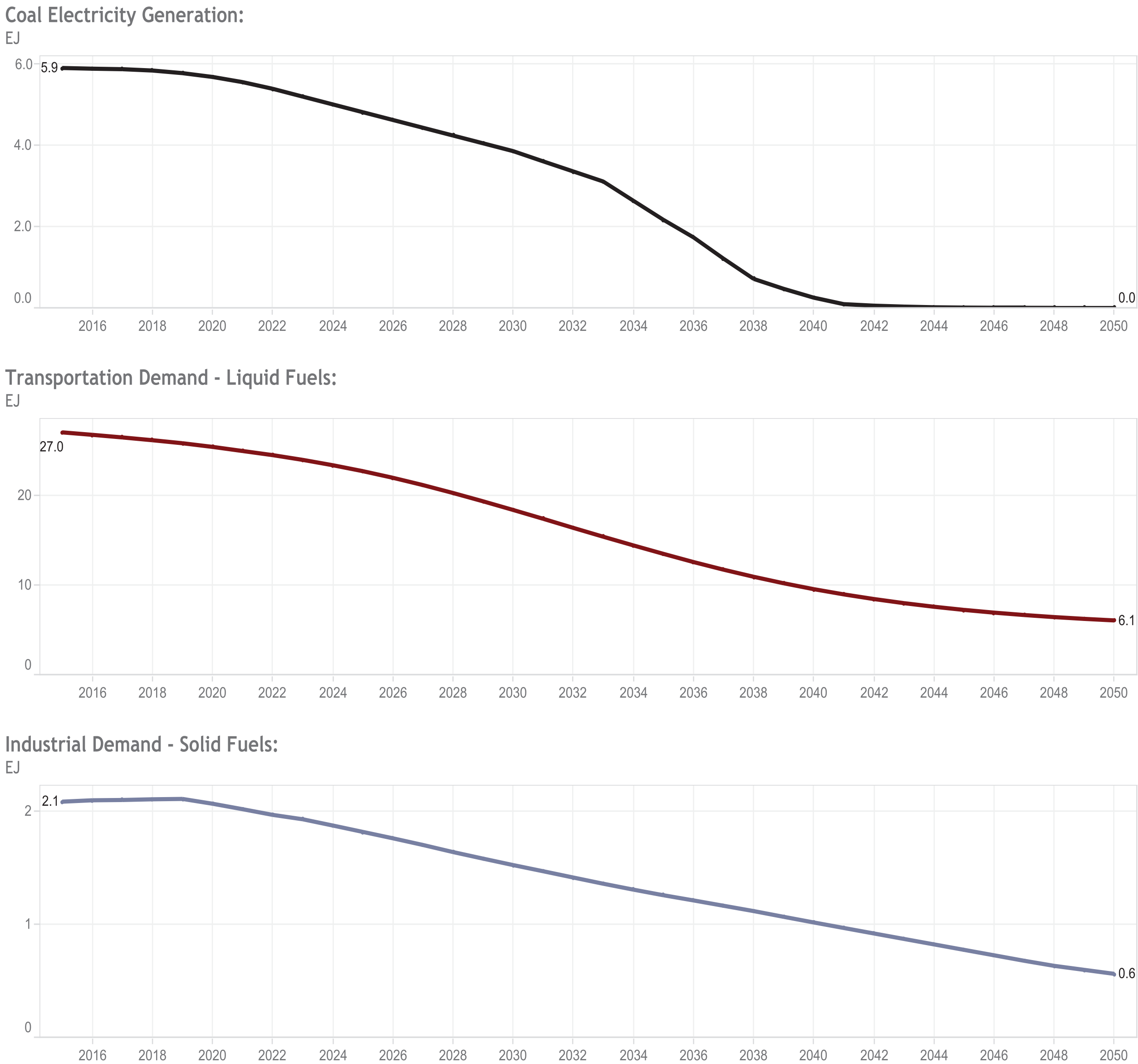


Figure 13. Reduction in Key Sources of Air Pollution as a Result of Deep Decarbonization



B. Macroeconomic and Energy Security

Stability and Predictability

In the deeply decarbonized energy economy, energy costs will be more stable and more predictable than the current system. Energy costs in the current system are dominated by fossil fuel prices, especially the price of crude oil, a scarce resource traded in a global market marked by high levels of both short and long term variability. The unpredictability of **fossil fuel prices** is illustrated for natural gas in Figure 14A and for crude oil in Figure 14b, in which actual prices over the last two decades are compared to the Department of Energy's long-term price forecast for these commodities in the *Annual Energy Outlook 1996*. For both natural gas and oil, actual prices are both higher than forecast prices throughout most of the period and highly variable.

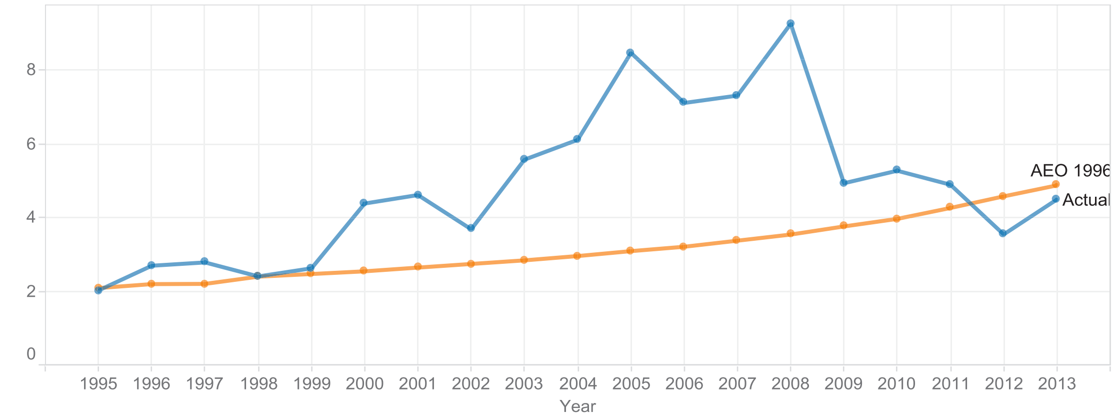
In the deeply decarbonized economy, energy costs are dominated by technology costs, which tend to be more stable and predictable. For electricity, the primary form of delivered energy in the 2050 low-carbon system, this is illustrated in Figure 14C, which shows actual average U.S. electricity rates over the same time period, compared to the *Annual Energy Outlook 1996* forecast. Historical U.S. **electricity rates**, which are dominated by the fixed capital costs of generation, transmission, and distribution equipment, track the forecast relatively smoothly, and in fact are lower than the *AEO* forecast price throughout the period. Most of the historic variation in electricity rates is due to changes in fuel prices, which would be a small share of cost in a deeply decarbonized system.

As long as oil remains the dominant form of primary energy in the U.S. energy system, the U.S. economy will continue to be vulnerable to the recessionary impacts of oil price shocks (Figure 15), insecurity over strategic resource availability, and the ongoing prospect of otherwise unwanted military and political engagement with unstable oil-producing regions. **Deep decarbonization reduces U.S. exposure to economic and security risks by dramatically reducing oil consumption and oil's share of GDP.** In the "mixed case," oil consumption drops to pre-1970 levels by 2030, and pre-1950 levels by 2050 (Figure 16). Residual fossil fuel costs by 2050 are only 1% of GDP (Figure 6).

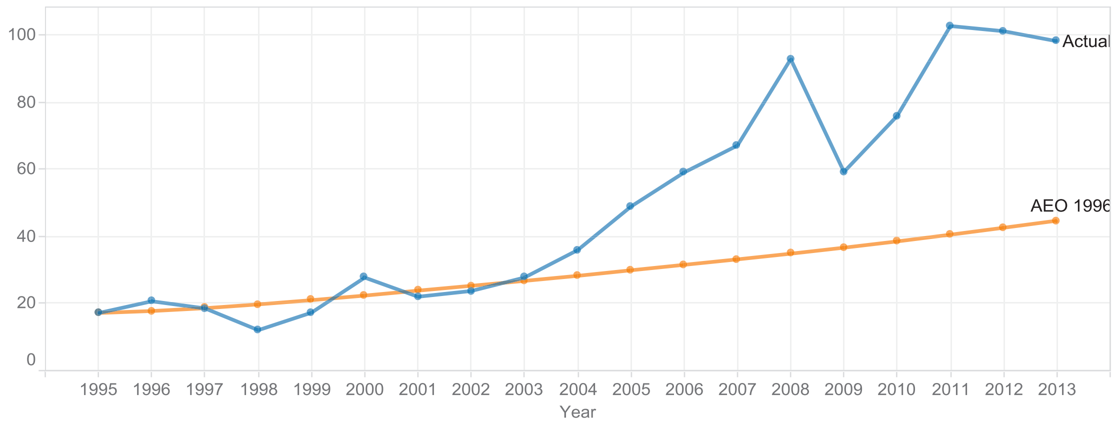
The technology-dominated costs of the deeply decarbonized system create a stable long-term environment for investors and more predictable energy costs for consumers. Overall energy investment will expand, driving vigorous competition within U.S. and global technology markets for equipment and infrastructure ranging from alternative fuel vehicles to efficient building technologies to low-carbon generation.

Figure 14. Forecast Versus Actual Prices for Oil, Natural Gas, and Electricity, 1995-2013

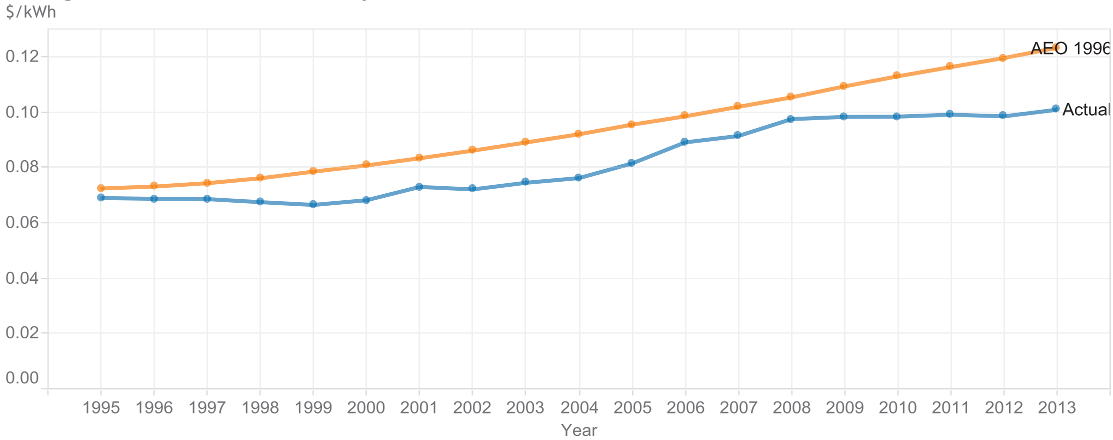
Natural Gas Actual vs. Projected:
$/MMBTU delivered to electricity generators



Crude Oil Actual vs. Projected:
$/barrel



Average Electric Rate Actual vs. Projected:
$/kWh



Source: (DOE, 1996; DOE, 2015)

Figure 15. Historical Correlation Between Oil Price Shocks and Economic Recession in the U.S. (Figure from Steven Kopits)

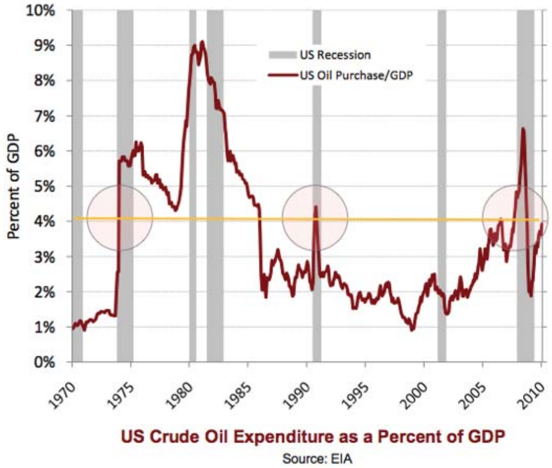
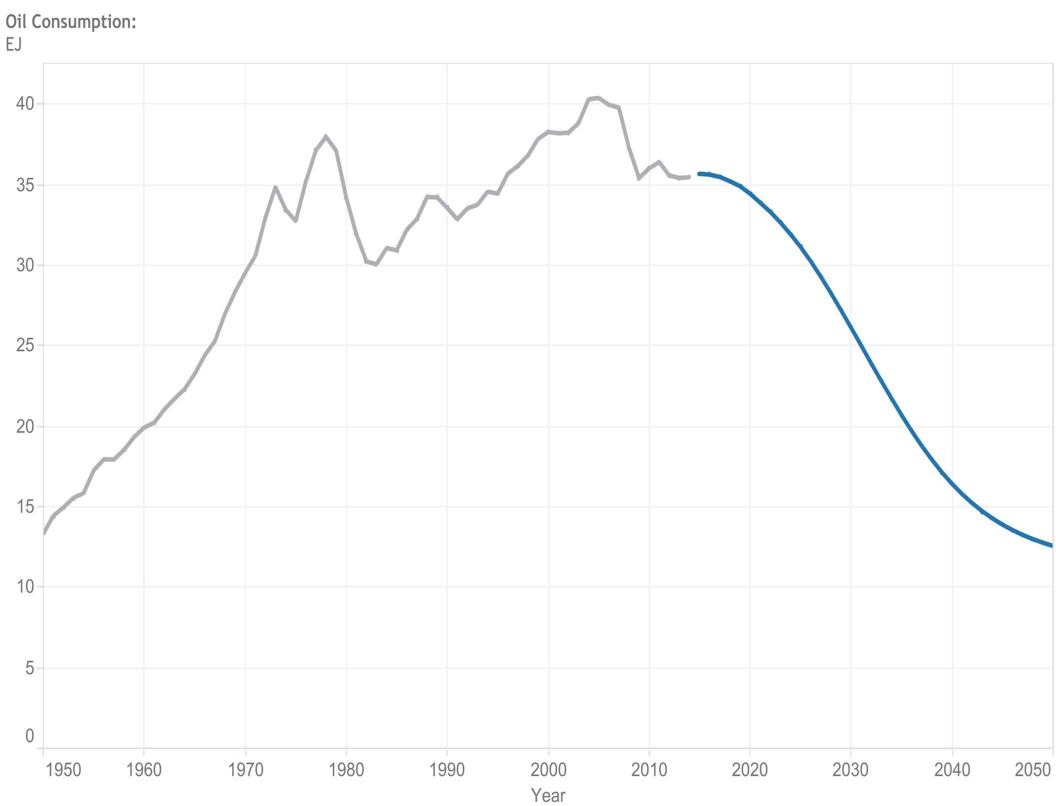


Figure 16. U.S. Oil Consumption, Historical 1950-2014 and Projected 2015-2050 for Deep Decarbonization, Mixed Case



Source: (DOE, 2015)

C. Widespread Economic Benefits

An Energy System with Many Winners

Most of the country will benefit economically from the transition to a deeply decarbonized energy system. The shift from fossil fuel to low-carbon energy will mean vastly increased and widely distributed investment across regions, industries, technologies, and energy types. **Meanwhile, the transition will reduce revenues that are currently concentrated in a few industries and regions involved in supplying fossil fuels, and in the production of low efficiency and fossil fuel based end-use technologies**. The gradual timeline of the transition will provide ample opportunities for a successful shift to a low-carbon business model.

On the energy demand side, **investment in efficient and low-carbon end-use technologies will increase dramatically**, while investment in inefficient and high-carbon end-use technologies decline. Large new revenue streams will flow into technology, manufacturing, and construction to build and supply the low-carbon infrastructure and equipment required. This is illustrated by examples from the U.S. study "mixed case."

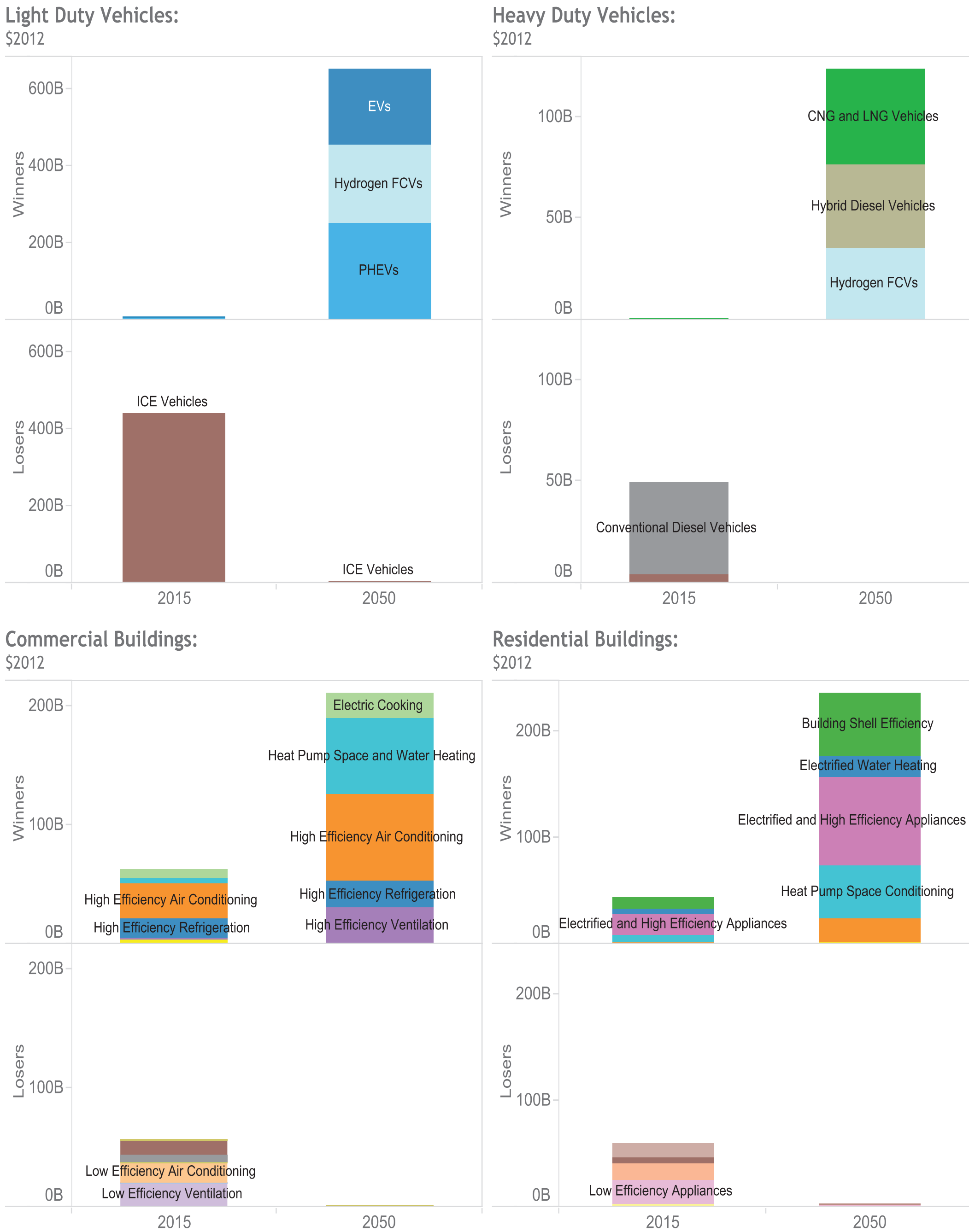
In **residential buildings** investment in clean technologies such as heat pump heating and air conditioning, high efficiency appliances, LED lighting, and building shell improvements will increase by a factor of six, from $35 billion annually today to $220 billion in 2050 (Figure 17B), while the low efficiency counterparts of these technologies fall from $50 billion today to zero in the 2050 deeply decarbonized system.

In **commercial buildings**, the story is very similar. Investment in heat pump space and water heating, and high efficiency air conditioning, ventilation, and refrigeration will triple, from $70 billion annually today to $210 billion in 2050 (Figure 17A), while the low efficiency counterparts fall from $50 billion today to zero in 2050.

In **passenger transportation**, the market for low-carbon light duty vehicles – electric, plug-in hybrid, and fuel cell – will grow from a small level today to over $600 billion in a deeply decarbonized 2050 energy system, while the market for conventional internal combustion engine LDVs will fall from $400 billion today to zero (Figure 17C).

In **freight transportation**, the market for lower carbon technologies such as compressed natural gas (CNG), liquefied natural gas (LNG), and hydrogen fuel cell HDVs, will grow to $80 billion in 2050, while the market for conventional HDVs will fall from $50 billion today to $40 billion in 2050 (Figure 17D). This substantial market for diesel HDVs in some applications that are expected to be difficult to replace with other technologies by 2050 will nonetheless feature high efficiency, low pollution diesel technologies, which may operate entirely or partly on bio-based renewable diesel.

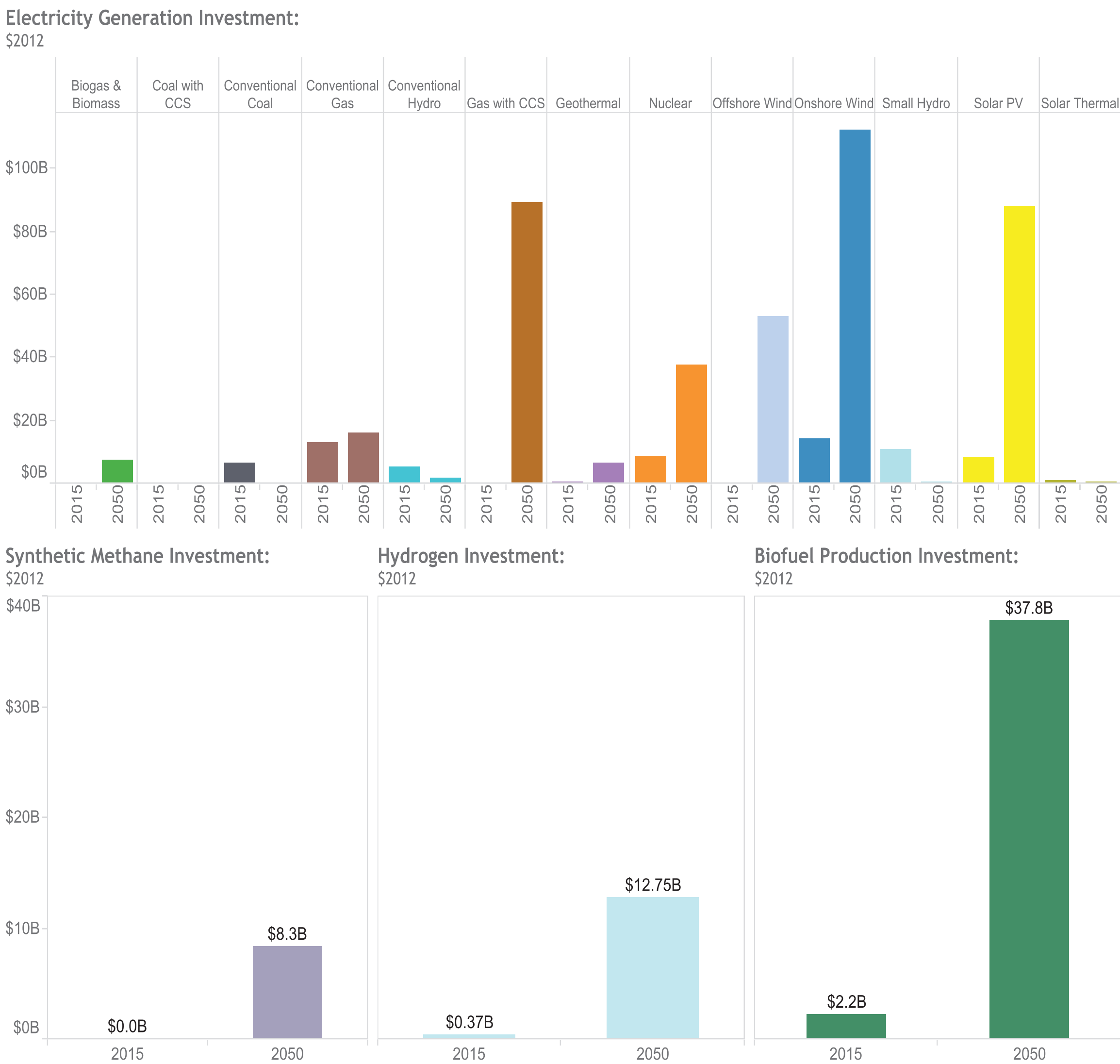
Figure 17. Annual Investment in Conventional and Low-Carbon Technologies in Buildings and Transportation, Current System versus Deeply Decarbonized System in 2050



Investment in low-carbon energy supplies will also increase dramatically. In **electricity**, as electrification of transportation and other sectors drives a doubling of electricity use while CO_2 emissions intensity is reduced to one-thirtieth of its present value, annual investment in generation will grow close to eight-fold, from $80 billion today to $630 billion in 2050 (Figure 18A). Almost all of the 2050 investment will be in low-carbon generation technologies – wind, solar, nuclear, and natural gas with CCS. Generation portfolios and investment differ by scenario, but all cases in the U.S. study show the same general features.

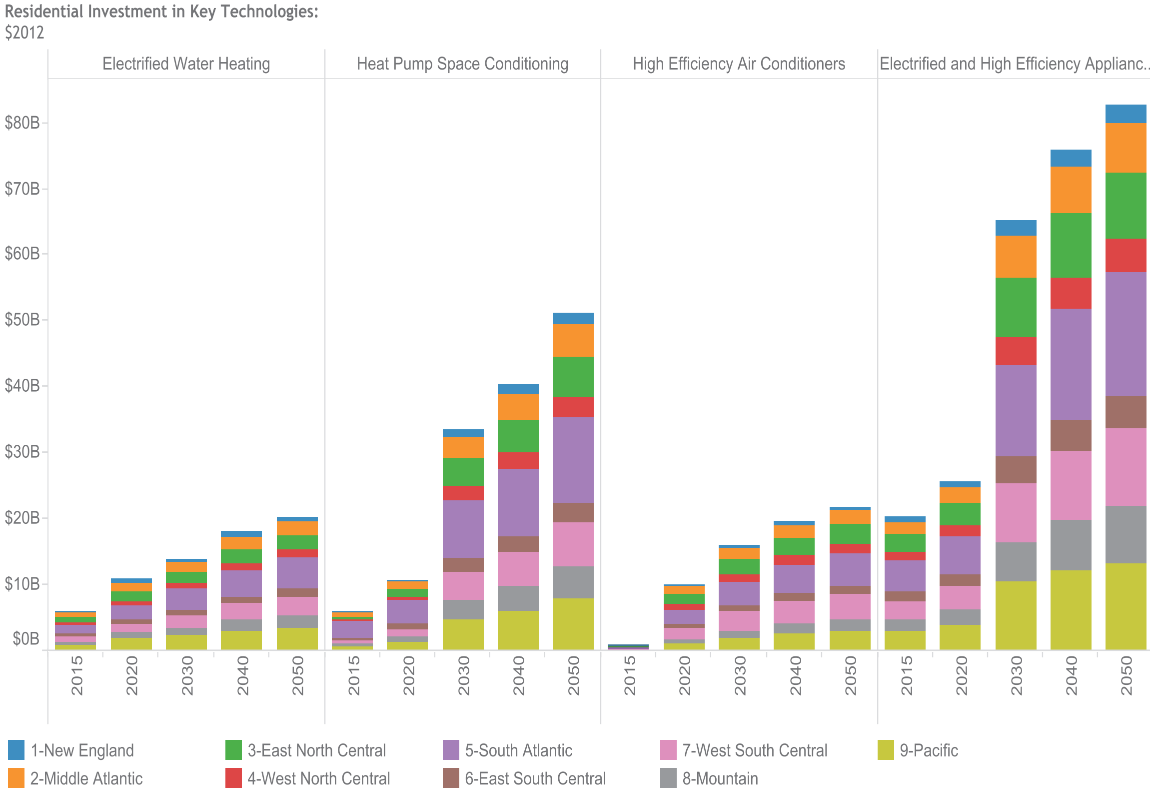
In **low-carbon fuels**, investment in production capacity for hydrogen and synthetic methane with grow from practically nothing today to more than $20 billion annually in 2050 (Figure 18B). Investment in biomass fuel production (renewable natural gas and renewable diesel) will grow from less than $200 million annually today to $4 billion in 2050.

Figure 18. Annual Investment in Conventional and Low-Carbon Technologies in Electricity Generation, Electric Fuels, and Biofuels, Current System versus Deeply Decarbonized System in 2050



Investment in energy efficient and low-carbon end-use technologies will expand rapidly and be widely distributed geographically. Figure 19 shows annual investment in residential sector electric water heaters, heat pump space conditioning, high efficiency air conditioners, and high efficiency appliances, at ten-year intervals for each of the nice U.S. census divisions. The U.S. has the opportunity to be the manufacturing base that provides these technologies.

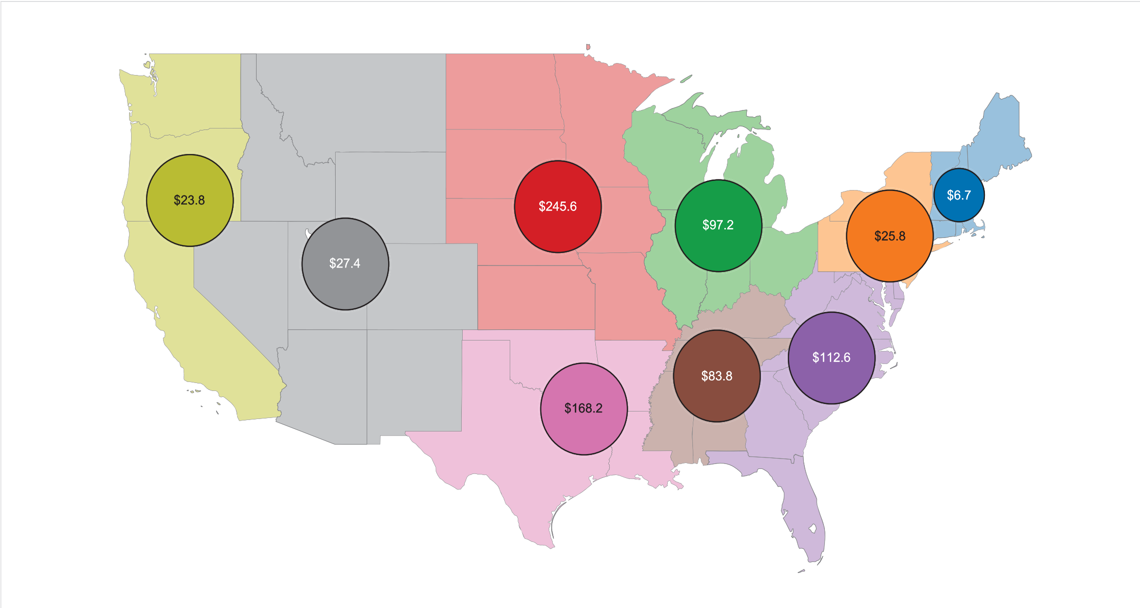
Figure 19. Annual Investment in High Efficiency Residential Technologies by Region, at 10-Year Intervals, for Mixed Case



Energy production in a deeply decarbonized system will be much decentralized geographically than today. The types of primary energy produced will be much more diverse (Figure 3), so that the term "energy production" will no longer be synonymous with fossil fuel extraction, and all regions will have an opportunity to become energy producers in some area, for example renewable generation. Investment in biomass production capacity of $130 billion will enable cumulative sales of biofuels of $800 billion by 2050 (Figure 20), with a wide geographic distribution, especially east of the Rocky Mountains. In every low-carbon scenario, in all nine U.S. census regions, investment in electricity generation is higher than in the reference case, and much higher than today (Figure 21).

Figure 20. Biomass Production Investment and Commodity Sales, Cumulative to 2050, Mixed Case

Cumulative 2015-2050 Biomass Commodity Payments:
$2012B



Cumulative 2015-2050 Biofuel Production Investment:
$2012B

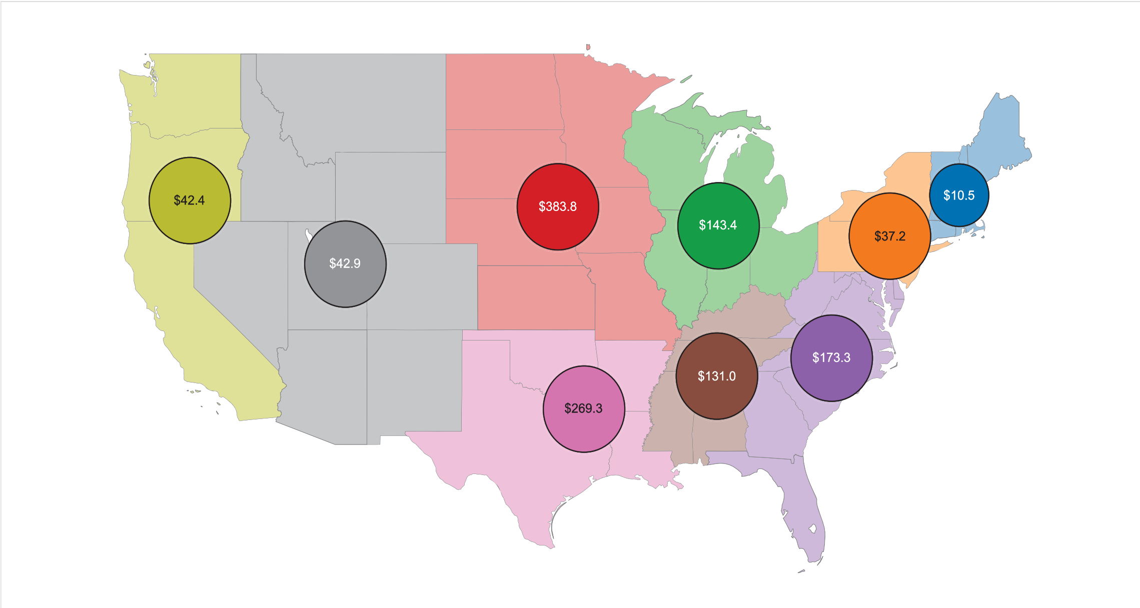
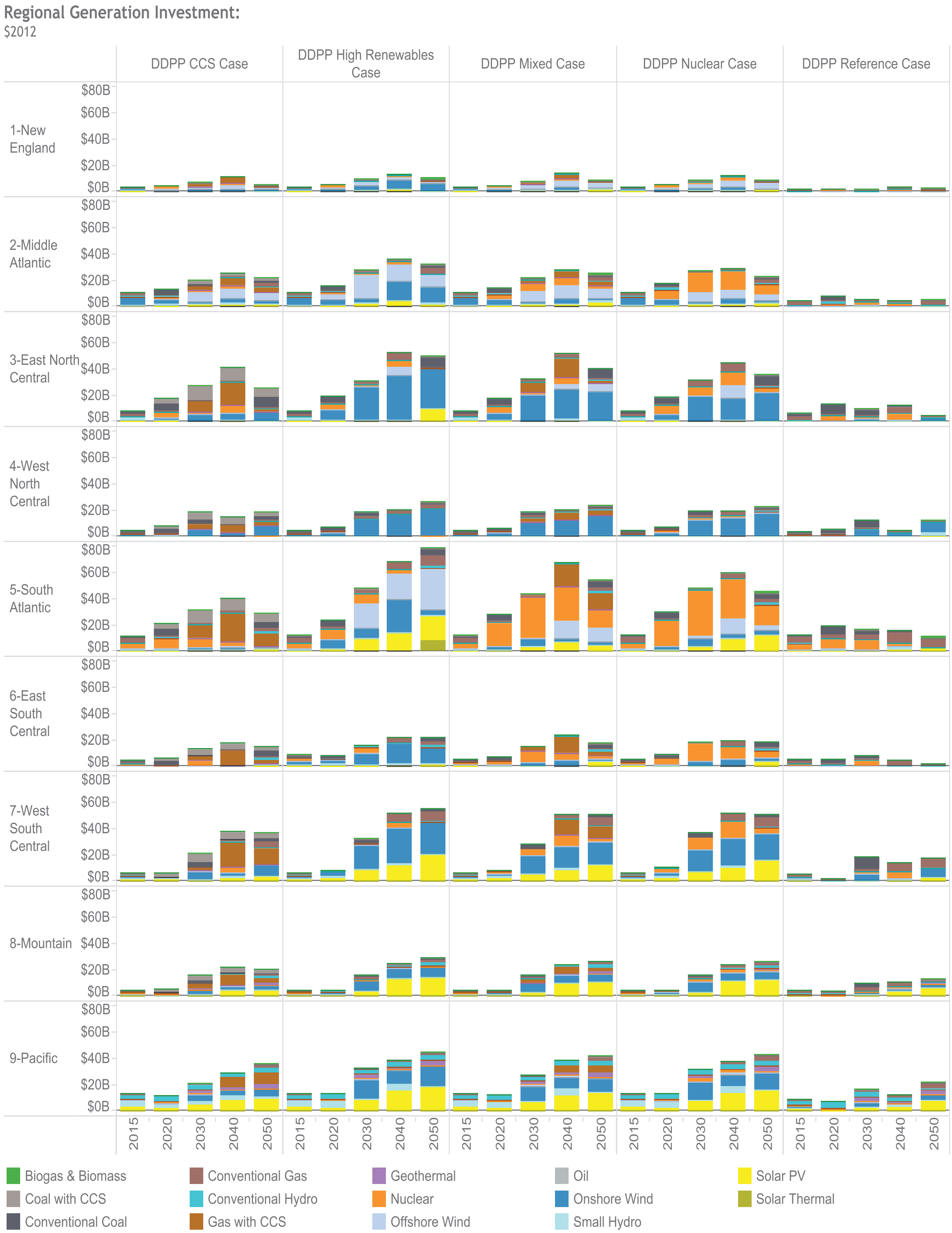


Figure 21. Annual Investment in Low-Carbon Generation by Region, at 10-Year Intervals, Reference Case and Four Deep Decarbonization Scenarios



D. Modernization, Competitiveness, and Jobs

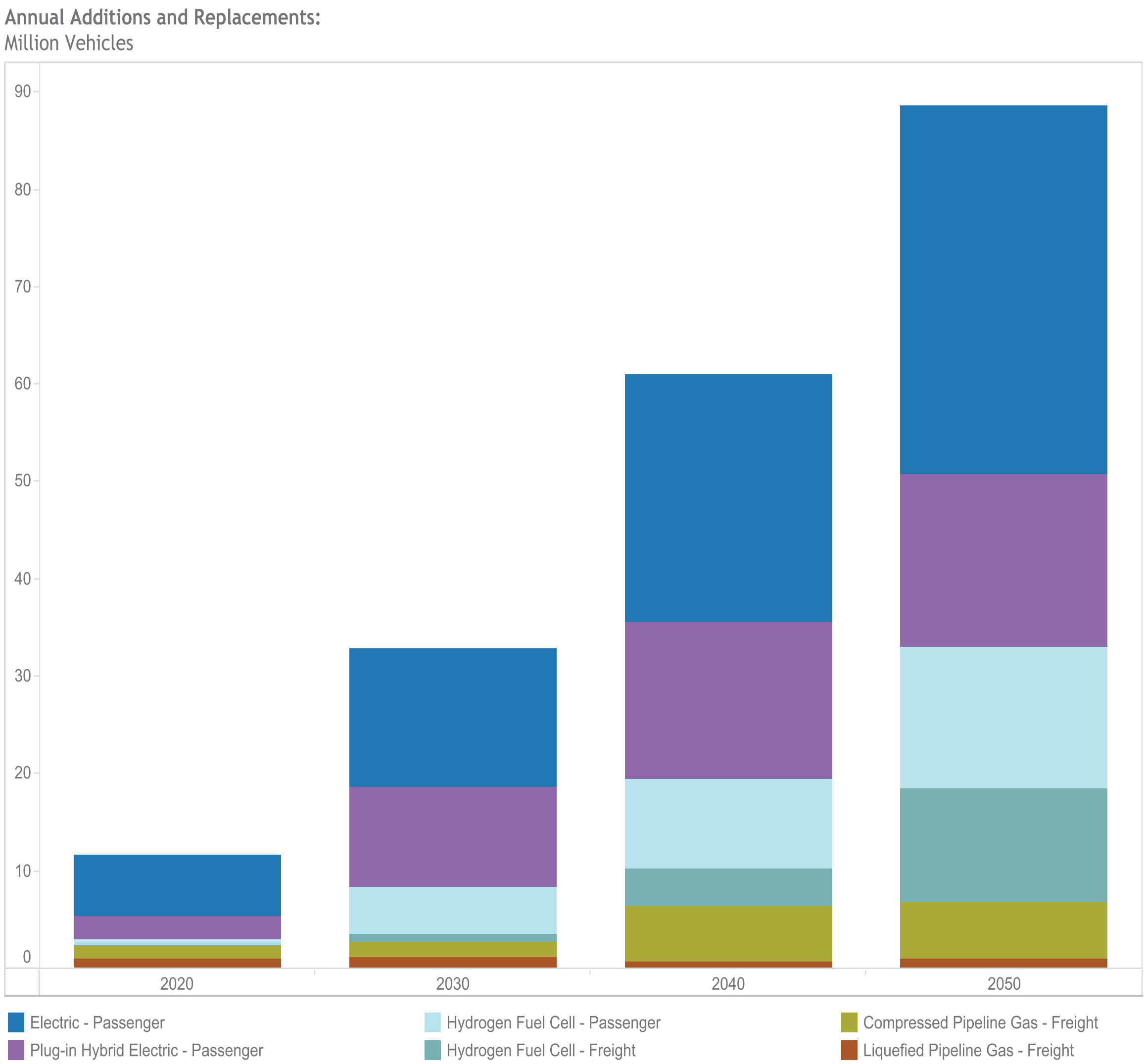
A High Tech Energy System

The deeply decarbonized energy system will be built on a sophisticated scientific and technological foundation. Nowhere is this more evident than the electricity grid, which will provide the majority of final energy in 2050. A wide variety of computer and information technology will be needed at all levels of the system to integrate intermittent generation and electric vehicles, intelligently control flexible loads and two-way flows in the distribution network, and maintain reliability and robust physical and cyber-security. Buildings will need a combination of high tech electric end-use equipment and widespread use of sensors and big data analytics to improve efficiency and flexibility. Biotechnology will be needed for developing low-impact feedstocks and to improve the efficiency of conversion processes. The frontiers for improving efficiency and lowering cost for batteries, fuel cells, and hydrogen lie in material science and nanotechnology.

The U.S. has a large competitive advantage in a high-tech, low-carbon energy world, due to its scientific and technology leadership in key fields, and also its institutional advantages in areas such as financial markets, government regulation, and public-private partnerships. The U.S. has a head start in the energy efficiency of its production processes and in the diversity and abundance of its energy resources, relative to some key global competitors. The stakes are high for the U.S. in continuing to press all these advantages, in order for its industries to become leaders in potentially **huge global markets.** To name just one example, annual sales of alternative vehicles could exceed 90 million by 2050 (Figure 22).

The economic winners in a low-carbon world will make products cheaper and better through high-tech processes, coordinated and efficient use of energy and materials, and clever use of information. The low-carbon transition provides an extraordinary opportunity for the U.S. to rebuild its industry on new terms, while also rebuilding its energy, transportation, and building infrastructure. With the right industrial, trade, R&D, and fiscal policies in place, **this transition will generate many desirable high technology, manufacturing, and building trades jobs**. The wider geographic distribution of energy production across the U.S. under deep decarbonization also provides an opportunity for new investment, businesses, and jobs in localities that don't currently have them.

Figure 22. Global Annual Sales of Alternative Vehicles Under Deep Decarbonization to 2050



Source: *DDPP Global Synthesis Report 2015*

III. Energy Transition

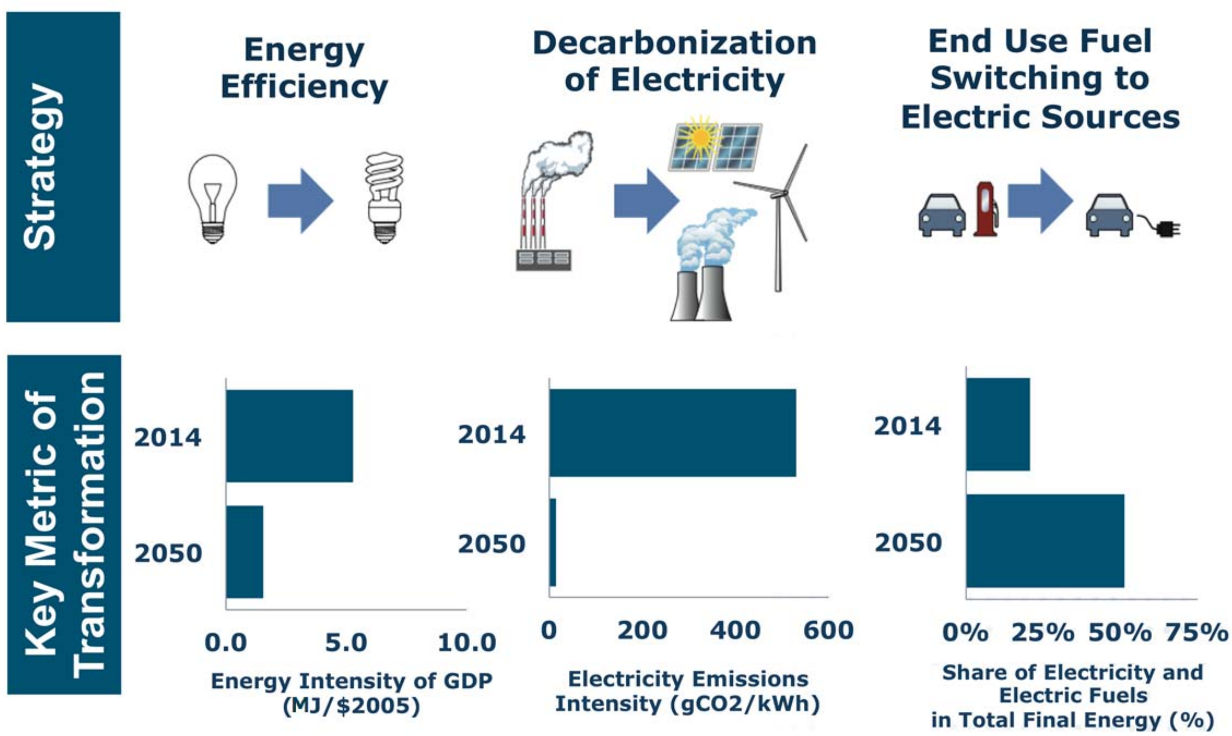
A. The Physical Transition: Metrics, Outcomes, Rates of Change

The Three Pillars

The transition to a low-carbon energy system rests on three pillars: (1) highly ***efficient end use*** of energy in buildings, transportation, and industry; (2) ***decarbonization*** of electricity and other fuels; and (3) ***fuel switching*** of end uses from high-carbon to low-carbon supplies, ***primarily electrification***. All three of these pillars are needed together to achieve the 2050 decarbonization goal.

Metrics for the three pillars are shown in Figure 23. The dramatic changes in these metrics demonstrate the extent of the low-carbon transformation required. The share of end-use energy from electricity or electrically-produced fuels such as hydrogen will need to increase from under 20% in 2010 to over 50% in 2050, displacing most fossil fuels. The carbon intensity of electricity will need to be reduced by a startling 97%, from more than 500 g CO_2/kWh in 2014 to less than 15 g CO_2/kWh in 2050. Energy intensity of GDP will need to decline by 70% over this period, with final energy use reduced by 20% from 68 to 54 EJ despite a forecast population increase of 40% and a 166% increase in GDP.

Figure 23. Three Pillars of Deep Decarbonization



Main 2050 Transitions by Sector

Scientists believe that limiting global warming to 2°C or less will require reaching net zero greenhouse gas emissions by around the year 2070. By 2050, that goal should be largely accomplished, and the stage set for moving to net zero emissions. This requires applying the "three pillars" strategies across the U.S. economy. Table 2 describes the transitions that must take place in each of the major sectors by 2050, along with key metrics indicating the extent of that transformation.

Table 2. Key Energy Transitions by Sector

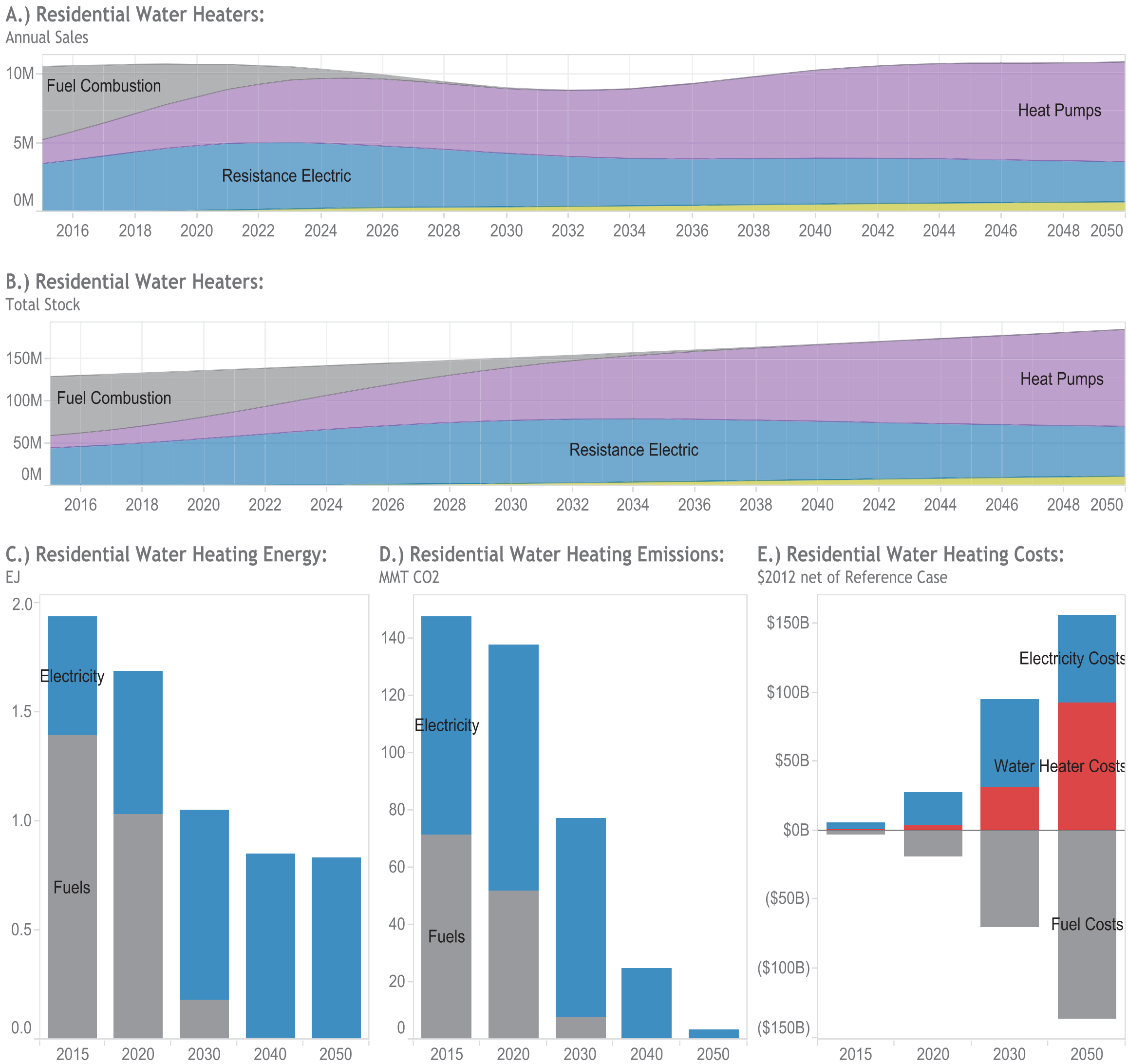
Sector	Current Energy System	Deep Decarbonized Energy System	Key Metrics in 2050
Electricity	Coal and natural gas dominated	Renewable, nuclear, or CCS	Double output while reducing CO_2/kWh 30x
Transportation	Oil dominated	Electricity, hydrogen, CNG, LNG, biodiesel	Fuel economy >100 mpg equivalent
Buildings	Natural gas and oil dominate heating	Electrification, end-use efficiency	Building energy use >90% electrified
Industry	Fossil fuel dominated	Electrification, CCS, efficiency, low-carbon fuels	Double efficiency, >40% electrification

Rates of Change

In addition to the key metrics that must be achieved by 2050, the rate at which current infrastructure and equipment must be replaced by low-carbon alternatives in order to achieve those targets can be specified. The U.S. analysis, taking into account equipment stocks, vintages, and economic lifetimes, yields benchmarks for the minimum required penetration rate of many technologies, from wind generators to fuel cell vehicles, at different points in time between now and 2050.

As an example, in the low-carbon transition for residential water heaters, units that directly combust fossil fuels are displaced by electric resistance heating and electric heat pumps when they come to replacement time. Figure 24A shows the share of annual sales of each technology, and Figure 24B shows the resultant mix of technologies in the stock over time, achieving 100% electric by 2040.b Figure 24C shows the final energy mix, which is all-electric by 2040. Figure 24D shows emissions approaching zero in 2050 as the carbon intensity of electricity is reduced over time. Figure 24E shows expected additional incremental cost of electric water heaters and electricity purchases, along with expected savings from avoided fuel purchases enabled by that equipment.

Figure 24. Residential Water Heater Transition, Mixed Case



B. Guidance for Policy

Five Principles of the Energy Transition

Five high-level observations on the low-carbon energy transition provide crucial touchstones for what policy should focus on if it is to achieve deep decarbonization. The observations arise from the results of the U.S. study, and are not a repetition of conventional wisdom. These principles of a low-carbon transition are unlikely to be incorporated into policy discussions unless there is a conscious effort to bring a 2050 perspective to bear on current decisions.

1. **"It's all about the transformation":** Deep decarbonization requires a sustained focus on transformation of the energy system by 2050. Policies that produce incremental improvements without facilitating transformation can result in dead ends for long-term emission reductions.

2. **Early retirement is not required, but timely replacement is:** Deep decarbonization can be achieved in the U.S. without retiring equipment before the end of its economic lifetime. However, when replacement time arrives, the new equipment must be consistent with the low-carbon transition path.

3. **Fundamentally new technologies are not required, but technical progress is:** Deep decarbonization can be achieved in the U.S. using existing commercial and near-commercial technologies. But policy must facilitate technical progress and volume production to keep transition costs low.

4. **Deep emission reductions require cross-sector coordination:** The further decarbonization proceeds, the more emissions reductions depend on interactions across sectors, e.g. transportation and electricity generation. Coordination and joint planning are required for best outcomes.

5. **Network supply of low-carbon energy requires a sustainable business model:** In a deeply decarbonized system, the majority of final energy is delivered through the electric grid and (decarbonized) natural gas pipeline. Policy makers must pay attention to the changing role of regulated utilities in the low-carbon transition, and the need for a sustainable business model.

"It's All About the Transformation"

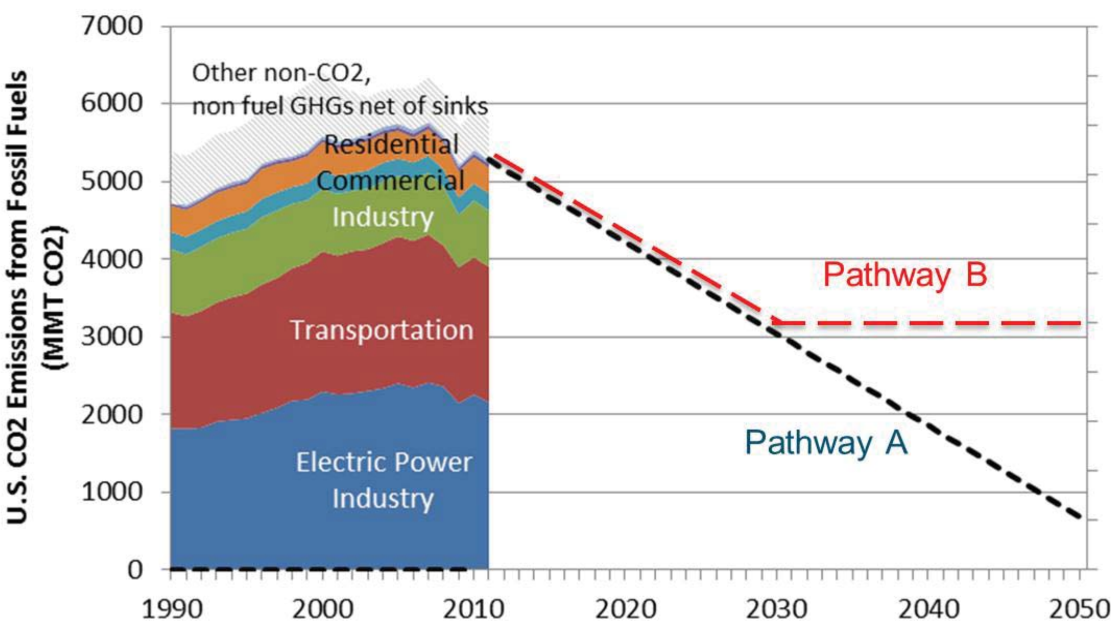
Deep decarbonization in the U.S. requires the economic intensity of GHG emissions to decrease 8% per year, and per capita emissions to decrease 5.5% per year. The U.S. analysis shows that these ambitious rates of change can be achieved technically and at an affordable cost, but it does required a sustained transformation of energy supply and demand infrastructure over the full period of time out to 2050 (and beyond, to net zero emissions by around 2070).

Policies that produce incremental improvements without facilitating transformation can result in technology lock-in and infrastructure build-outs that are dead ends from the standpoint of long-term emission reductions, meaning that economy-wide emissions decline for a period, but then reach a plateau beyond which further emission reductions don't occur or are difficult to achieve without early retirement.

A hypothetical dead-end emission trajectory situation is illustrated in Figure 25. Pathway A represents a linear trajectory from 2010 emissions of energy-related CO_2 to the 2050 target level. Pathway B represents policies that reduce emissions in the short-term but don't lead to deep decarbonization in the long-term.

Some examples of potential dead-ends include a focus on building energy efficiency without end-use electrification, improvement in internal combustion engine (ICE) economy without widespread deployment of electric or fuel cell LDVs, and a coal to conventional natural gas transition in electric generation without the necessary build-out of renewable, nuclear, or CCS generation.

Figure 25. Illustrative Deep Decarbonization Trajectory and "Dead End" Trajectory



Early Retirement Is Not Required, But Timely Replacement Is

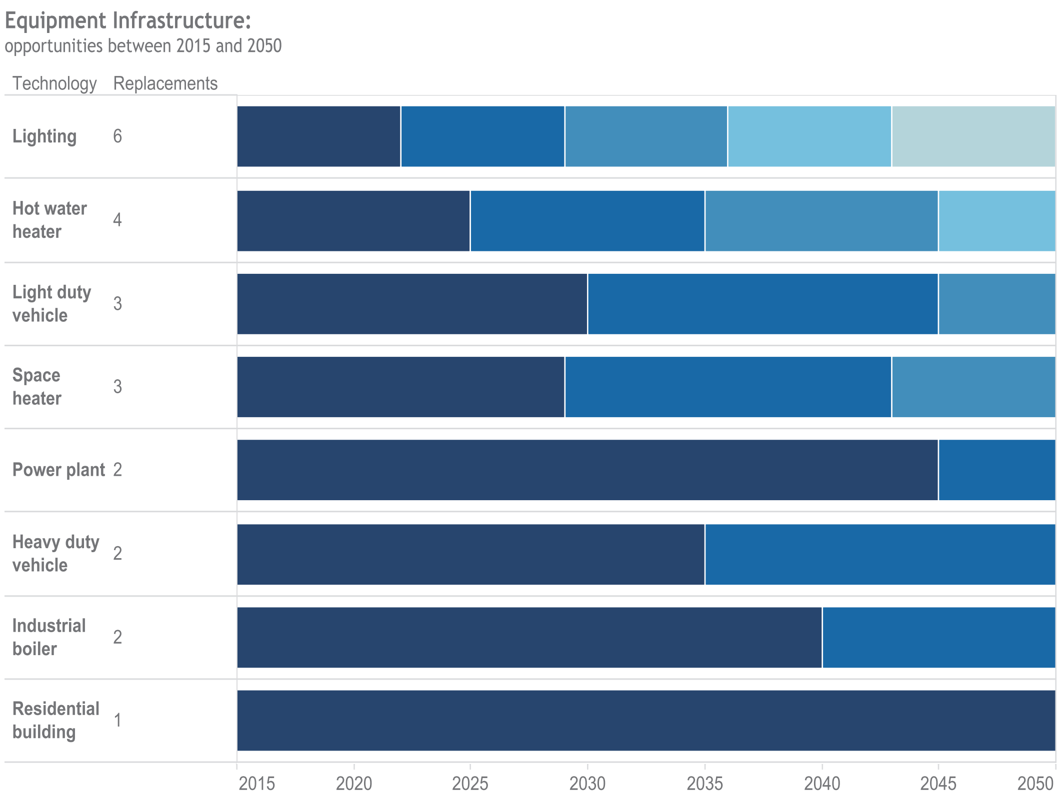
Deep decarbonization is fundamentally a sustained transition to efficient and low-carbon equipment and infrastructure. This can be achieved in the U.S. without retiring existing equipment and infrastructure before the end of its economic lifetime, which greatly reduces the expected cost of the transition.

However, the economic lifetime of most energy supply and end-use equipment is of the same order of magnitude as the time remaining between now and mid-century. As a consequence, there are four or fewer natural replacement cycles for most energy-related equipment, and for some of the most important types, such as electric power plants and industrial boilers, there is at most only one cycle. This is illustrated in Figure 26.

While early retirement can be avoided in the U.S. (in part because of the age of U.S. infrastructure, which is not necessarily universal across countries), it is also true that when replacement time arrives, the energy and emissions characteristics of the new equipment installed must be consistent with the low-carbon transition path.

Put differently, failure to replace retiring infrastructure and equipment with efficient and low-carbon successors will either lead to failure to achieve deep decarbonization by mid-century, or will subsequently require early retirements of the replacement equipment to meet the target.

Figure 26. Lifetimes Until Replacement for Key Equipment and Infrastructure



Fundamentally New Technologies Are Not Required, But Technical Progress Is

Deep decarbonization can be achieved in the U.S. using existing commercial and near-commercial technologies, meaning technologies that exist at significant scale in the field. Technologies that are *not required* in order for the U.S. to meet the 80% by 2050 target include such widely touted prospects as Gen IV nuclear, deep offshore wind, advanced geothermal, advanced cellulosic ethanol, advanced biodiesel, and CCS with greater than 90% capture rate. The development of some of these technologies may reduce costs and provide other benefits, but U.S. ability to reach the target does not depend on them. Table 3 illustrates the conservative assumptions about technology readiness underlying the U.S. deep decarbonization scenarios.

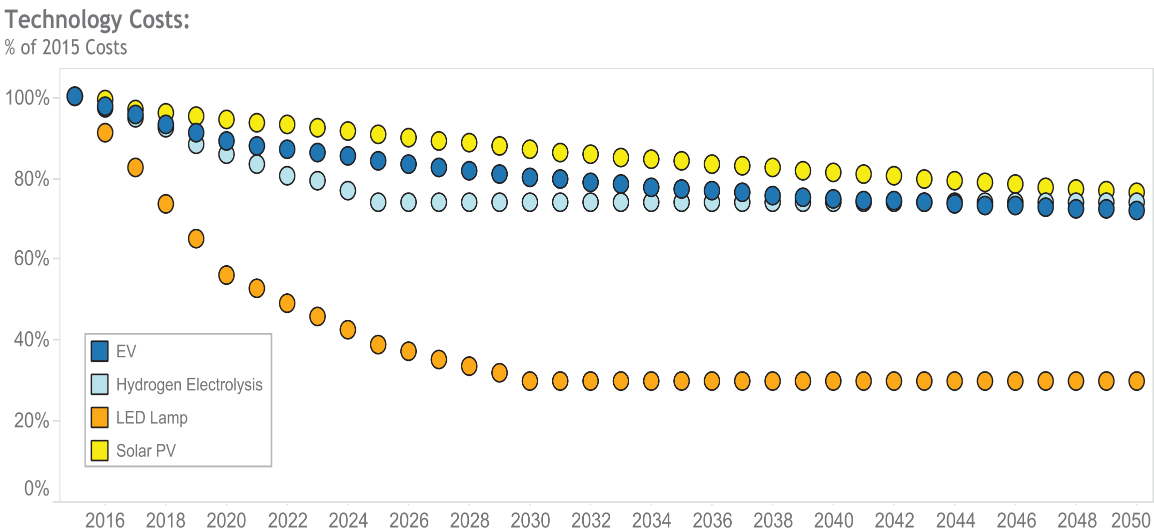
Table 3. Technologies Included in Four U.S. Deep Decarbonization Scenarios

	Included in 2050 Scenario?			
Technology	Mixed	Renewables	CCS	Nuclear
CCS for generation, 90% capture	Y	N	Y	N
CCS for generation, >90% capture	N	N	N	N
Nuclear Gen III	Y	Y	Y	Y
Nuclear Gen IV	N	N	N	N
Solar PV	Y	Y	Y	Y
Concentrating solar power	Y	Y	Y	Y
Onshore wind	Y	Y	Y	Y
Shallow offshore wind	Y	Y	Y	Y
Conventional geothermal	Y	Y	Y	Y
Deep offshore wind	N	N	N	N
Advanced geothermal	N	N	N	N
CCS for industry, 90% capture	Y	N	Y	N
CCS for industry, >90% capture	N	N	N	N
H_2 from electricity generation	Y	Y	N	Y
H_2 from natural gas reforming with CCS	N	N	Y	N
Continental scale H_2 distribution pipeline	N	N	N	N
Power-to-gas - SNG from electricity generation	Y	Y	N	N
Biomass conversion to SNG by AD or gasification	Y	Y	N	Y
Fischer-Tropsch liquid biofuels, 35% efficiency	N	N	Y	Y
Advanced cellulosic ethanol	N	N	N	N
Advanced biodiesel	N	N	N	N
Advanced bio-jet fuel	N	N	N	N
Biomass generation w CCS	N	N	N	N
Fuel cell LDVs	Y	N	N	Y
Battery electric LDVs	Y	Y	Y	Y
CNG passenger and light truck	N	N	N	N
LNG freight	Y	Y	Y	N
Fuel cell freight	N	N	N	Y
Heat pump HVAC	Y	Y	Y	Y
LED lighting	Y	Y	Y	Y
Heat pump electric water heat	Y	Y	Y	Y
Maximum efficiency shell for new buildings	Y	Y	Y	Y

Maximum efficiency shell for retrofits	N	N	N	N
Industrial process redesign	N	N	N	N
Manufactured product redesign	N	N	N	N

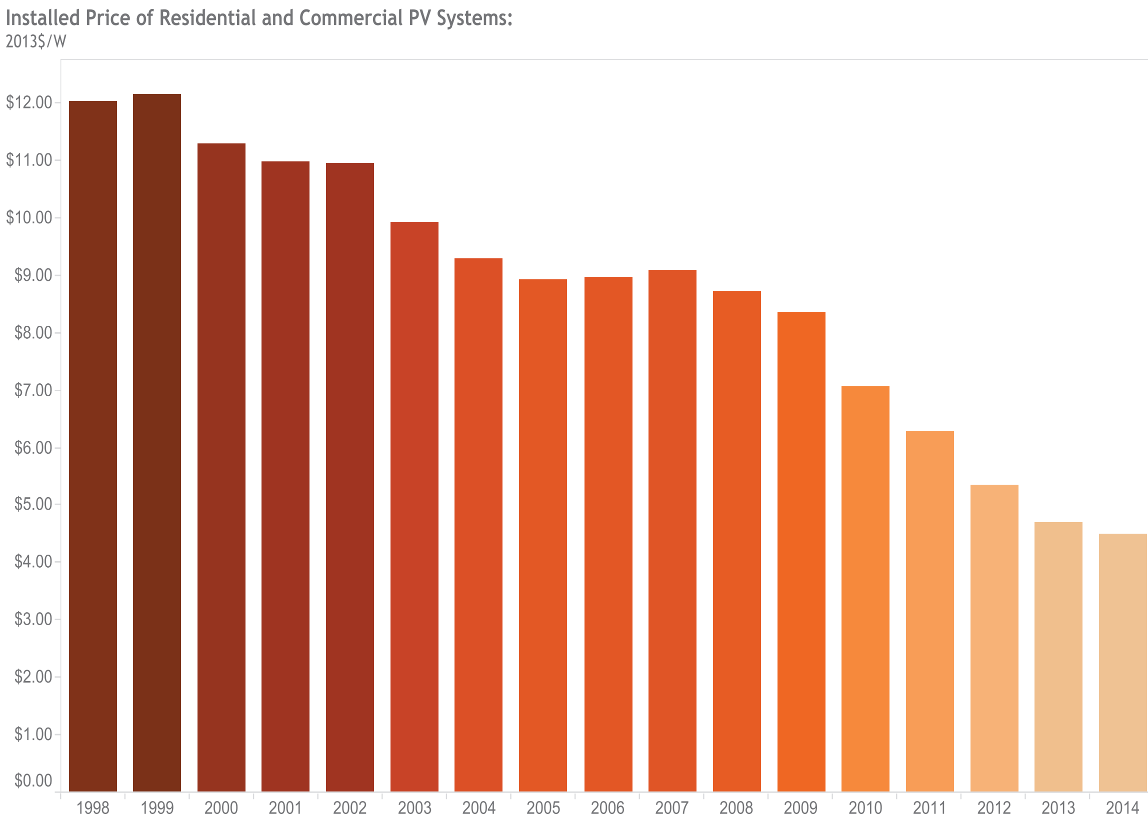
What is required, however, is steady progress in current technologies that facilitates rapid and widespread consumer adoption, high volume production, and corresponding price declines that keep transition costs low. As an illustration, Figure 27 shows cost trajectory assumptions in the U.S. study for key technologies such as solar PV, electric vehicles, LED lights, and hydrogen electrolysis. To achieve relatively low overall transition costs, the combination of R&D, market forces, and policy must result in cost reductions at least as significant as shown here, 20-30% below current for solar PV, EVs, and hydrogen electrolysis, and 70% for LED lights.

Figure 27. Technology Cost Trajectories Assumed for Solar PV, Electric Vehicles, Hydrogen Electrolysis, and LED Lamps, 2015-2050



Price declines assumed in the U.S. analysis over time as a function of technology maturity and market potential are not unreasonable. Falling cost trajectories as a result of technological learning that occurs as production volumes increase are common in many industries. For example, in the semiconductor industry "Moore's Law" has long been a widely recognized rule of thumb for projecting future prices as a function of cumulative global production. This phenomenon has also occurred in the energy industry, long ago in the case of many conventional technologies, and much more recently in the case of new low-carbon technologies. Figure 28 shows a 60% decline in historical prices of installed solar PV systems in the U.S. from 1998 to 2014.

Figure 28. Historical Prices for Installed Solar PV Systems, 1998-2014



Source: *(LBNL, 2015)*

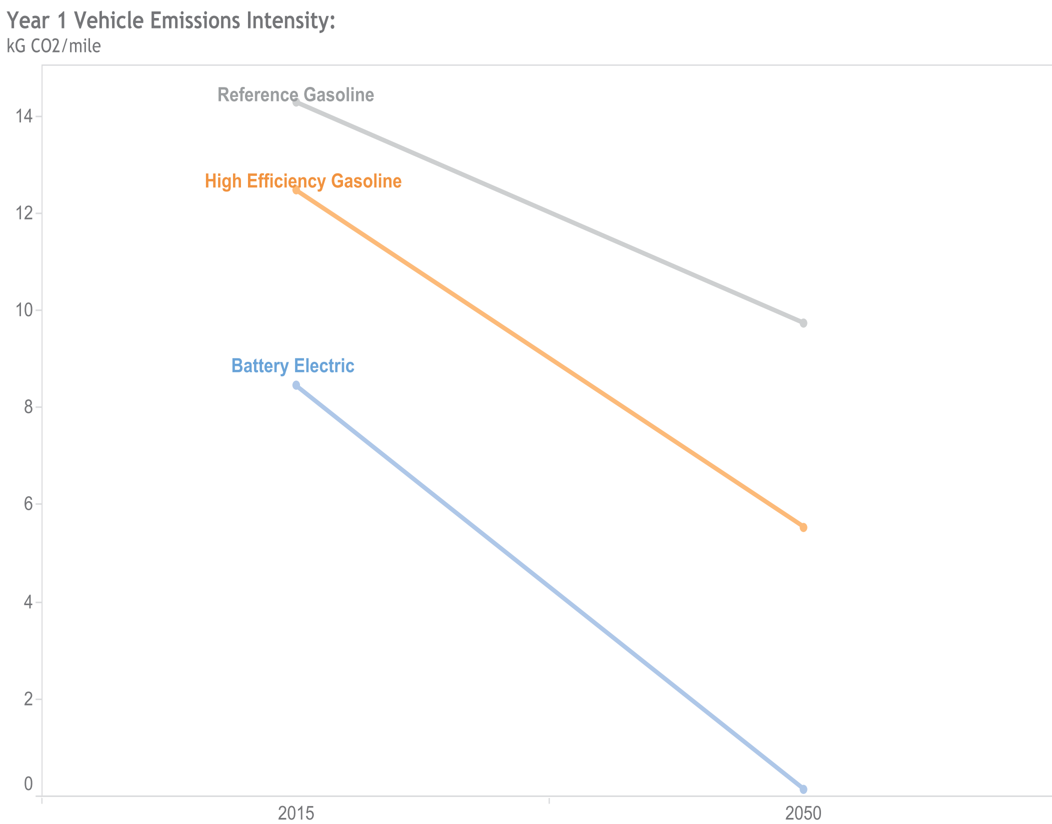
Deep Emission Reductions Require Cross-Sector Coordination

Decarbonization is an interplay between the carbon intensity of final energy supply and the fuel type and energy efficiency of end-use equipment. In early stages of decarbonization, the interactive impact between these factors on overall emissions is modest, and the effect of single-fuel strategies (e.g. higher efficiency use of the same fossil fuel supply) can be similar to that of fuel switching to lower carbon sources. As deep decarbonization proceeds, however, fuel switching to lower carbon sources becomes the paramount factor in lowering emissions.

This can be visualized in the case of LDVs (Figure 29). The difference in emissions intensity of efficient ICE vehicles and EVs on an average grid is significant but not overwhelming (around 30%) in 2015. By 2050, as grid electricity approaches full decarbonization, the difference is like night and day, with EV emission intensities 30 times lower. From this perspective, ICE-only emissions strategies are a dead end.

Achieving the full emissions benefit of parallel investments in supply side carbon intensity reduction and demand side fuel switching requires well-coordinated timing of deployment, for example ensuring the readiness of charging infrastructure for EVs in proportion to demand. This indicates the need for joint planning and well coordinated policy signals (pricing and/or quantity) across economic sectors that traditionally have had little to do with each other from either a market or regulatory perspective, such as electric power and transportation.

Figure 29. Vehicle Emission Intensities for Reference Case Gasoline Engine, High Efficiency Gasoline Engine, and Battery Electric Vehicle



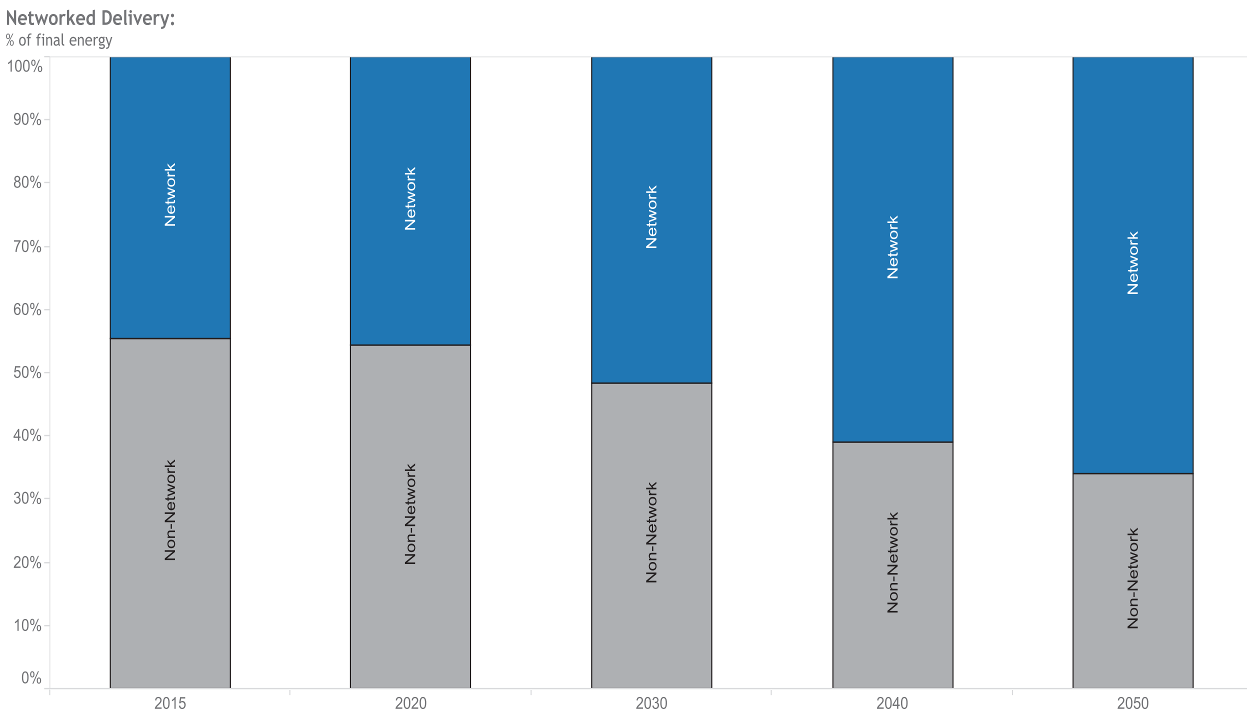
Network Supply of Low-Carbon Energy Requires a Sustainable Business Model

In a deeply decarbonized system, the majority of final energy will be delivered to end users either in the form of low-carbon electricity or partly decarbonized pipeline gas (Figure 30). This energy is supplied by network providers – the electric power grid and the natural gas pipeline. Network providers have traditionally been regulated (or public) electric and natural gas utilities.

The role of network providers in implementing low-carbon policies is potentially critical, since they would constitute the main institutional vehicles for acquiring most of the large, long-lived, high capital cost equipment and infrastructure required for deep decarbonization. Policy makers who currently pay little attention to utilities will need to readjust their focus to ensure that the regulatory signals relevant to procurement, rate-making, and cost allocation are compatible with the needs of the low-carbon transition.

The demands on regulated utilities will grow heavier as deep decarbonization proceeds, and the traditional balancing act between reliable service provision, environmental performance, and cost containment will become more critical to decarbonization outcomes. The current practices and business models of regulated utilities (and/or their unregulated suppliers) will be challenged – concrete examples being their adequacy for dealing with higher levels of solar PV distributed generation, and decreasing capacity factors for natural gas generators.

Figure 30. Final Energy Delivery, Network versus Non-Network Delivery to End User, Current and 2050 Deep Decarbonization



IV. Policy Pathways

The U.S. deep decarbonization analysis supports three fundamental conclusions regarding GHG mitigation policy:

- Achieving deep decarbonization of the U.S. energy system by mid-century is technically feasible and economically affordable. The policy question is not if deep decarbonization should be pursued, but how best to accomplish it.

- Deep decarbonization entails a transformation of energy supply and end-use infrastructure, in which incumbent technologies predicated on uncontrolled fossil fuel combustion are replaced by efficient and low-carbon technologies. The task of policy makers is to create conditions for that transformation.

- Most key infrastructure has an economic lifetime on the same order as the time remaining until mid-century. Near-term policy and investment decisions must be consistent with the transformation path, or else risk missing the target, stranded assets, and higher costs.

This chapter continues four sections to illuminate the considerations involved in constructing a successful policy approach to deep decarbonization:

Section A. What policies must accomplish. Policy formation must begin with an understanding of what policies must accomplish – the physical, financial, and institutional outcomes required by deep decarbonization.

Section B. The policy landscape. Effective policy requires fitting the available policy tools to the policy landscape, which differs by jurisdictional level, sector, and region.

Section C. Rethinking common assumptions. Effective policy needs to start with questions, observations, and analysis. It is important to be aware of the limitations of many conventional policy prescriptions and analytical approaches with regard to deep decarbonization.

Section D. Rethinking current policy. Current policies such as the Clean Power Plan, the Renewable Fuel Standard, CAFE standards, and building energy codes should be re-evaluated in terms of what will be required for deep decarbonization in the electricity, fuel supply, transportation, and building sectors.

A. What Policies Must Accomplish

Climate mitigation policies are not an end in themselves. Policy design must begin not as a theoretical exercise, but with an understanding of what policy needs to accomplish, namely the physical, financial, and institutional outcomes required by deep decarbonization. The key policy objectives emerging from the U.S. 2050 study are described in this section, beginning with the summary list below.

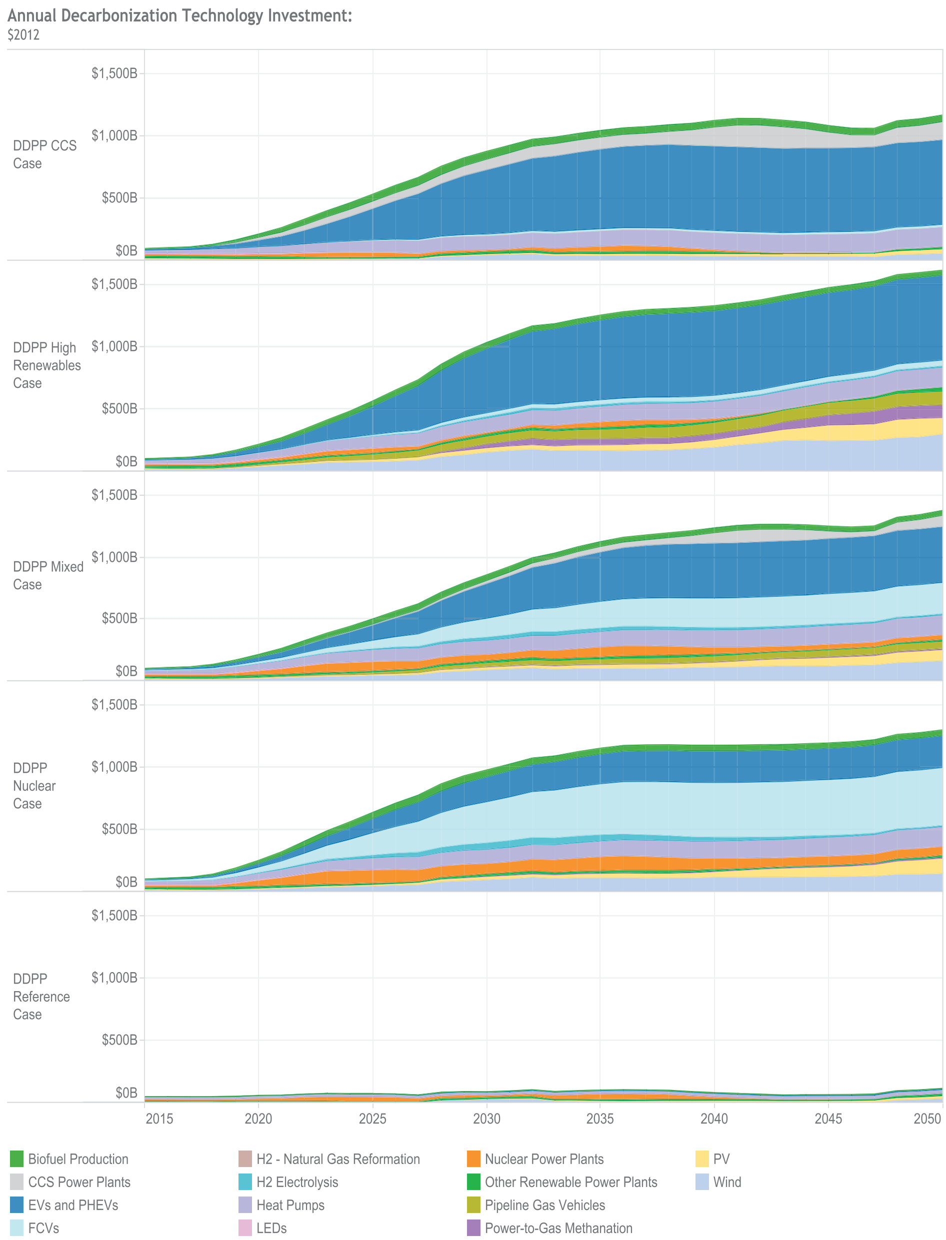
Key Policy Objectives

- Anticipate investment needs and build a suitable investment environment
- Incorporate future carbon consequences in current purchasing decisions
- Create stable drivers for sustained long-term transitions
- Develop institutional structures for coordination across sectors
- Integrate supply and demand-side planning and procurement
- Create the right kinds of competition
- Enable the required rates of consumer adoption
- Catalyze the needed cost reductions in key technologies
- Limit cost increases faced by consumers
- Minimize inequitable distributional effects

Anticipate Investment Needs and Build a Suitable Investment Environment

Across all U.S. deep decarbonization scenarios, the total annual investment requirement for low-carbon and efficient technologies rises from less than $100 billion today to over $1 trillion in about 20 years (Figure 31). This is not large relative to total investment in a much larger 2030s economy, and financial markets can readily supply this level of capital if returns are adequate and mechanisms are in place. To ensure that these conditions are met, investment needs must be anticipated and a suitable policy framework constructed. A policy framework that achieves the objectives laid out in the rest of this chapter will provide most of the enabling conditions for adequate investment.

Figure 31. Annual Investment Cost for Key Low-Carbon Technologies, All U.S. Deep Decarbonization Scenarios

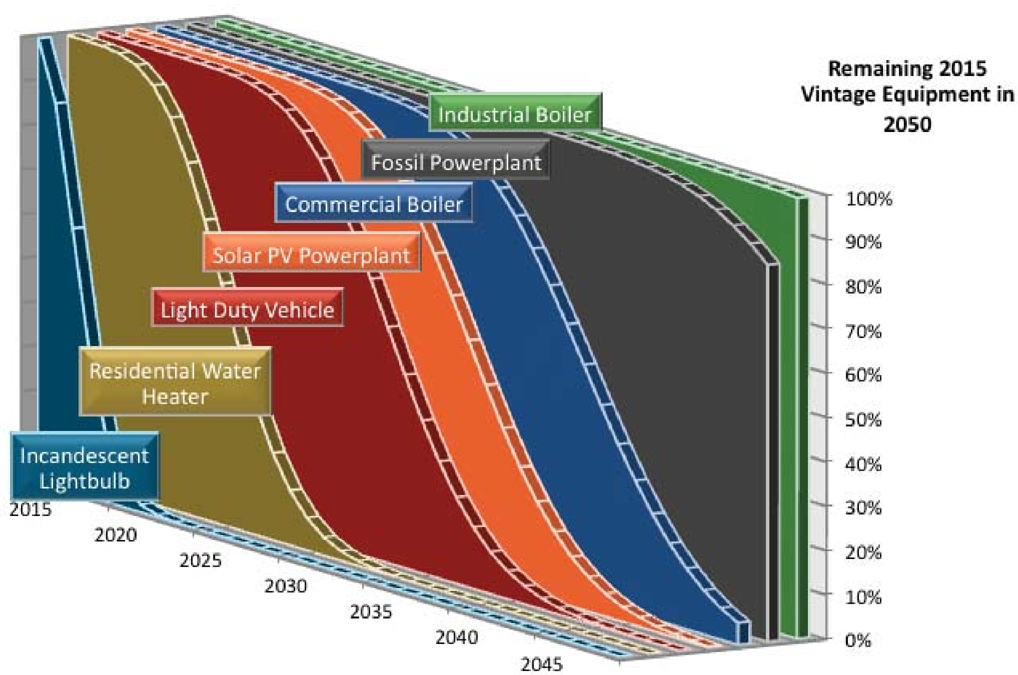


Incorporate Future Carbon Consequences In Current Purchasing Decisions

A key finding of the U.S. 2050 study is that deep decarbonization can be achieved by replacing existing equipment and infrastructure at the end of its economic lifetime, but that failure to replace it with sufficiently low-carbon equipment risks either missing emission reduction goals or early retirement. Much of the most important equipment and infrastructure is long-lived, with lifetimes on the order of the time remaining between now and 2050. Put differently, this means that for many kinds of equipment and infrastructure installed today, a substantial amount of it may still be in service at mid-century (Figure 32).

For a natural replacement strategy to succeed, current purchasing decisions for long-lived equipment and infrastructure must incorporate future carbon consequences. It is not obvious that currently proposed carbon pricing schemes will achieve this outcome, as the low-carbon replacements for many long-lived items – for example, electric industrial boilers – fall high on a marginal abatement cost curve based on current energy costs and electricity emissions intensities. "Working up the supply curve" based on a forward looking perspective could lead to emission reduction dead ends. The alternative needed is to incorporate back-casting into purchasing decisions, through pricing, emission standards, or other approaches.

Figure 32. Survival Curves for Equipment Important for Carbon Emissions

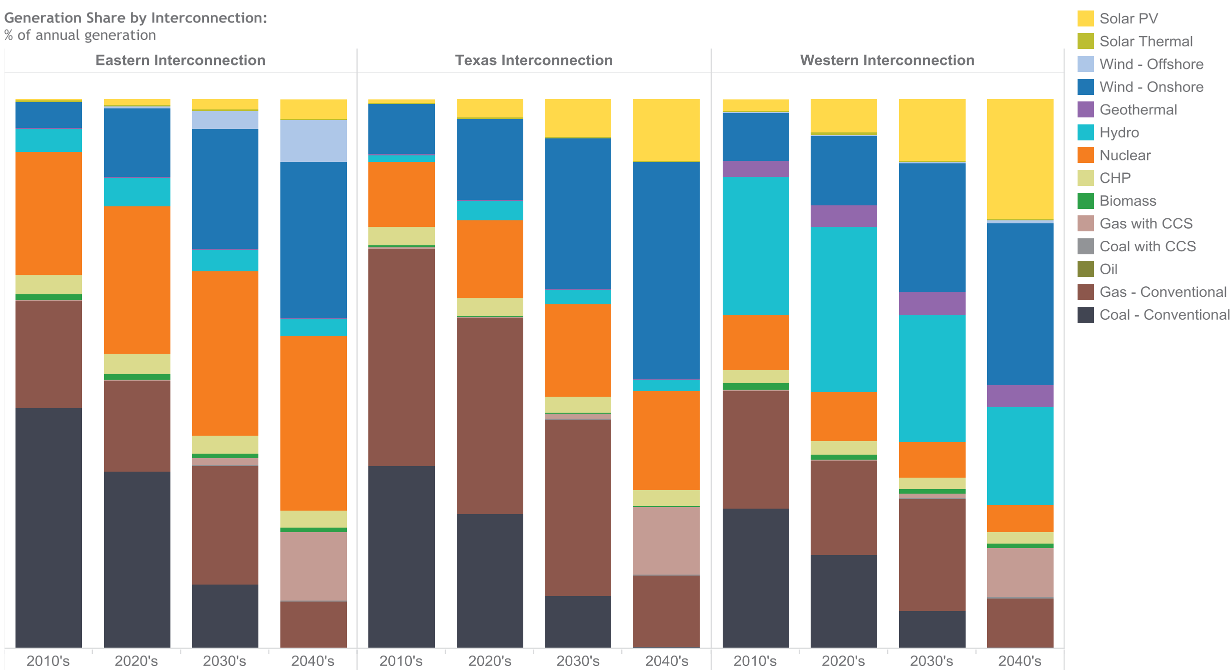


Create Stable Drivers for Sustained Long Term Transitions

A corollary to the need for timely replacement of infrastructure and equipment with low-carbon versions is the need for sustaining that approach over a time horizon of several decades. Decarbonization of the electricity sector provides a good example, as uncontrolled fossil generation is retired from the system and replaced with low-carbon generation (Figure 33).

Simultaneously expanding electricity supply and increasing the share of low-carbon generation implies not a one-time whirlwind of new purchases but a steady procurement process over three decades based on stable policies and stable incentives for investors, utilities, and developers of generation and transmission resources. It will also require consistent and streamlined treatment of siting and other regulatory processes. Ad hoc decision-making and inconsistent incentives will create serious obstacles to a sustained long-term transition.

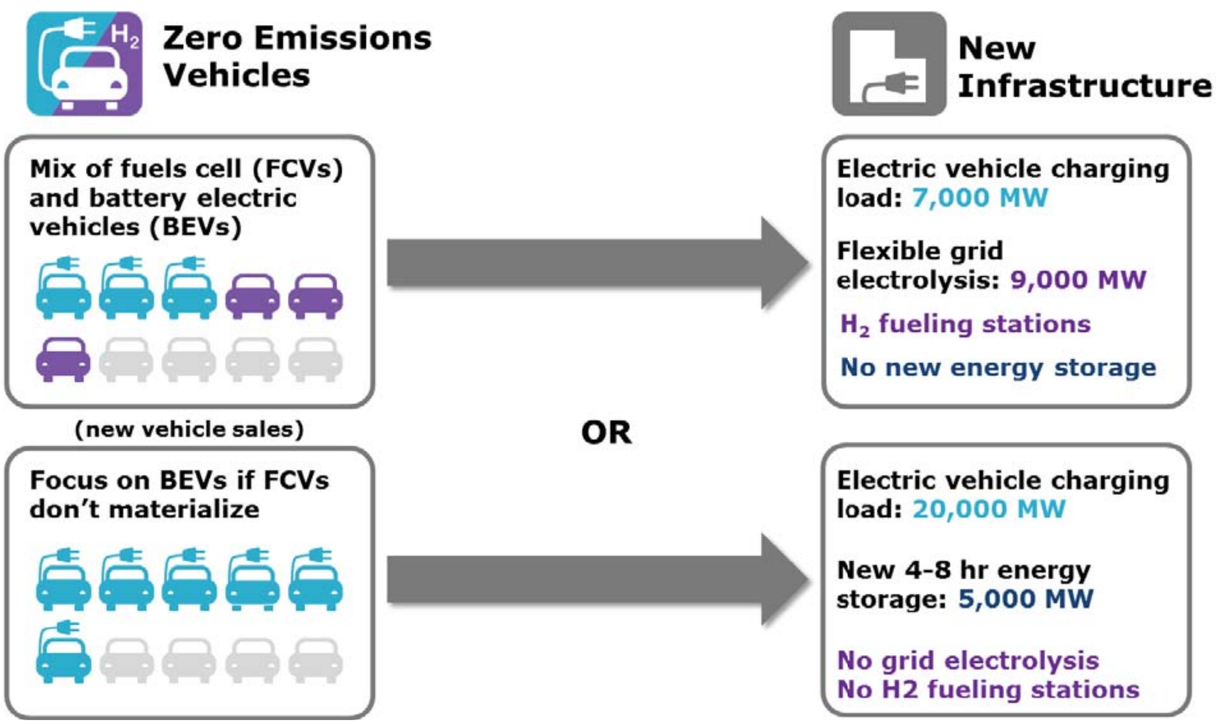
Figure 33. Generation Mix by Decade for the Three U.S. Interconnections



Develop Institutional Structures for Coordination Across Sectors

Cross-sector interactions will become increasingly important for both emissions reductions and costs in a low-carbon transition. Many cross-sector interactions that are of little significance in the current system will become central concerns in the future. For example, California will soon face decisions that link choices between fuel cell and electric vehicles with choices between hydrogen production and battery grid storage (Figure 34). Currently there is no shared institutional structure, either market or regulatory, to coordinate such interactions between the transportation and electricity sectors.

Figure 34. Pathways-Dependent Interactions Between Transportation and Electricity Balancing, Zero-Emission Vehicle (ZEV) Options for California

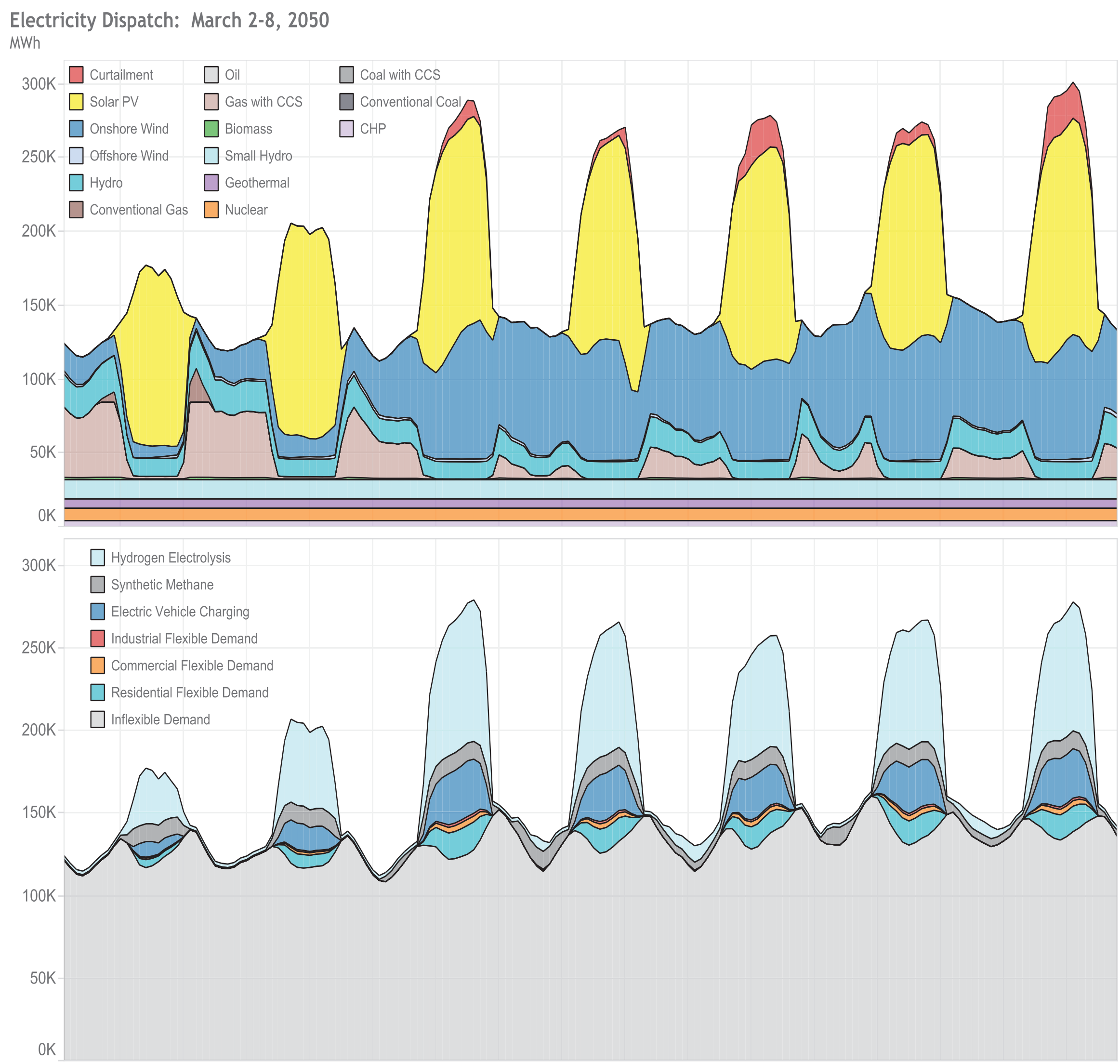


Source: (E3, 2015)

Integrate Supply and Demand-Side Planning and Procurement

A major challenge in cross-sector coordination comes when planning and procurement in a multi-sector system need to be closely integrated, as they would be in a deeply decarbonized electricity system comprising both supply-side generation and a variety of demand-side loads including transportation and fuel production. Maintaining reliability in a system with high penetration of inflexible generation (wind, solar, and baseload nuclear) requires correspondingly high levels of flexible demand (EV charging, hydrogen and SNG production, industrial and building loads) (Figure 35). The capability to provide demand-side flexibility at the required capacity, spatial, and time scales must be planned and procured in tandem with supply-side resources, and on the operational side wholesale electricity markets and reliability standards must be re-designed to work on both sides.

Figure 35. Electricity Dispatch in WECC, Generation and Load, March 2050, Mixed Case

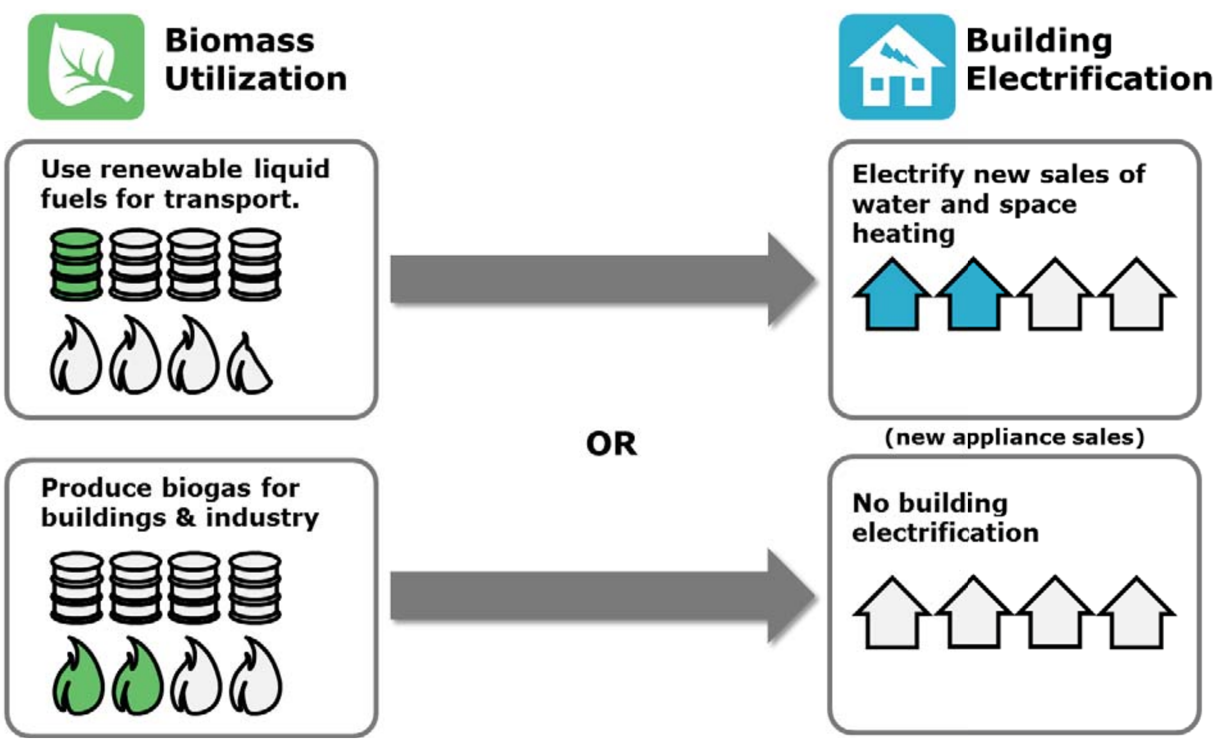


Create the Right Kinds of Competition

Competition among technologies is potentially an important way to drive innovation and reduce costs. However, unexamined conventional assumptions about what technologies might be in competition, for what applications, are likely to lead to the construction of policies and markets that result in unproductive competition. The development of long-term low-carbon pathways is essential to understanding what types of competition have value. For example, the U.S. 2050 study shows that the use of scarce biomass feedstocks to produce ethanol as a gasoline substitute is a misallocation of resources in the long run, since there are other ways (EVs, FCVs) to eliminate gasoline use from light-duty transportation. Policies that produce competition between ethanol and alternative vehicle technologies are unproductive from a deep decarbonization perspective.

Higher value uses of biomass lie in other applications, such as biodiesel to replace fossil diesel and renewable pipeline gas to replace fossil natural gas in building and industrial use. A "fork in the road" that California may confront in the 2020s is the unexpected tradeoff between allocation of biomass and the extent of building electrification (Figure 36). The competition implied in these pathway choices is between biodiesel and pipeline gas for use of biomass resources, and between building shell improvements and electrification for reducing emissions from building energy use. There is currently no institutional structure, either market or policy, for encouraging these kinds of competition (or for managing the cross-sector implications of how these competitions turn out).

Figure 36. Biofuel Pathway-Building Electrification Tradeoff, Options for California

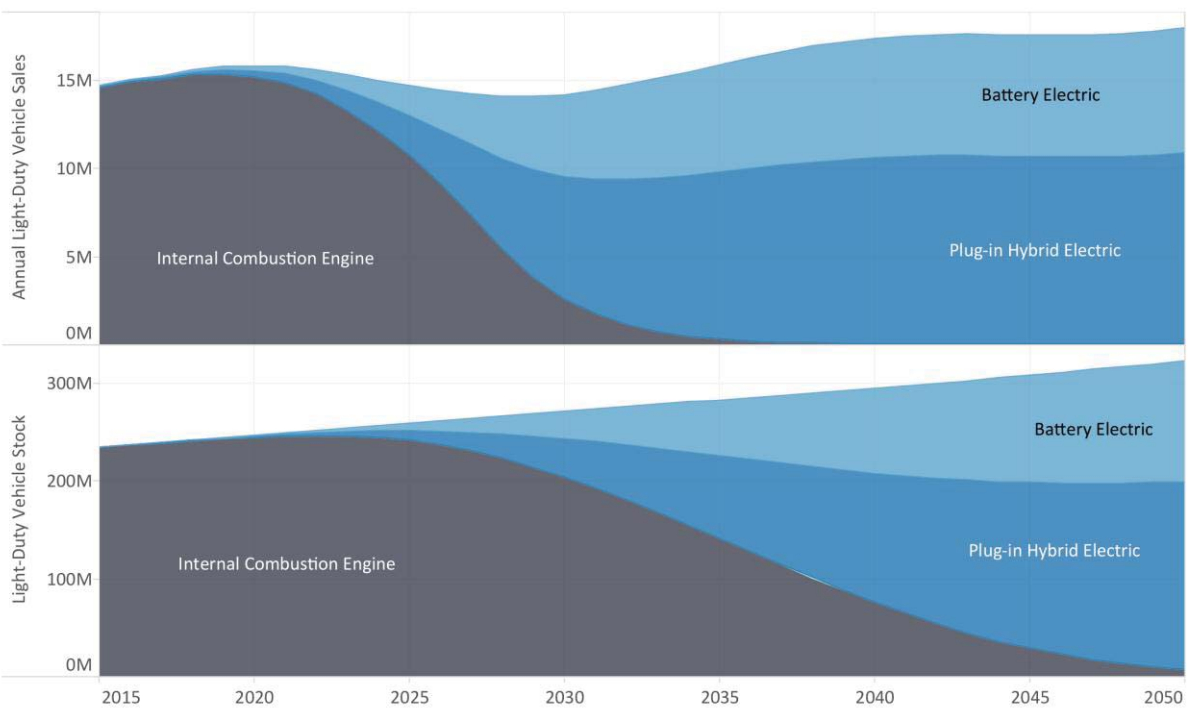


Source: (E3, 2015)

Enable the Required Rates of Consumer Adoption

The rate of energy supply side decarbonization – electricity and fuels – is amenable to control by a variety of policy, regulatory, and market mechanisms. On the other hand, the rate of demand-side adoption of efficient and electric end-use technologies, from buildings to industry to transportation, fundamentally involves consumer choices. Enabling the required rates of consumer adoption is a critical policy requirement. Deep decarbonization pathways analysis provides insight into the required adoption rates, for example in the light duty vehicle fleet (Figure 37). To achieve this level of adoption is likely to require a combination of upfront cost reductions, consumer incentives, and roll-out of a convenient fueling infrastructure coordinated with the share of alternative vehicles in the LDV fleet. Such strategies require working across industries – for example, with auto manufacturers and electric utilities – and need to be robust to changes in factors that affect consumer purchasing decisions, such as gasoline prices and interest rates.

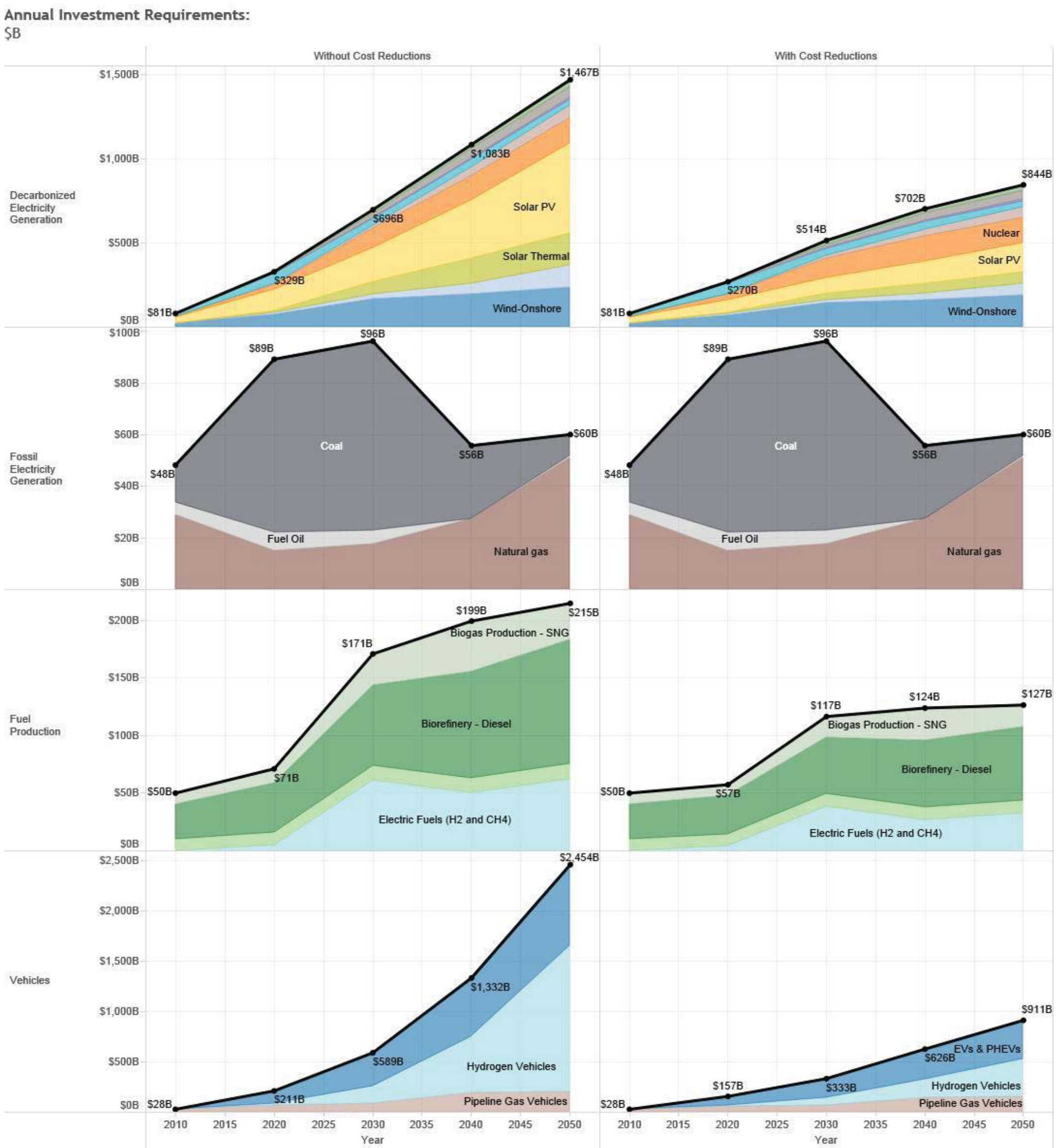
Figure 37. Light Duty Vehicle Sales and Total Stocks, 2015-2050, Deep Decarbonization High Renewables Case



Catalyze the Needed Cost Reductions In Key Technologies

Deep decarbonization is fundamentally the process of infrastructure transformation through the adoption of efficient and low-carbon technologies. Reducing investment requirements and upfront costs to consumers requires reducing the cost of the technologies themselves. Policy makers can catalyze the needed cost reductions by creating large markets for these technologies, leading to high production volumes and technological learning. Analysis of deep decarbonization pathways for the sixteen largest global emitting countries shows that learning-by-doing in large global markets for low-carbon generation, fuel production, and alternative vehicles potentially reduces annual investment costs, compared to stand-alone markets in the individual countries, by a factor of two (Figure 38). Coordinated RD&D and demonstration projects also play a role at earlier stages of technology development.

Figure 38. Annual Investment Cost for Low-Carbon Technologies With and Without Global Markets

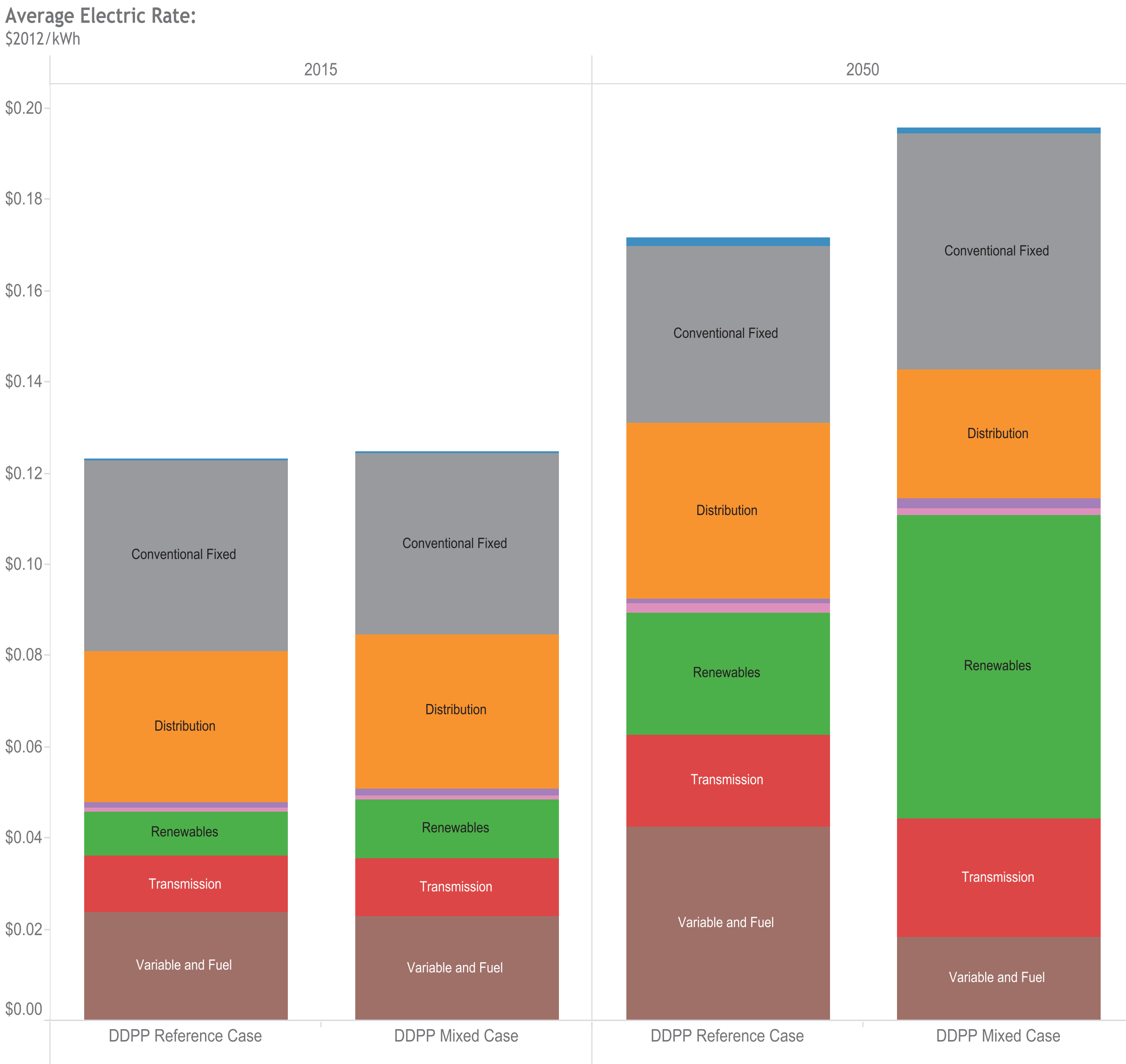


Source: (DDPP, 2015B)

Limit Cost Increases Faced by Consumers

Limiting the cost increases, and the rate of increases, faced by consumers is a key to the political sustainability of a low-carbon transition. Taking a long-term view can be helpful to policy makers in determining how to mitigate cost increases or make them more gradual. For example, in the U.S. 2050 mixed case, average retail electricity rates increase about 50% in real dollars, but if spread evenly over a 35-year period, this constitutes only a 1.6% average annual rate increase (Figure 39). Reference case rates during this period increase 1.1% per year, so the incremental increase in the decarbonized mixed case is 0.5% per year. Energy efficiency is a key to cost management, as reducing the amount of energy consumed to provide an energy service – for example, lighting a room or heating a building – can offset the effect of increased rates on the overall consumer bill.

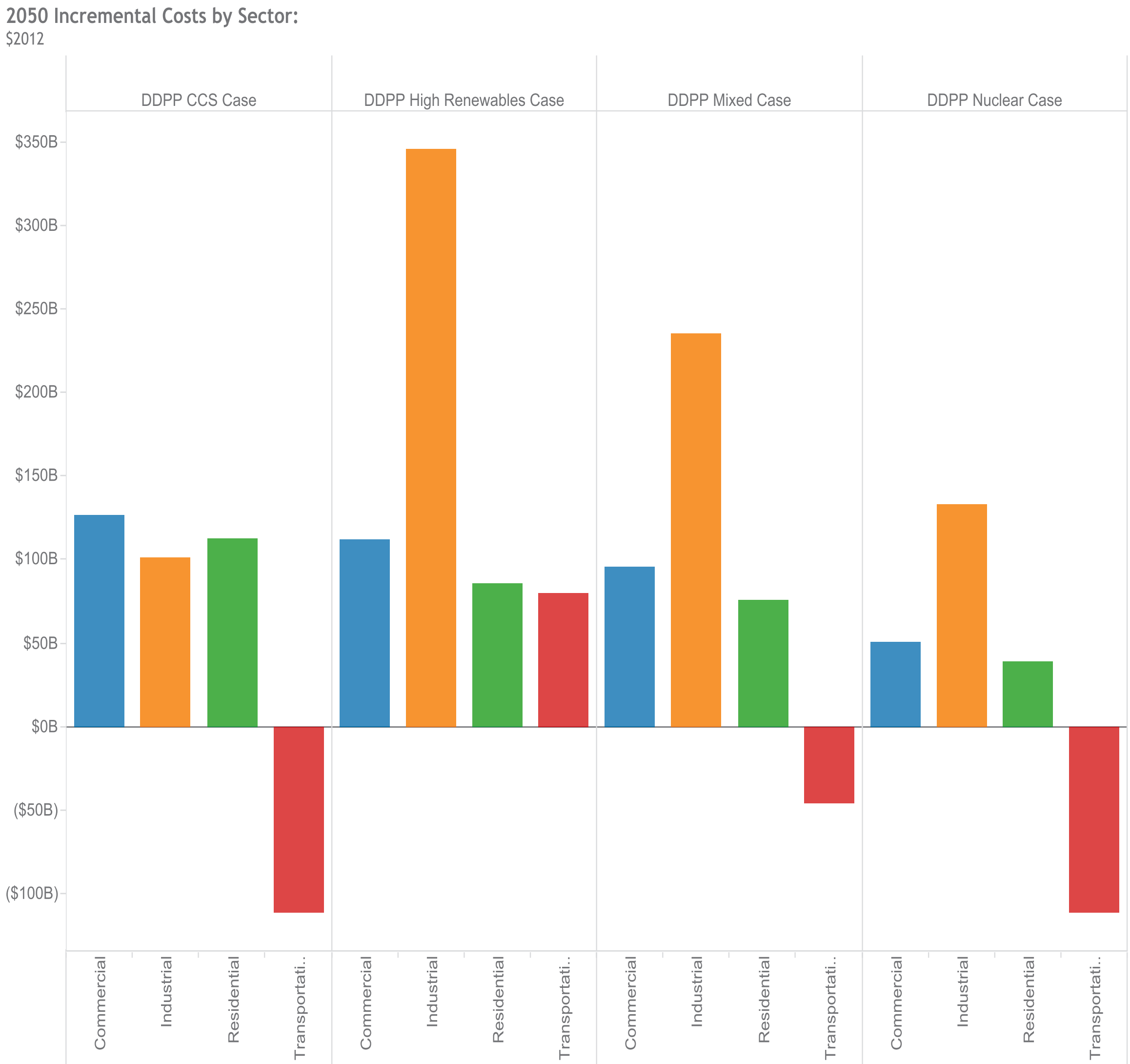
Figure 39. U.S. Average Retail Electricity Rates, Current and 2050 Deep Decarbonization Mixed Case



Minimize Inequitable Distributional Effects

Another requirement for the political sustainability of a low-carbon transition is minimizing inequitable distributional effects, whether these are regressive cost impacts on individuals as a function of income level, or differential costs across sectors or regions. There are many ways policy can address these impacts, for example cost allocation in utility ratemaking that maintains lower rates for low income customers. The low-carbon pathway pursued, with different technology transition strategies by sector and industry, can have major implications for the distribution of costs across sectors (Figure 40).

Figure 40. Net Costs by Sector in U.S. Deep Decarbonization Scenarios in 2050, Relative to Reference Case



B. Developing Deep Decarbonization Policy

Basic Guidance for Policy Makers

The key to deep decarbonization is a transformation of energy supply and end-use infrastructure. The question facing policy makers is not whether but how to undertake this transformation. Basic guidance for policy makers as they pursue this goal can be summarized in the following five points.

Identify clearly what policy must accomplish. As described in the previous section, creating the right policy instruments depends above all on being clear about what policy must accomplish, and using that as the test for its suitability. Many of the key objectives for deep decarbonization were described in the previous section – the physical, financial, and institutional needs of energy system transformation. Understanding these objectives will inform the kinds of economic and environmental regulations, markets and incentive structures, standards and RD&D programs required.

Have a plan. Deep decarbonization will not occur as a byproduct of undirected market activity. Planning is required to coordinate decarbonization measures within and across sectors, regions, and time periods. Deep decarbonization planning is necessarily a public-private partnership, across a wide range of activities – investment, manufacturing, interoperability standards, RD&D, etc.

Have a business model. In each domain of the energy transition there must be a workable business model that attracts investors, encourages innovation, and allows the providers of energy and equipment to make money and consumers to have options and control costs. Policy proposals that can't be expressed in terms of a viable business model are likely to be poor policies in practice. Thinking from a business perspective is an essential discipline for policy makers and analysts.

Prepare strategy for future choices. Many key pathways decisions will be made in the future, meaning that planning must be adaptable rather than rigid, and robust against uncertainty. A strategy for informing future choices includes such questions as what metrics will we use to decide? How can we generate the information we need? How shall we gauge risk? What is the point of no return? Having such a strategy is also a useful tool in the present.

Set a high bar for analysis. Many claims about the technical feasibility and cost of energy system changes and specific technologies and policies are based on analysis that is biased, poorly executed, or lacks rigor. Success in deep decarbonization requires policy makers to set a higher bar for the quality and relevance of analysis. This starts with having capable, technically competent advisors and asking the right questions.

Measures of Effective Policy

As a general and high-level diagnostic, some key characteristics of effective policy include the following:

- **Focused** on high priority areas, not spread overly thin
- **Workable** implementation strategy
- **Simple** to explain, clear messages

- **Coherent** across policy components, aligns incentives of key actors
- **Adaptive** to new information and actual results
- **Anticipatory** of future needs, impending forks in the road
- **Robust** to different failure modes, has alternatives

By contrast, ineffective policy is often based in poor analysis, ideology, or narrow self-interest, and will tend to be theoretical rather than empirical, hard to explain, lack a workable implementation plan, brittle, unprepared for problems that may emerge, and result in minimal GHG reductions for the cost and effort, or dead-end pathways that do not lead to deep decarbonization.

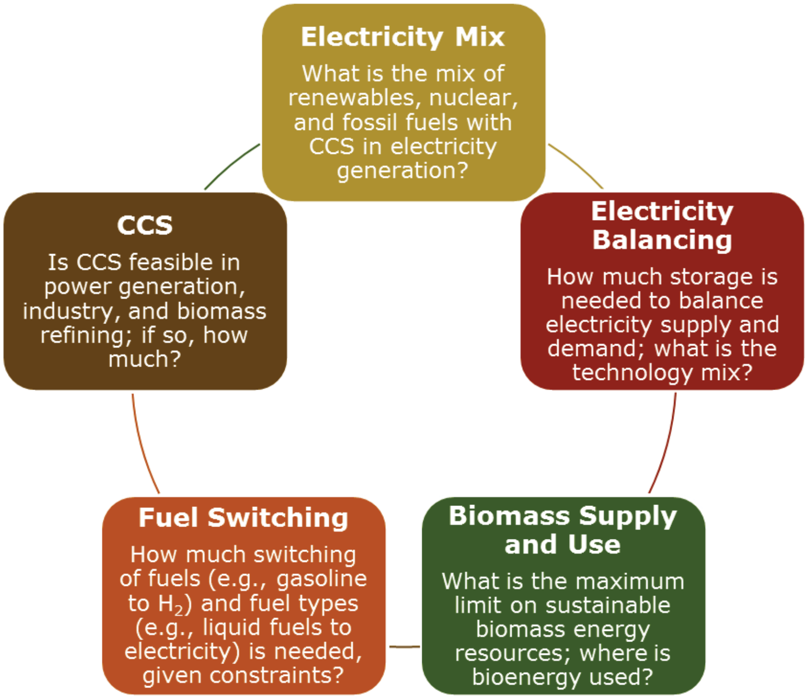
Two Transformations and Five Elements

Cut to its essentials, the U.S. study shows that the two main transformations required in the medium term are a high level of electricity decarbonization and a high share of alternative (electric or fuel cell) LDVs in new vehicle sales by 2030. During the same period, the groundwork needs to be laid for other transformations that will take place in bulk mostly after 2030 – high uptake of alternative HDVs, building and industrial electrification, decarbonized pipeline gas, low-carbon biofuels, and large scale flexible loads such as hydrogen production for electricity balancing.

Reflecting on what is required to substantially decarbonize electricity and new LDVs by 2030 reveals some of the complexities of the policy challenge. First, the kinds of government action needed in these two areas are fundamentally different. Electricity carbon intensity can be directly controlled by regulatory action, which for success must also maintain reliability, limit costs, meet other environmental standards (e.g., water, land use), and provide a viable business path for utilities and the power industry. Alternative LDV uptake depends on consumer adoption, in which the role of government is less direct – e.g., establishing markets, incentives, operability standards, manufacturing partnerships, and fueling infrastructures.

Second, technology choices, investment decisions, and policy design in generation and LDVs cannot be made independently of those in other domains of the low-carbon transition. The U.S. study identifies five fundamental elements of deeply decarbonized energy systems (Figure 41) – generation, electricity balancing, fuel switching, CCS, and biofuels – where the choice of pathway in one area can profoundly affect the options in others. For example, balancing solutions in a highly renewable generation mix will be very different from those in a high CCS mix.

Figure 41. Five Interacting Elements that Determine a Deep Decarbonization Pathway



Addressing the interdependence and contingency implied by these relationships will require government to anticipate and plan for future choices – for example, through RD&D, sectoral benchmarks, market discovery, and new institutional arrangements that cross jurisdictional silos. It will also require boldness by the private sector, which must bootstrap markets, attract investment, test new technologies, improve products, and gain consumer confidence on a short timeline.

The Policy Toolkit

Policy can attempt to reduce GHG emissions in many different ways, both direct and indirect, using a varied set of tools. It can set limits on emissions or emission intensities. It can create price signals to incorporate externality costs and influence purchasing decisions. It can directly require the adoption of efficient and low-carbon technologies, or it can provide incentives for investment in them, or consumer adoption of them. It can encourage the development or improvement of such technologies. Some common types of policy tools and examples of how they are used to affect GHG emissions, along with observations on their implications, are shown in Table 4.

Table 4. Some Common Types of Policy Tools for Energy and Climate Policy

Policy Tool	Example	Comment
Carbon target	U.S. Copenhagen commitment, California 2030 target	Provides clarity about end point, gives coherence to policies
Pricing mechanisms	Carbon tax, cap & trade, time of use pricing for electricity	Useful if price is right level, stable, actionable, equitable
Technology mandates	Renewable portfolio standard, EV sales requirements	Cost control and consumer adoption critical to success
Minimum standards	Building energy efficiency codes, emission intensity standard, CPP	Corrects market failures, requires cost control

Tax incentives and subsidies	Investment tax credit, federal loan guarantees	Subject to political change, challenge is consistency
RD&D support	DOE Sun Shot, California EPIC	Effective if well-targeted, consistent, adequate in scale
Consumer incentives	Utility rebates for customer purchase of LED lights	Standard tool for EE, can provide cost savings to society
Public-private partnerships	Energy Star labeling, manufacturing partnerships	Can be fraught (e.g. FutureGen) but many success stories
Decarbonization pathways analysis	US 2050 DDPP analysis	Keeps long-term transformation visible, illuminates choices

The Policy Landscape

Having identified what policy must accomplish for deep decarbonization to be achieved – the long-term objectives for policy – the effective formation of policy will require understanding the policy tools available, the policy landscape, and how these fit best together. It goes without saying that policy landscapes will change over time as technologies, costs, and political environments change. A key principle of sound policy in the energy arena is that policies must be empirically-based and adaptive as conditions change. Actual results must be compared to intended outcomes, and policies adjusted accordingly.

Key elements of the energy policy landscape include energy markets, governmental jurisdictions, sectoral characteristics, and state/regional conditions. Each of these topics is highly complex and the subject of a large literature, with many volumes of published law and regulation as well as economic, legal, and policy analysis. For the purposes of guiding deep decarbonization policy formation at a general level, a few broad observations on the policy landscape are helpful.

Energy Markets Are Fragmented and Imperfect

Electricity and natural gas distribution have the characteristics of natural monopolies, requiring public ownership or regulated private ownership to avoid monopoly abuses of consumers. Allocation of costs in these domains is a regulated process, not a direct market function. Wholesale markets and transmission in these domains also require sophisticated regulatory oversight to avoid abuse of consumers, often resulting in market distorting measures such as price caps.

Fossil fuel supply markets are fragmented geographically – only oil is a truly global market – and local supplies are often treated as strategic resources or local champion industries by governments, with many non-competitive implications. Both fossil and non-fossil energy supplies receive market-distorting subsidies. Environmental and social externalities of fossil fuel supply and use are well-documented and large, but difficult to quantify with precision and to incorporate in market prices. Information in both the supply and demand side of energy markets is highly asymmetric. Consumers and producers have very different access to information. Very little about energy markets can be approximated as ideal.

Sector Characteristics Determine the Suitability of Policy Instruments

The efficacy of policy instruments in achieving emission reductions depends on how well they match the characteristics of the market segment, sector, or industry to which they are applied. In general, four key characteristics will determine likely outcomes: (A) the expected payback period on investments; (B) the sophistication of market participants and their access to market information; (C) the presence of readily available substitute products; and (D) the ability to mitigate regressive distributional cost impacts of the policy.

Consider the application of four types of policy instruments commonly proposed for mitigation of GHG emissions: (1) price signals that incorporate externality costs such as a carbon tax or equivalent price from cap and trade; (2) incentives and subsidies; (3) minimum technology performance or content standards and other forms of direct regulation, and (4) RD&D support. An illustrative mapping of these instruments onto sector/industry characteristics is shown in Table 5. Emissions pricing is generally seen as the most economically efficient approach to GHG mitigation. However, conditions to generate an efficient market response to a tax or other emissions price signal are often not present. Incentives, such as tax credits and consumer rebates, are considered less economically efficient but are also less restrictive than minimum standards or other forms of direct regulation. Incentives change upfront costs faced by investors and consumers, and can be effective when payback periods exceed market participant willingness to wait for a return on investment. In addition, under circumstances in which the distributional impacts of an emissions tax are difficult to mitigate, incentives can be an effective alternative strategy.

Minimum standards are a common response in situations with serious market failures, including lack of transparent market information and/or consumers with limited knowledge. Finally, for new or underdeveloped industries, characterized by very long payback periods on investments and few substitute products, government support for RD&D is often necessary to encourage technology development.

Table 5. Matching Industry/Market Segment/Sector Characteristics to Policy Types

Industry/market segment/sector example	Willingness to see a relatively long payback period on investment?	Sophisticated buyers with access to transparent market information?	Many substitute products?	Ability to mitigate regressive distributional cost impacts of emissions price?	Suitable Policy Instruments
1) Utility investment in electricity generation	**Yes**	**Yes**	**Yes**	**Yes**	Emissions tax
2) Consumer purchase of EVs/PHEVs/FCVs	**No**	**Yes**	**Yes**	**Difficult**	Incentives & minimum standards
3) Consumer purchase of efficient/electric appliances	**No**	**No**	**Yes**	**Yes**	Incentives
4) Homeowner purchase of energy efficient building	**No**	**No**	**No**	**Yes**	Minimum standards
5) Business development of emerging technologies	**No**	**N/A**	**No**	**N/A**	Research & development support

"Energy Policy" Is Divided Across Federal, State, and Local Jurisdictions

The constitutional separation of state and federal jurisdictions is a defining feature the U.S. energy system. The state role is at least as important as the federal role in the U.S. energy system, and likely to grow even more important under in a transition away from an oil-based energy economy to one based on low-carbon infrastructure. States have the strongest jurisdictional levers over infrastructure investment decisions underlying the "three pillars" of supply decarbonization, energy efficiency, and fuel switching: state public utility commissions over utility procurement and rate making; state building codes and incentive programs over building energy use; state policies on fuel emission standards, transit system investment, and alternative vehicles in the transportation sector. California's ability to single-handedly set and control the outcome of statewide GHG emission targets is one indicator of a state's jurisdictional prerogatives in shaping its energy system and integrating carbon policies across its supply and demand-side components.

This is not to say that the federal role is unimportant, including potentially in cross-cutting areas such as a national carbon price and trade policies that encourage large global markets in low-carbon technologies. Some current important sectoral roles include setting vehicle and appliance efficiency standards, R&D, tax and incentive policies, biofuels, and FERC's role in regulating hydropower and electric and natural gas transmission and wholesale markets. EPA may be most important federal agency in providing drivers for a low-carbon transition, but the actions taken in response to these drivers lie mostly under state control.

An example of a policy ensemble acting across all levels from federal to local, based on their different jurisdictional authorities, is given below in Table 6 for the case of electricity generation.

Table 6. Generation Decarbonization Policy Approaches

Assessment	• 2050 requirement: reduce emissions intensity 30x while doubling generation • Uncontrolled coal is out, even CCS coal limited in quantity due to residual emissions & storage rate limits • Some natural gas for balancing, budget depends on gas use elsewhere in economy • New operating and procurement environment for power sector with high penetrations of intermittent renewables
Policy challenges	• Encouraging regional approach to generation and transmission for CO_2 compliance (e.g. CPP) • Market design for low-carbon operations, including flexible demand and gas generation with very low capacity factors • Mechanisms that simultaneously eliminate uncontrolled coal, reduce uncontrolled natural gas, and expand low-carbon generation
Federal	• CO_2 price through tax or cap and trade • Nuclear waste policy • CCS demonstration, rules for transport and storage • Extension of investment tax credit and production tax credit • Anticipatory site assessment on federal land (e.g. DRECP)

	• Wholesale market design consistent with decarbonization and regionalization
State	• CO_2 price through tax or cap and trade • Renewable portfolio standards • Emissions performance standards • Distributed PV policy with sustainable business model • Utility business model • Incorporate generation planning in larger portfolios (e.g. flexible load) • Regional integration of electricity planning and operations • Rate design consistent with decarbonization • Statewide anticipatory site assessment
Local	• Site permitting • Local incentives/financing for distributed energy resources

Energy Systems Have Strong Regional Identities

Energy systems have regional identities, in terms of both physical features and political economy, that affect the policy landscape for decarbonization. Location-specific resource endowments of fossil fuels and hydroelectric potential have shaped regional energy supply systems. Regional climate has shaped construction practices and building energy requirements, and regional patterns of settlement have shaped transportation options and fuel demand. Other physical patterns – renewable resource endowments, water availability, transmission distance, land use constraints, sub-surface geologic resources – may become increasingly prominent in shaping energy options and costs going forward.

Resource endowments have created regional industries (for example, oil production in Texas and Alaska, and coal production in West Virginia and Wyoming) with strong historical legacies, ties to local economies, and influence over policy. Regional energy supply systems are significant sources of employment and tax revenues, and these characteristics are good predictors of political positions taken by state representatives in Congress vis-à-vis energy and carbon policy. In some regions (for example, the southeastern US) electric utilities have extraordinary influence over a range of policy issues at the state level, from acceptance of nuclear power and its fuel cycle, to the adoption of renewable portfolio standards, to the existence of utility energy efficiency programs and/or the application of cost-effectiveness tests that determine the scope and effectiveness of such programs.

Regional energy characteristics will affect the cost and difficulty of the low-carbon transition, with distributional implications. Policies that are tied to relative changes – for example, fixed percentage reductions below a given year's emissions – may be relatively lower cost for states that have done little to date, as they still have potential low hanging fruit options, such as basic energy efficiency measures, to contain costs. On the other hand, policies that are tied to absolute targets, for example 1.7 tonnes CO_2 per capita in each state in 2050, may be more challenging for current high per capita emitting states.

A different aspect of regional energy identity can be seen in the wide range of state by state prices and expenditures for energy, shown for 2012 in

Table 7. Even ignoring data from Hawaii, an island that imports most of its energy supplies, there is a factor of two spread in average energy prices, a factor of three in energy expenditures per capita, and a factor of eight in energy expenditures as a percentage of GDP. Beyond simply underscoring regional variation, some interesting patterns emerge, with the highest energy prices generally in states that are not fossil fuel producers and the lowest in those that are. Yet the states with lowest energy prices also tend to have the highest expenditures on energy per capita and as a share of GDP. Demonstrating how deep decarbonization could benefit consumers in these states could be valuable in lowering political barriers to a low-carbon transition.

Table 7. Energy Prices and Expenditures Ranked by State, 2012 (EIA data)

Table E15. Energy Prices and Expenditures, Ranked by State, 2012

2012 RANKINGS

Rank	Prices		Expenditures [a]		Energy Expenditures per Person		Energy Expenditures as Percent of Current-Dollar GDP [b]	
	State	Dollars per Million Btu	State	Million Dollars	State	Dollars	State	Percent
1	Hawaii	40.04	Texas	155,921	Alaska	10,484	Louisiana	16.2
2	Vermont	29.11	California	136,364	North Dakota	10,049	North Dakota	15.3
3	New Hampshire	28.35	Florida	66,876	Wyoming	9,828	Mississippi	15.1
4	Connecticut	28.25	New York	65,134	Louisiana	8,544	Alaska	14.8
5	Rhode Island	26.35	Pennsylvania	53,954	Texas	5,983	Wyoming	14.7
6	Massachusetts	26.04	Ohio	49,326	Hawaii	5,608	Montana	13.5
7	Arizona	25.98	Illinois	48,091	South Dakota	5,598	Alabama	13.2
8	District of Columbia	25.83	Georgia	40,144	Montana	5,443	Maine	13.0
9	Florida	25.41	New Jersey	39,426	Nebraska	5,440	Kentucky	12.9
10	Maryland	25.41	Louisiana	39,322	Iowa	5,339	West Virginia	12.7
11	Alaska	25.33	Michigan	39,315	Maine	5,270	Arkansas	12.4
12	New York	25.24	North Carolina	36,204	Oklahoma	5,168	Oklahoma	12.3
13	California	24.70	Virginia	35,135	Mississippi	5,132	South Carolina	11.9
14	Delaware	24.64	Indiana	32,267	Kentucky	5,125	Vermont	11.6
15	New Jersey	24.11	Tennessee	28,636	Alabama	5,042	Idaho	11.5
16	North Carolina	23.69	Washington	27,570	Vermont	5,041	Texas	11.2
17	Nevada	23.47	Massachusetts	26,317	Kansas	4,944	New Mexico	11.1
18	Virginia	23.05	Missouri	26,146	Indiana	4,935	South Dakota	11.0
19	New Mexico	22.95	Alabama	24,291	West Virginia	4,757	Indiana	10.8
20	Maine	22.92	Minnesota	24,159	Arkansas	4,618	Iowa	10.8
21	Pennsylvania	22.73	Wisconsin	23,871	Minnesota	4,491	Hawaii	10.8
22	Missouri	22.50	Arizona	22,759	South Carolina	4,458	Tennessee	10.3
23	Oregon	22.28	Maryland	22,595	New Hampshire	4,447	Kansas	10.3
24	Tennessee	21.97	Kentucky	22,447	New Jersey	4,446	Nebraska	10.1
25	Montana	21.93	South Carolina	21,057	Tennessee	4,436	Missouri	10.1
26	Colorado	21.71	Oklahoma	19,719	Delaware	4,377	Michigan	9.8
27	South Carolina	21.67	Colorado	19,456	Missouri	4,340	Ohio	9.7
28	Georgia	21.60	Iowa	16,419	Virginia	4,292	Georgia	9.3
29	Washington	21.45	Mississippi	15,327	New Mexico	4,285	Wisconsin	9.1
30	Michigan	21.39	Connecticut	15,051	Ohio	4,269	New Hampshire	9.1
31	Wisconsin	21.05	Oregon	14,918	Pennsylvania	4,227	Pennsylvania	9.0
32	Kansas	20.90	Kansas	14,265	Idaho	4,215	Florida	8.6
33	Utah	20.82	Arkansas	13,623	Connecticut	4,190	Arizona	8.5
34	West Virginia	20.79	Utah	10,579	Wisconsin	4,170	Minnesota	8.2
35	Kentucky	20.65	Nebraska	10,093	Georgia	4,049	Utah	8.1
36	South Dakota	20.54	Nevada	9,982	Washington	3,998	North Carolina	7.9
37	Mississippi	20.46	New Mexico	8,928	Michigan	3,978	Virginia	7.9
38	Ohio	20.37	West Virginia	8,833	Massachusetts	3,960	New Jersey	7.8
39	Oklahoma	20.12	Hawaii	7,796	Maryland	3,839	Oregon	7.5
40	Minnesota	19.99	Alaska	7,656	Oregon	3,825	Nevada	7.5
41	Idaho	19.87	North Dakota	7,048	Colorado	3,749	Rhode Island	7.4
42	Arkansas	19.87	Maine	7,001	Illinois	3,737	Washington	7.3
43	Alabama	19.74	Idaho	6,725	North Carolina	3,714	Maryland	7.1
44	Nebraska	19.63	New Hampshire	5,877	Utah	3,706	Colorado	7.1
45	Illinois	19.10	Wyoming	5,667	Nevada	3,624	Illinois	6.9
46	Texas	18.82	Montana	5,473	California	3,589	California	6.8
47	Wyoming	18.51	South Dakota	4,669	Rhode Island	3,568	Connecticut	6.6
48	North Dakota	18.14	Delaware	4,014	Arizona	3,474	Massachusetts	6.5
49	Indiana	17.86	Rhode Island	3,748	Florida	3,461	Delaware	6.1
50	Iowa	17.82	Vermont	3,155	District of Columbia	3,398	New York	5.4
51	Louisiana	15.54	District of Columbia	2,152	New York	3,327	District of Columbia	2.0
	United States	21.65	United States	1,355,677	United States	4,319	United States	8.6

[a] The U.S. total includes $175 million of coal coke net imports, which are not allocated to the states.
[b] GDP = Gross domestic product.
Note: Rankings are based on unrounded data.

Web Page: All data are available at http://www.eia.gov/state/seds/seds-data-complete.cfm.
Sources: Data sources, estimation procedures, and assumptions are described in the Technical Notes.

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Low-carbon policies need to account for and leverage the physical and political economic realities of regional systems. Standards used to promote efficient building shells, air-conditioners, and electric heat pumps cannot be "one size fits all," but appropriately formulated for climate zones to avoid waste and frustration at the state level. In rural areas of the U.S., the main providers of electricity are the more than 900 rural electric co-ops, which have been beneficiaries of low cost federal hydroelectric power since the New Deal. The same federal policy vehicles offer an opportunity to support decarbonized electricity supplies for rural co-ops.

C. Policy Frames in Context

Effective policy begins with questions, observations, and rigorous analysis. Accepting unexamined assumptions can lead to ineffective or counterproductive policies. Many common policy frames and analytical approaches used in energy and climate policy were developed in the context of incremental changes to fossil fuel-dominated energy systems, not an energy transformation. Below is a preliminary look through the lens of deep decarbonization at the uses and limitations of a few widely applied conceptual approaches in guiding the energy transition.

Carbon price. Economists generally see carbon pricing as the foundational policy approach for reducing GHG emissions, by incorporating an externality cost into fossil fuel prices to eliminate a market failure. This premise has been accepted in the policy community to the extent that other approaches are often referred to as "complementary policies." There are energy market segments in which a carbon price may indeed provide a useful signal to sophisticated market players. For example, in industry, a carbon price might lead industries with different cost structures to adopt quite different responses – fuel switching, energy efficiency, CCS, process changes, dematerialization, and product redesign. These can be efficient outcomes that would be difficult to achieve solely through regulatory means. From the standpoint of deep decarbonization, however, establishing carbon pricing as the primary or only policy instrument has some important potential drawbacks.

(1) Carbon prices are an unstable price signal for attracting large-scale, long-term capital investment, which is essential to deep decarbonization. Because carbon prices are fundamentally tied to the price of fossil fuels either through a carbon tax or cap and trade, they are also tied to the rise and fall of those notoriously volatile prices. Consumers ultimately bear the costs of technology procured to supply energy to them, and there is a tradeoff between downward pressure due to competition, and upward pressure due to risk. For example, a potential wind energy developer facing only a carbon price and selling into a wholesale electricity market must make a very complex investment and return calculation, including such factors as long-term forecasts of carbon prices, natural gas prices, construction of other renewable and non-renewable generation in order to estimate system-level curtailment, construction of transmission to estimate local curtailment, permitting cost uncertainty, etc. These uncertainties impose high risks on investors, and will be reflected in a high premium on the cost of capital.

(2) Carbon prices are consistent with a "low-hanging fruit" policy that procures carbon reductions sequentially on the basis of marginal abatement cost (MAC). However, deep decarbonization requires systemic changes in which measures with high apparent MACs must occur in tandem with those with lower MACs.

(3) Carbon prices are likely to be capped, for political reasons, at levels too low to catalyze the transformations required for deep decarbonization. Carbon prices remain linked to analytically unsound expectations ("$20/ton"). Actual or implied prices greater than these expectations are often assumed to imply negative economic impacts, even though marginal carbon costs are actually a poor indicator of the impact on energy system costs.

(4) Price signals are very imperfectly refracted through fragmented energy markets, many segments of which are highly inelastic with regard to price. This can contribute to impacts on low-income consumers that must be counteracted by other policies, which may themselves not be politically feasible or easily implementable.

(5) Carbon pricing can contribute to an unfavorable political environment by creating an impression among the public of climate policy as a cost only, rather than as a physical transformation that can provide widespread economic benefits and a hopeful vision of the future.

Marginal abatement cost. Marginal abatement cost is seen as a complement to carbon pricing, by providing a sequence of abatement actions ordered by increasing cost ($/ton) and thus has figured prominently in climate policy discussions and analysis approaches. Increasing carbon prices, achieved through a mechanism such as a carbon tax or cap-and-trade, are often assumed to lead in practice to an orderly progression of abatement in the real economy, following the MAC curve. Most common energy system and integrated assessment models used for climate policy use MAC curves as the basis of their optimizations, determining the technology deployment resulting from a given carbon price. The MAC concept can be problematic from a deep decarbonization perspective for the following reasons.

(1) MAC is defined as the marginal cost of a decarbonization measure divided by the marginal emissions reductions from that measure; both of these factors are analytically ambiguous in a real-world energy system, because they are path dependent. Emission reductions are system responses that involve cross-measure and cross-sector interactions – for example, the emissions reduction impact of an EV depends both on the EV and on the emissions intensity of the grid – and thus are not a single-valued function of the measure. Thus the MAC of two identical EVs with identical costs is different depending on the electricity emissions intensity, either as a function of location or time. Especially in the case of deep decarbonization, involving many measures over long periods of time, there is no unique MAC curve – there are many different MAC curves depending on the order of deployment.

(2) The pairing of MAC with carbon pricing has long been at the heart of climate policy discussions, as it offers the prospect of a concise approach in which price reflects marginal benefit and is set equal to marginal cost. This creates the prospect of a smooth sequential climb up the MAC curve as carbon price increases. However, the U.S. analysis shows that deep decarbonization requires transformations in which multiple physical elements must change in tandem to achieve emissions goals. Some of these changes will have MACs – however ambiguous – that are quite different from each other. MAC based procurement, even if it were meaningfully defined – could well cause essential components to either be delayed or omitted.

(3) Attempts to make practical use of MAC curves, such as the iconic McKinsey curve, have succeeded in focusing policymakers on concrete actions needed to decarbonize, but have also demonstrated how hard it is to assign globally or nationally meaningful values to MAC. MACs based on global averages have little utility in specific locations where the underlying costs and emissions characteristics are very different. It's hard to imagine a policymaker even having the purview to decide between, say, variable speed motors versus micro-hydro generation, much less deciding on the basis of a MAC. These curves had an instructional value at a certain stage in the policy discussion, but they serve as a poor guide to practical energy-system decision making.

Social cost of carbon. The climate policy discussion often takes place in a cost-benefit framing, in which the costs of emissions mitigation are juxtaposed against the cost of economic damages from climate change. The marginal damage associated with a marginal emission is sometimes referred to as the social cost of carbon (SCC). SCC plays a useful role in regulatory decision making at the federal level, where it provides a non-zero proxy for the public benefits of reducing GHG emissions, for example in the setting of appliance standards. However, as an overall framework for climate policy SCC is problematic.

(1) The problem analytically with SCC is that future damages are fundamentally unknowable, since the relationships between emissions, radiative forcing, and climate response are uncertain and may be highly non-linear, and the economic consequences of the climate response depend on unknown tipping points. This is compounded by the problem of time scales and discounting of future damages.

(2) The cost-benefit framing for climate policy is not appropriate in situations in which societies are already committed to deep decarbonization, because it limits ambition to the level of the SCC, rather than whatever is required to achieve deep decarbonization. Once the transformational commitment is made, policy should be informed by the system costs of alternative pathways within an energy context. Fundamentally, the SCC was intended to guide "how much" mitigation is economically appropriate. Unfortunately, its application to decisions on "how" reductions may be achieved, once their level is established, is limited.

D. Rethinking Current Policy

The current ensemble of energy and climate policies in the U.S. has reduced GHG emissions and laid important groundwork for future reductions. Federal CAFE standards and appliance efficiency standards, and state level RPS and building standards, for example, have reduced energy use and carbon intensities relative to what would otherwise have occurred.

The circumstances shaping the ambition and effectiveness of these policies have varied: changes in technology costs; accommodating political reality in Washington or in state capitals; adjusting to national or regional economic conditions; pursuing the mandates of executive branch agencies; setting or following legal precedents; building political coalitions around common interests.

In most cases, policies were designed to work within a particular policy environment in the pursuit of short-term goals, generally incremental rather than transformational. While this can be a valid response to circumstances, the policy community must be aware of the difference between what is tactically expedient and what is required for the U.S. to be on the path to deep decarbonization.

This section provides a deep decarbonization perspective on four key areas of the energy transition and the current policy vehicles being used to advance them. The goal is not to criticize current policy, or to comment on the details of policy mechanisms, but to point out broad directions that must be followed to be consistent with achieving deep decarbonization and meeting U.S. commitments under the UNFCCC:

- **Electricity decarbonization** and the Clean Power Plan
- **Fuel decarbonization** and the Renewable Fuel Standard
- **Transportation energy** and CAFE standards
- **Building electrification and** energy codes and standards

Electricity Decarbonization and the Clean Power Plan

The federal Clean Power Plan proposes to use the EPA's authority under the Clean Air Act Sections 111.b and 111.d to regulate GHG emissions from power plants. It is intended by its advocates primarily to inhibit the construction of new non-CCS coal power plants, and to reduce emissions from existing uncontrolled coal plants, both of which are important steps. However, the statutory language of the CAA has dictated the CPP approach to a great extent, as the CPP was designed largely around the need to withstand federal judicial review, rather than from an electricity system perspective. Three important features of the CPP as currently proposed are the level of ambition for emission reduction targets, emphasis on state implementation plans, and the use of demand-side measures as flexibility mechanisms for compliance.

From the deep decarbonization perspective, for the CPP to serve as a driver of deep electricity decarbonization will require a significant evolution from its current form, or augmentation by complementary policies at the federal and state levels, which it is important that the CPP not undermine. Key priorities for electricity policy going forward as identified by the U.S. 2050 study include the following:

- **Drive near-complete decarbonization.** The U.S. study shows that generation emission intensities must be 30 times lower than current levels by 2050. This allows only a very low level of non-CCS fossil generation by mid-century, equivalent to less than 5% of total generation from uncontrolled natural gas plants. Across all scenarios, very high levels of near-zero carbon generation are required. While non-CCS natural gas generation can be important for renewable integration, in a deeply decarbonized system it can only be operated infrequently. With regard to the CPP, policies that drive a "natural gas transition" without also driving a great expansion of renewable, nuclear, or CCS generation, will not achieve the needed emission levels in the long run. State policies such as RPS may continue to be the most important driver of generation mix.

- **Encourage regional integration.** The U.S. study shows that the need for diversity of load and generation for balancing demand with supply in a low-carbon electricity system increases with the level of inflexible generation such as renewables and baseload nuclear. Expanding the locus of electricity planning and operations beyond present-day balancing authorities (aka utility control areas) to the regional scale will be essential for limiting cost and reserve requirements. Greater regional integration is a negative-cost, no-regrets policy priority in both the short and long term. The proposed version of the CPP provides few incentives for regional integration, and could provide counter-incentives in some cases.

- **Promote electrification.** The U.S. study shows that one pillar of deep decarbonization is a high level of electrification of transportation and buildings. Energy efficiency policies as currently practiced may work at cross-purposes to electrification. For this reason, the flexibility mechanisms in the proposed version of the CPP could be counterproductive. In general, energy policy should encourage coordinated planning on both the demand and supply side (see below on flexibility), but should avoid treating energy efficiency and supply decarbonization as interchangeable.

- **Enable flexible loads.** The U.S. study shows that flexible loads (i.e. those that are not "must-serve" on an hourly basis) constitute a large share of electricity demand in many deep decarbonization scenarios, and are essential to reliability and controlling cost by making use of generation that would otherwise be curtailed. In the future, demand will need to be fully integrated into electricity sector planning processes, as the procurement of generating capacity and flexible load will be inextricably linked. Policy has to address institutional and regulatory design for ownership, interconnection, and cost allocation for flexible load.

- **Redesign wholesale markets.** The U.S. study shows that nearly all generation will have near-zero operating cost in a deeply decarbonized electricity system, and that the function of markets will be the allocation of capacity and flexibility costs. This situation is drastic departure from the history of electricity markets, in which the cost of energy supply was the primary economic concern, and in which a strict dichotomy between generation and demand was the norm. The new normal will require market design innovation – in which FERC could play a leading role – to address the temporal and spatial allocation of capacity investments on both the supply and demand side. Market designs will need to be robust to large shares of flexible demand, rationalize direct-access and bundled demand, and allow differentiated levels of electricity reliability.

- **Anticipate siting requirements.** The U.S. study shows a large increase in renewable generation will be required in all cases, including high nuclear and high CCS scenarios. In combination with a need for increased intra- and inter-regional transmission, there will be significant land use requirements. Positive outcomes in terms of ecosystem, water, and cultural impacts require long-term anticipatory signals to renewable developers based on science and stakeholder based site assessments far in advance of need. The federal-state joint Desert Renewable Energy Conservation Plan provides a potential model for anticipatory planning.

Fuel Decarbonization and the Renewable Fuel Standard

The Renewable Fuel Standard, administered by the federal EPA, mandates a minimum quantity of "renewable fuel" in the transportation fuel mix. From its beginnings in the Energy Policy Act of 2005, bolstered by arguments about energy independence, RFS targets have grown over time. The target for 2022 is 36 billion gallons, equivalent to more than one-fourth of current gasoline consumption. While "renewable fuels" include a variety of alternatives to gasoline and diesel, including electricity, the RFS has served primarily as a vehicle for adding corn-based ethanol to the country's gasoline mix, along with some sugar cane-based ethanol imported from Brazil. There are valid scientific concerns about the carbon benefits of these fuels, especially when indirect land use change is taken into account. The RFS in practice has been shaped as much by a desire to provide farm subsidies to politically important states as by strategic thinking about decarbonized fuels.

From the deep decarbonization perspective, for the RFS to serve as a key driver of fuel decarbonization will require major changes in its present form. Key priorities for low-carbon fuel policy going forward as identified by the U.S. 2050 study include the following:

- **Encourage the development of fuels produced from electricity.** The U.S. study shows that electrically produced fuels such as hydrogen and synthetic natural gas have high value as fuel substitutes under all scenarios and can provide demand flexibility for electricity sector balancing. The RFS should be expanded to include hydrogen and SNG, and to facilitate their incorporation into the pipeline gas mix, including RD&D and regulations related to safety, blend criteria, purity requirements, and interconnection protocols from production to pipeline.

- **Redirect biomass resources toward high value uses.** The U.S. study shows that the best use of limited biomass resources is to replace fuels that lack other technical alternatives. Most biofuel is currently ethanol, which is used as a gasoline substitute in passenger cars. However, passenger cars have several viable technical alternatives, including electric vehicles, plug-in hybrids, and fuel cell vehicles. Across all scenarios, prioritizing the use of scarce biomass resources as a substitute either for diesel fuel (mostly for freight), jet fuel, or natural gas (mostly for industry) has a much greater carbon benefit. Policies that promote competition between biofuels and electricity or hydrogen for light duty vehicle use are not consistent with deep decarbonization.

- **Move away from biofuels with marginal emissions benefits.** The U.S. study shows that combustion fuels with only slightly lower lifecycle GHG emissions than their fossil alternatives – for example, corn ethanol substituted for gasoline – cannot play a significant part in long-term mitigation. As with non-CCS natural gas power generation, well before mid-century emissions constraints will be too stringent to permit such fuels to play a large role in the energy system. Policy should emphasize bioenergy with near zero lifecycle carbon, when feedstocks, fuel production, and fuel transportation are taken into account, including a strong constraint on indirect land use change. In the short term, reforming the RFS to include a multiplier for per-unit emissions reductions could provide better incentives for using biomass feedstocks with low fossil fuel inputs such as miscanthus and switchgrass.

- **Create a glide path for reducing existing biofuels.** The U.S. study shows that gasoline demand will decline, even in the reference case, due to increased LDV efficiency. Changing the definition of RFS to a percentage of final demand, instead of an absolute volume, and expanding the definition to include the replacement of fossil natural gas, would lead to reductions of corn-ethanol even without its explicit retirement from RFS.

Transportation Energy and CAFE Standards

The federal Corporate Average Fuel Economy (CAFE) standards set the requirements for fuel economy for passenger cars and light trucks. After stagnating at 27 mpg for over 20 years, new rules starting in 2011 have steadily raised the standard at a rate of about 2 mpg per year, with a target of 54 mpg in 2025. This change was catalyzed by California's Pavley standards for vehicle GHG emissions, which were upheld in 2007 by the U.S. Supreme Court. In return for California dropping separate standards for vehicles sold in the state, the Obama Administration adopted new rules for CAFE broadly consistent with California's. Coming on the heels of the federal bailout of the auto industry in the wake of the 2008 financial crisis, the Administration was in a strong position to make demands on an auto industry that had resisted fuel economy improvements for decades.

From a deep decarbonization perspective, CAFE as envisioned out to 2025 is generally consistent the direction required for the U.S. LDV fleet. In addition to essentially doubling fuel economy in internal combustion engine LDVs, CAFE provides extra incentives for electric, fuel cell, and hybrid vehicles. CAFE will be revisited in 2018, and likely face resistance to continuing the upward targets, even though the levels set for the 2020s will only be equivalent to those already achieved in Europe and Japan a decade earlier. To follow a deep decarbonization path beyond the mid-2020s, not only must CAFE maintain its existing targets, it must become more aggressive in transforming the vehicle fleet, in combination with complementary policies at the state level. Key priorities for transportation energy policy going forward as identified by the U.S. 2050 study include the following:

Make CAFE standards more aggressive. The U.S. study shows that average fuel economy for LDVs will need to be over 100 mpg equivalent across all scenarios by 2050, meaning that these levels will need to be achieved in new models before 2040. Future CAFE updates should unambiguously set increasing targets over time consistent with this transformation.

Facilitate a rapid transformation of the LDV fleet. The U.S. study shows that by 2030, the majority of new LDV sales must be either electric, fuel cell, or plug-in hybrid vehicles, and that allowing for slow turnover of stocks virtually the entire fleet must be composed of these vehicles by 2040. Achieving this transformation within about two average vehicle lifetimes will require policy support for high levels of consumer adoption, partnerships with auto manufacturers, and close coordination with electricity and/or hydrogen providers.

Build the necessary infrastructure. Fueling/charging infrastructure requirements must be anticipated and met in coordination with the expansion of low-carbon vehicle fleets. For EVs, of this must take place at the state level, where electric utility planning must account for growing electric vehicle loads at the distribution level. In the case of FCVs, development of hydrogen fueling infrastructure is a top priority for RD&D and pilot projects. Federal involvement will be required if hydrogen transport requires the development of a new transmission pipeline infrastructure.

Create large markets to bring down costs. The DDPP Synthesis Report investment study shows that technological learning has the potential to greatly reduce the incremental capital costs of electric, fuel cell, and plug-in hybrid vehicles. To take advantage of learning, large markets with high production volumes must be developed. These markets can be facilitated by regional collaborations within the U.S., and by U.S. climate and trade policy at the global level.

Develop technologies for low-carbon freight and air transport. The U.S. study shows that multiple options exist for low-carbon freight and air transport fuels, including biodiesel, fuel cells, and compressed and liquefied pipeline gas containing various mixes of natural gas, synthetic natural gas, and hydrogen. Recent proposed EPA rules that drive efficiency improvements for existing diesel and jet engines while also encouraging RD&D and technology competition in these areas is a positive step.

Building Electrification and Energy Codes and Standards

Building energy policy is primarily focused on energy efficiency, with the minimum energy efficiency of dozens of kinds of appliances and end-use equipment ranging from motors to light bulbs to refrigerators regulated by federal standards, while building energy efficiency in areas such as insulation and glazing is regulated by state codes. These are augmented by the federal EnergyStar program, a partnership of DOE and EPA, which provides a high-efficiency certification for products that improve substantially on minimum standards, and by state-level programs, carried out either through state offices, non-profit agencies, or utilities – that provide incentives to consumers to purchase energy efficient products. A fundamental element of codes, standards, and incentives at both the federal and state level is that they are typically set based on cost-effectiveness tests.

Despite some major gaps – weakness or absence of energy efficiency policies in some states, difficulties in developing effective policies for retrofitting existing buildings even in the most advanced states – energy efficiency has been perhaps the most sustained success story for clean energy over the decades since the oil crises of the 1970s first spawned widespread energy consciousness in the US. However, from the deep decarbonization perspective, some of the fundamental paradigms that have made these programs successful in the past will need to be reoriented going forward, requiring significant policy innovation in both state and federal codes and standards.

- **Focus on reducing carbon emissions, not primary energy use.** Reducing carbon is not only a function of improving energy efficiency, but also removing carbon from energy supplies. In some cases, emission reductions may entail increasing primary energy use from a low-carbon source relative to a more efficient use of primary energy from a higher carbon supply. This is a departure from a longstanding paradigm of energy efficiency policy – from a time when oil imports were a central concern – which sought always to maximize source Btu efficiency as a mechanism to achieve both cost savings and energy security.

- **Develop incentives for fuel switching.** The U.S. study shows that fuel switching becomes the most important measure on the demand side as electricity and fuel supplies are decarbonized. Current codes and standards are oriented toward improving the efficiency of an existing fuel use, rather than providing incentives to switch fuels. Developing fuel-switching incentives will require a fundamental rethinking of the scope and priority areas of energy efficiency policy.

- **Rethink cost-effectiveness.** Societally optimal fuel switching likely outpaces the current analysis framework for cost effectiveness, suggesting the need for a new planning framework that takes carbon emissions, energy consumption, and demand flexibility into account.

- **Make better use of advanced meter data.** Currently, vast quantities of building energy data are being collected by utilities, but this data is generally not being used to develop targeted programs to improve building energy performance. Policies ranging from privacy protection to enabling third-party providers are needed to take advantage of this data to mobilize advanced technology and expand the adoption of cost-effective energy efficiency and fuel switching. Targeting customers with large potential benefits from fuel switching – for example, electric heat pumps – can create a pool of early adopters, expand markets, and catalyze cost reductions.

- **Make an early decision on the fate of gas use in buildings.** The U.S. study shows that fossil natural gas use in buildings must be almost completely eliminated by mid-century, and replaced either by decarbonized pipeline gas or electricity. Since building energy demand can be met entirely by electricity, while industrial uses still require combustion fuels, avoiding competition for scarce biomass and electricity derived pipeline gas may mean the end of gas use in buildings. If this is the case, rapid reduction in building gas use will threaten new investments in pipeline infrastructure. To avoid stranded assets, it is important for policy to create a context for early decisions on the fate of gas in buildings, starting with permitting of gas supplies to new structures.

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EXHIBIT F. RESEARCH ARTICLE: THE TECHNOLOGY PATH TO DEEP GREENHOUSE GAS EMISSIONS REDUCTIONS: THE PIVOTAL ROLE OF ELECTRICITY

Science AAAS

The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050: The Pivotal Role of Electricity

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The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050: The Pivotal Role of Electricity

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Several states and countries have adopted targets for deep reductions in greenhouse gas emissions by 2050, but there has been little physically realistic modeling of the energy and economic transformations required. We analyzed the infrastructure and technology path required to meet California's goal of an 80% reduction below 1990 levels, using detailed modeling of infrastructure stocks, resource constraints, and electricity system operability. We found that technically feasible levels of energy efficiency and decarbonized energy supply alone are not sufficient; widespread electrification of transportation and other sectors is required. Decarbonized electricity would become the dominant form of energy supply, posing challenges and opportunities for economic growth and climate policy. This transformation demands technologies that are not yet commercialized, as well as coordination of investment, technology development, and infrastructure deployment.

In 2004, Pacala and Socolow (*1*) proposed a way to stabilize climate using existing greenhouse gas (GHG) mitigation technologies, visualized as interchangeable, global-scale "wedges" of equivalent emissions reductions. Subsequent work has produced more detailed analyses, but none combines the sectoral granularity, physical and resource constraints, and geographic scale needed for developing realistic technology and policy roadmaps (*2*–*4*). We addressed this gap by analyzing the specific changes in infrastructure, technology, cost, and governance required to decarbonize a major economy, at the state level, that has primary jurisdiction over electricity supply, transportation planning, building standards, and other key components of an energy transition.

California is the world's sixth largest economy and 12th largest emitter of GHGs. Its per capita GDP and GHG emissions are similar to those of Japan and western Europe, and its policy and technology choices have broad relevance nationally and globally (*5*, *6*). California's Assembly Bill 32 (AB32) requires the state to reduce GHG emissions to 1990 levels by 2020, a reduction of 30% relative to business-as-usual assumptions (*7*). Previous modeling work we performed for California's state government formed the analytical foundation for the state's AB32 implementation plan in the electricity and natural gas sectors (*8*, *9*).

California has also set a target of reducing 2050 emissions 80% below the 1990 level, consistent with an Intergovernmental Panel on Climate Change (IPCC) emissions trajectory that would stabilize atmospheric GHG concentrations at 450 parts per million carbon dioxide equivalent (CO_2e) and reduce the likelihood of dangerous anthropogenic interference with climate (*10*). Working at both time scales, we found a pressing need for methodologies that bridge the analytical gap between planning for shallower, near-term GHG reductions, based entirely on existing commercialized technology, and deeper, long-term GHG reductions, which will depend substantially on technologies that are not yet commercialized.

We used a stock-rollover methodology that simulated physical infrastructure at an aggregate level, and built scenarios to explore mitigation options (*11*, *12*). Our model divided California's economy into six energy demand sectors and two energy supply sectors, plus cross-sectoral economic activities that produce non-energy and non-CO_2 GHG emissions. The model adjusted the infrastructure stock (e.g., vehicle fleets, buildings, power plants, and industrial equipment) in each sector as new infrastructure was added and old infrastructure was retired, each year from 2008 to 2050. We constructed a baseline scenario from government forecasts of population and gross state product, combined with regression-based infrastructure characteristics and emissions intensities, producing a 2050 emissions baseline of 875 Mt CO_2e (Fig. 1). In mitigation scenarios, we used backcasting, setting 2050 emissions at the state target of 85 Mt CO_2e as a constrained outcome, and altered the emissions intensities of new infrastructure over time as needed to meet the target, employing 72 types of physical mitigation measures (*13*). In the short term, measure selection was driven by implementation plans for AB32 and other state policies (table S1). In the long term, technological progress and rates of introduction were constrained by physical feasibility, resource availability, and historical uptake rates rather than relative prices of technology, energy, or carbon as in general equilibrium models (*14*). Technology penetration levels in our model are within the range of technological feasibility for the United States suggested by recent assessments (table S20) (*15*, *16*). We did not include technologies expected to be far from commercialization in the next few decades, such as fusion-based electricity. Mitigation cost was calculated as the difference between total fuel and measure costs in the mitigation and baseline scenarios. Our fuel and technology cost assumptions, including learning curves (tables S4, S5, S11, and S12, and fig. S29), are comparable to those in other recent studies (*17*). Clearly, future costs are very uncertain over such a long time horizon, especially for technologies that are not yet commercialized. We did not assume explicit life-style changes (e.g., vegetarianism, bicycle transportation), which could have a substantial effect on mitigation requirements and costs (*18*); behavior change in our model is subsumed within conservation measures and energy efficiency (EE).

To ensure that electricity supply scenarios met the technical requirements for maintaining reliable service, we included an electricity system dispatch algorithm that tested grid operability. Without a dispatch model, it is difficult to determine whether a generation mix has infeasibly high levels of intermittent generation. We developed an electricity demand curve bottom-up from sectoral demand, by season and time of day. On the basis of the demand curve, the model constrained generation scenarios to satisfy in succession the energy, capacity, and system-balancing requirements for reliable operation. The operability constraint set physical limits on the penetration of different types of generation and specified the requirements for peaking generation, on-grid energy storage, transmission capacity, and out-of-state imports and exports for a given generation mix (table S13 and figs. S20 to S31). It was assumed that over the long run, California would not "go it alone" in pursuing deep GHG reductions, and thus that neighboring states would decarbonize their generation such that the carbon intensity of imports would be comparable to that of California in-state generation (*19*).

Electrification required to meet 80% reduction target. Three major energy system transformations were necessary to meet the target (Fig. 2). First, EE had to improve by at least 1.3% $year^{-1}$ over 40 years. Second, electricity supply had to be nearly decarbonized, with 2050 emissions intensity less than 0.025 kg CO_2e/kWh. Third, most existing direct fuel uses had to be electrified, with electricity constituting 55% of end-use energy in 2050 versus 15% today. Results for a mitigation scenario, including these and other measures, are shown in Fig. 1. Of the emissions reductions relative to 2050 baseline emissions, 28% came from EE, 27% from decarbonization of electricity generation, 14% from a combination of energy

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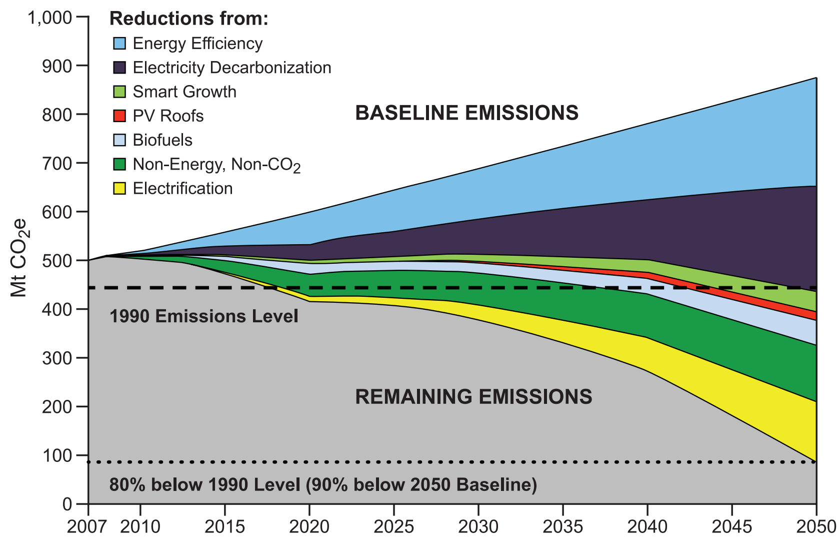
Exhibit F F3

conservation and alternative energy measures [including "smart growth" urban planning, biofuels, and rooftop solar photovoltaics (PV)], 15% from measures to reduce non-energy CO_2 and non-CO_2 GHGs, and 16% from electrification of existing direct fuel uses in transportation, buildings, and industrial processes. Table 1 shows changes from 2010 to 2050 in primary and end-use energy and emissions by sector and fuel type for the baseline and mitigation cases, along with per capita and economic intensity metrics.

The most important finding of this research is that, after other emission reduction measures were employed to the maximum feasible extent, there was no alternative to widespread switching of direct fuel uses (e.g., gasoline in cars) to electricity in order to achieve the reduction target. Without electrification, the other measures combined produced at best 2050 emissions of 210 Mt CO_2e, about 50% below the 1990 level. The largest share of GHG reductions from electrification came from transportation, in which 70% of vehicle miles traveled—including almost all light-duty vehicle miles—were powered by electricity in 2050, along with 20% powered by biofuels and 10% powered by fossil fuels. Other key applications for fuel switching occurred in space heating, water heating, and industrial processes. Figure 3A shows that even with aggressive EE keeping other demand growth nearly flat, fuel-switching to electricity led to a doubling of electricity generation by 2050. "Smart charging" of electric vehicles was essential for reducing the cost of electrification, by raising utility load factors and reducing peak capacity requirements through automated control of charging times and levels (Fig. 3B).

In the electricity sector, three forms of decarbonized generation—renewable energy, nuclear, and fossil fuel with carbon capture and storage (CCS)—each have the potential to become the principal long-term electricity resource in California, given its resource endowments. All currently suffer from technical limitations and high cost relative to the conventional generation alternative, natural gas, so it is not obvious which of these (if any) will dominate in the long run. Therefore, we built separate high–renewable energy, high-nuclear, and high-CCS scenarios that met the target, plus a mixed case. Because these technologies have very different operating characteristics—CCS, when commercialized, is expected to be flexibly dispatchable generation that can follow demand; nuclear is baseload generation that operates at a constant output level; and the most abundant renewable energy resources (wind and solar) are intermittent—they also have very different needs for supporting infrastructures, including capacity resources, high-voltage transmission, and energy storage. Figure 3C shows the generation scenarios. The high–renewable energy case has the highest requirements for installed capacity, transmission, and energy storage; the high-nuclear case requires the largest export market for excess generation, along with an expansion of upstream and downstream nuclear fuel cycle infrastructure; and the high-CCS case requires construction of CO_2 transportation and storage infrastructure. In addition, water, land use, and siting issues are quite different for each of these options. Residual electricity-sector carbon emissions in 2050 came primarily from combustion of natural gas for peaking generation and CCS. CCS fleet-average carbon storage efficiency in 2050 was 90%, but new CCS units were required to reach 98% efficiency. Within the western grid of which California is part, all existing conventional coal plants were retired at the end of their planning lives of 30 years.

Some studies suggest that 100% of future electricity requirements could be met by renewable energy, but our analysis found this level of penetration to be infeasible for California (*20*, *21*). We found a maximum of 74% renewable energy penetration despite California's large endowment of renewable resources, even assuming perfect renewable generation forecasting, breakthroughs in storage technology, replacement of steam generation with fast-response gas generation, and a major shift in load curves by smart charging of vehicles. Using historical solar and wind resource profiles in California and surrounding states, the electricity system required 26% nonrenewable generation from nuclear, natural gas, and hydroelectricity, plus high storage capacity to maintain operability. It would be possible to forecast higher



Wedge Category:	Emissions Reduction Mt CO_2e (% of Total) 2030	2050	Types (and Numbers) of Measures Used	Key Attributes in 2050
Energy Efficiency	102 (33%)	223 (28%)	Building EE (18); Vehicle EE (9); Other EE (6)	Energy efficiency improved 1.3% per year on average for 40 years
Electricity Decarbonization	72 (23%)	217 (27%)	High renewables, high nuclear, high CCS, and mixture of the three	90% of generation requirement met with CO_2- free sources. Equivalent decarbonization in each scenario
Smart Growth	13 (4%)	41 (5%)	Reductions in vehicle miles traveled (VMT) (6)	VMT reduced in light duty vehicles (LDV) by 10%; freight trucks 20%; other transportation 20%
Rooftop PV	8 (3%)	21 (3%)	Residential and commercial PV roofs (2)	10% of electricity demand displaced by rooftop PV
Biofuels	18 (6%)	49 (6%)	Transportation biofuels; ethanol, biodiesel, biojet fuel (9); Residential, commercial, industrial biomethane (3)	2% of natural gas use in buildings displaced by biomethane, and 10-20% of petroleum-based fuels for vehicles displaced by biofuels
Non-Energy, Non-CO_2	67 (22%)	116 (15%)	Cement, agriculture, and other (3)	Non-fuel; non-CO_2 GHG emissions reduced 80% below baseline
Electrification	29 (9%)	124 (16%)	Transportation electrification (9); Other end-use electrification (5)	75% of LDV gasoline use displaced by PHEVs & electric vehicles; 30% of fuel use in other transport sectors electrified; 65% electrification of non-heating/cooling fuel use in buildings; 50% electrification of industrial fuel uses
Baseline Case Emissions	688	875		
Mitigation Case Emissions	380	85		
Total Reduction	308	790		

Fig. 1. Emission reduction wedges for California in 2050. **Top:** Measures grouped into seven "wedges" reduce emissions from 875 Mt CO_2e in the 2050 baseline case to 85 Mt CO_2e in the mitigation case. In the 2020 model results, the wedge contributions are consistent with implementation plans for California's policy objectives (AB32) for 2020. **Bottom:** Reductions by wedge are shown for the 2030 and 2050 mitigation cases, in Mt CO_2e and as a percentage of total reductions. The top three contributions are from energy efficiency (EE) (28%), electricity decarbonization (27%), and electrification of direct fuel uses (16%). For each wedge, the types of measures included and key assumptions are shown.

Exhibit F F4

penetration in cases with a higher resource base and/or much lower energy demand—for example, as a result of lower population growth or lower economic growth.

Unprecedented energy efficiency; limited contribution from biofuels. The rate of EE improvement required to achieve the target and enable feasible levels of decarbonized generation and electrification—1.3% year^{-1} reduction relative to forecast demand—is less than the level California achieved during its 2000–2001 electricity crisis (*22*) but is historically unprecedented over a sustained period. This level is, however, consistent with the upper end of estimates of long-term technical EE potential in recent studies (*23*, *24*). In our model, the largest share of GHG reductions from EE came from the building sector, through a combination of efficiency improvements in building shell, HVAC systems, lighting, and appliances. EE improvements were complemented by other measures to reduce new energy supply requirements for electricity, transportation, and heating. EE in combination with on-site distributed energy resources (in the form of solar hot water and rooftop PV) reduced the net consumption of grid-supplied electricity and fuels in new residential and commercial buildings to zero by 2030 (*25*). Structural conservation in the form of "smart growth" urban planning to reduce driving requirements was responsible for 5% of total emission reductions in 2050.

Biofuels, although essential (because not all transportation can be electrified), made only a modest 6% contribution to the 2050 emissions reduction when feedstocks were constrained to be carbon-neutral, produced in the United States, and limited to California's consumption-weighted proportional share of U.S. production (*26*–*28*). This feedstock was sufficient to provide 20% of transportation fuels in the form of cellulosic ethanol and algal biodiesel, assuming that these technologies achieve commercialization (fig. S15). In our model, biofuel feedstocks were dedicated to the production of transportation fuels as their highest-valued economic use, and these fuels were allocated to applications for which electrification is not a practical option, such as long-haul freight trucking and air travel. A small amount of biomethane was used in power generation.

In the baseline forecast, 2050 emissions of non-energy CO_2 (e.g., from cement manufacturing) and non-CO_2 GHGs [e.g., methane and nitrous oxide from agriculture and waste treatment, and high–global warming potential (GWP) gases used as refrigerants and cleaning agents] were 145 Mt CO_2e, more than the entire economy-wide target of 85 Mt CO_2e. Relative to CO_2 emissions from energy sectors, scientific understanding of long-term mitigation potential for these sectors is poorly developed (*29*–*32*). Nevertheless, it was clear that if these emissions were not abated, the 2050 target could not be met. We modeled mitigation by extrapolating California's AB32 implementation plan for 2020 (*7*) in three broad areas. Agricultural and forestry measures contributed 47 Mt CO_2e of reductions, cement-related measures contributed 8 Mt CO_2e, and industrial and other measures contributed 61 Mt CO_2e, for a total reduction of 116 Mt CO_2e below the 2050 baseline, which maintained the current share of non-energy/non-CO_2 in overall emissions.

There is evidence that the three key energy system transformations identified here are broadly generalizable to developed economies. A recent report on 80% GHG reductions in the European Union found that similar transformations were required, including electrification of transportation and buildings (*33*). In other studies, where reductions rely on EE and generation decarbonization but not electrification, lower GHG reduction levels were achieved. For example, in a recent International Energy Agency study of technology paths in Organization for Economic Cooperation and Development member countries as a whole, the most aggressive scenario had a 2050 reduction of about 50% below 1990 levels, with a 6% contribution from electrification (*34*). The consistency among these results is predictable, in that developed economies broadly share the same challenges for reaching deep reduction targets—the need to virtually eliminate fossil fuel use in electricity supply and in final consumption, especially in vehicles and buildings.

Infrastructure deployment and technology investment require coordination. In contrast to the findings of Pacala and Socolow, we found that achieving the infrastructure changes described above will require major improvements in the functionality and cost of a wide array of technologies and infrastructure systems, including but not limited to cellulosic and algal biofuels, CCS, on-grid energy storage, electric vehicle batteries, smart charging, building shells and appliances, cement manufacturing, electric industrial boilers, agriculture and forestry practices, and source reduction/capture of high-GWP emissions from industry (*35*).

Not only must these technologies and systems be commercially ready, they must also be deployed in a coordinated fashion to achieve their hoped-for emission reduction benefits at acceptable cost. For example, switching from fuels to electricity before the grid is substantially decarbonized negates the emissions benefits of electrification; large-scale deployment of electric vehicles without smart charging will reduce utility load factors and increase electricity costs; and without aggressive EE, the bulk requirements for decarbonized electricity would be doubled, making achievement of 2050 goals much more difficult in terms of capital investment and siting. Figure 3D shows the impact of aggressive EE on three key metrics of decarbonized electricity supply:

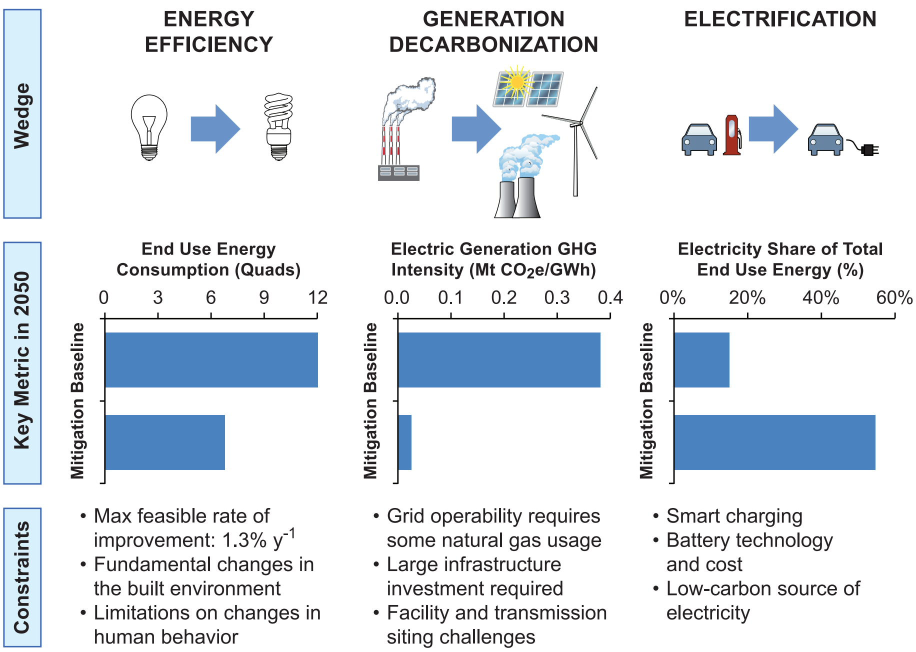


Fig. 2. The three main energy system transformations required to reduce GHG emissions 80% below 1990 levels by 2050 in California. End-use EE must be improved very aggressively (annual average rate 1.3% year^{-1}), electric generation emissions intensity must be reduced to less than 0.02 kg CO_2e/kWh, and most direct fossil fuel uses in transport, buildings, and industry must switch to electricity, raising the electricity share of end-use energy from 15% today to 55% in 2050. Both economics and the current state of technology development suggest a staged deployment in large-scale infrastructural transformation. Without aggressive levels of EE, the scale of decarbonized generation required to simultaneously replace fossil plants and meet both existing and newly electrified loads would be infeasible. Until high levels of electricity decarbonization are achieved, emission benefits from electrification would be limited. Without electrification, constraints on the other measures would limit total reductions to about 50% below 1990 levels.

Exhibit F F5

generating capacity, energy storage, and miles of high-voltage transmission line. For the mixed-generation case, achieving the 2050 target with baseline levels of EE raised the requirement for annual construction of decarbonized generation from a very formidable 3.7 GW $year^{-1}$ to a practically unachievable 7.0 GW $year^{-1}$, and the requirement for new transmission lines from 400 to 960 miles $year^{-1}$.

Our model shows a net mitigation cost to California, relative to the baseline, of 0.5% of gross state product (GSP) in 2020, 1.2% in 2035, and 1.3% in 2050 ($65 billion or $1200 per capita) (Fig. 4 and fig. S34). The transportation sector bore the highest share of these costs, reflecting the cost of fleet electrification. These results are highly sensitive to both measure costs and fuel price assumptions; using the upper value of the U.S. Energy Information Administration (EIA) long-term crude oil price forecast makes net mitigation costs negative (fig. S12). Cumulative net costs from 2010 to 2050 were $1.4 trillion. The average cost of carbon in 2050 was $90/t CO_2e, whereas the highest average cost by measure type was $600/t CO_2e for electrification measures (*36*). Because mitigation measures reduce fuel use by investing in energy-efficient infrastructure and low carbon generation, a much higher percentage of energy cost will go to capital costs; our model indicates a cumulative investment of $400 billion to $500 billion in current dollars (figs. S35 and S36) for electricity generation capacity in the mitigation case, a factor of about 10 higher than the baseline case (*37*).

The transition to an energy-efficient, low-carbon, electrified infrastructure thus requires mobilizing investment and coordinating technology development and deployment on a very large scale over a very long time period. How best to achieve this is the focus of active debate over the relative roles of markets, government, carbon pricing, R&D policy, regulation, and public investment (*38*). Many consider carbon pricing the key to achieving efficient investment and providing incentives for consumer adoption; others argue that carbon

Table 1. Primary and end-use energy and emissions by sector and fuel type in 2010 and 2050. The numerical difference between primary and end-use energy is due to conversion and other losses. Sources for population and economic data are given in the supporting online material.

	Energy consumption (EJ)					Emissions (Mt CO_2e)		
	2010	2050 Baseline	2050 Mitigation	2010 (%)	2050 Mitigation (%)	2010	2050 Baseline	2050 Mitigation
Primary energy consumption and emissions, by sector								
Residential	1.60	2.56	0.52	18%	8%	71.3	117.1	5.4
Commercial	1.68	2.60	0.94	19%	14%	70.9	114.5	10.0
Industrial	1.41	1.39	0.96	16%	14%	67.4	67.3	6.4
Petroleum	0.81	0.82	0.58	9%	9%	46.7	47.5	5.6
Agriculture	0.34	0.52	0.21	4%	3%	16.3	27.1	1.0
Transportation	2.86	5.67	3.60	33%	53%	189.4	374.1	45.0
Non-energy, non-CO_2 GHG emissions						56.4	127.8	11.4
Total all sectors	8.70	13.56	6.81	100%	100%	518.4	875.4	84.8
Primary energy consumption and emissions, by fuel type								
Direct fuel use								
Natural gas	2.73	3.40	0.38	31%	6%	148.9	185.1	20.5
Gasoline	2.09	4.36	0.13	24%	2%	135.9	283.4	8.3
Diesel	0.73	1.23	0.39	8%	6%	50.2	84.7	26.6
Jet fuel	0.04	0.08	0.04	0%	1%	3.3	6.0	3.4
Biomethane and biofuels	0.00	0.00	0.73	0%	11%	0.0	0.0	0.0
Total direct fuel use	5.59	9.06	1.67	64%	25%	338.3	559.2	58.8
Electric generation (primary)								
Natural gas (non-CCS)	1.45	2.90	0.01	17%	0%	72.1	135.3	0.4
Coal (non-CCS)	0.49	0.49	0.00	6%	0%	43.2	43.2	0.0
Fossil fuel w/ CCS	0.00	0.00	2.18	0%	32%	0.0	0.0	10.6
Nuclear	0.30	0.26	0.74	3%	11%	0.0	0.0	0.0
Renewables and hydroelectricity	0.71	0.66	2.04	8%	30%	0.4	0.4	0.8
Other	0.16	0.18	0.16	2%	2%	8.0	9.6	2.9
Total electric generation	3.11	4.49	5.14	36%	75%	123.7	188.4	14.7
Non-energy, non-CO_2 GHG emissions						56.4	127.8	11.4
Total all fuel types	8.70	13.56	6.81	100%	100%	518.4	875.4	84.8
End-use energy consumption and emissions, by fuel type								
Total direct fuel use	5.59	9.06	1.67	85%	45%	338.3	559.2	58.8
Electricity (end-use)	0.98	1.63	2.03	15%	55%	123.7	188.4	14.7
Direct fuel use + electricity	6.57	10.69	3.70	100%	100%	462.0	747.6	73.4
Non-energy, non-CO_2 GHG emissions						56.4	127.8	11.4
Total end use by fuel type	6.57	10.69	3.70	100%	100%	518.4	875.4	84.8
Intensity metrics								
CA population (millions)	38.8	56.6	56.6					
Per capita energy use rate (kW/person)	7.1	7.5	3.8					
Per capita emissions (t CO_2e/person)	13.3	15.5	1.5					
Energy intensity ($/GJ)	$249	$383	$762					
Economic emissions intensity (kg CO_2e/$)	0.239	0.169	0.016					
Electric emissions intensity (kg CO_2e/kWh)	0.42	0.39	0.02					

Exhibit F F6

pricing is insufficient and requires complementary policies to address market failures, public goods, and coordination problems (*16*, *39*, *40*). Some make the specific case that pollution pricing is effective in encouraging technology adoption but not technological innovation (*41*, *42*). Others are concerned that the venture capital model is mismatched with the scale and timeline of investment required for an energy transformation (*43*) and with the risks created by the need for multiple technologies to achieve commercialization in parallel (*44*). These concerns have led to calls for novel public-private partnerships to address investment failures through government absorption of private capital risk (*43*) and to address coordination and sequencing through industry-government roadmapping (*45*).

Electricity's role in future energy costs and climate policy. Another model result deserving special attention is the expanded role of electricity, which increases from 15% to 55% of end-use energy, essentially switching places with petroleum products, which fall from 45% to 15% (Table 1). If electricity does become the dominant component of the 2050 energy economy, the cost of decarbonized electricity becomes a paramount economic issue. Our results show that generation mixes dominated by renewable energy, nuclear, and CCS, in the absence of cost breakthroughs, would have roughly comparable costs, raising the present average cost of electricity generation by a factor of about 2—a result also noted by other researchers (*17*). These findings indicate that minimizing the cost of decarbonized generation should be a key policy objective. By some estimates, aggressive R&D policies could reduce the cost of low-carbon generation in the United States from 2020 to 2050 by about 40% or $1.5 trillion (*17*).

For electrified transportation, the inherently higher efficiencies of electric drivetrains would still allow a net reduction in fuel costs even with electricity prices doubled and oil prices at $100 per barrel, as well as shifting cash flows away from foreign oil imports toward domestic purchases of electricity. On the other hand, electrification of direct fuel uses will increase costs in the residential, commercial, and industrial sectors, especially for heating; hence, there is a need for EE and design of new infrastructure in these sectors to minimize lifecycle costs. Because much of the required technology and infrastructure for a basic transformation of the energy system is not yet commercialized, comparative lifecycle costs are highly uncertain. However, because decarbonized generation technologies are dominated by capital costs and are insensitive to oil and natural gas price volatility, an electrified economy would have a long-term cost stability that could lower investment risk and make the optimal level of EE more certain (*46*). Even varying measure costs from one-half to twice the nominal values in the mitigation scenario produced no more variation in overall energy system costs than did varying crude oil prices in the baseline scenario over the range in the EIA's long-term forecast (fig. S12).

The climate policy community has proposed a suite of policies to complement carbon pricing (e.g., EE standards, renewable energy standards, and R&D support) that reflect not only economic and technology goals but also sociopolitical considerations such as equity, local initiative, and adaptability (*16*). The central role of electricity in our results suggests the importance of electricity-sector governance as a tool of climate policy, but this has received relatively little attention until recently (*47*). Although some argue that regulation impedes innovation and increases implementation costs (*43*), state-level electricity regulation has existing tools for pursuing many climate policy goals, through both market mechanisms and direct regulation. Regulators can require that utilities procure renewable generation, limit carbon intensities, implement customer EE and distributed energy programs, and set retail electricity rates that encourage conservation and electric vehicle charging, internalize pollution costs, and allocate the

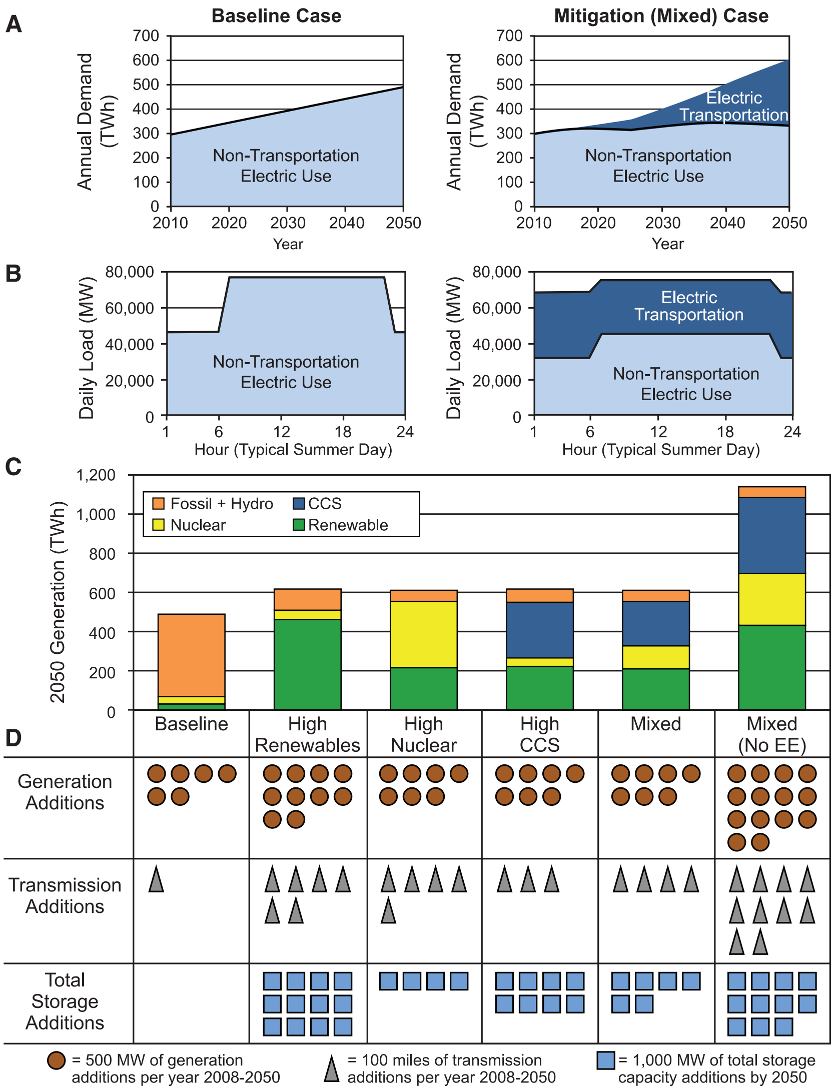


Fig. 3. Electricity consumption, load profiles, and fuel mix in baseline and mitigation scenarios. (**A**) In the mitigation case, aggressive end-use efficiency flattens baseline load growth. However, electrification of transportation adds a major new load, so that 2050 consumption is similar in both cases. (**B**) Smart charging of electric vehicles flattens the average daily load curve, reducing capacity requirements. (**C**) In the 2050 baseline scenario, load growth is met primarily with natural gas generation. Four mitigation scenarios are shown with different fuel mixes, constrained by California's existing fuel mix and policy requirements (e.g., 33% renewable portfolio standard, continued licensing of existing nuclear generation). The mixed case, which contains all three generation types, yields the results discussed in this paper and shown in Figs. 1 to 4. (**D**) New capacity requirements for each generation fuel mix are shown for generation, transmission, and energy storage. Without aggressive EE, new capacity requirements increase by roughly a factor of 2. The high–renewable energy case has higher new-capacity requirements than the high-CCS and high-nuclear cases; however, the high–renewable energy case does not have the high-CCS case requirements for CO_2 transmission and storage capacity, or the high-nuclear case requirements for upstream and downstream nuclear fuel cycle facilities.

Exhibit F F7

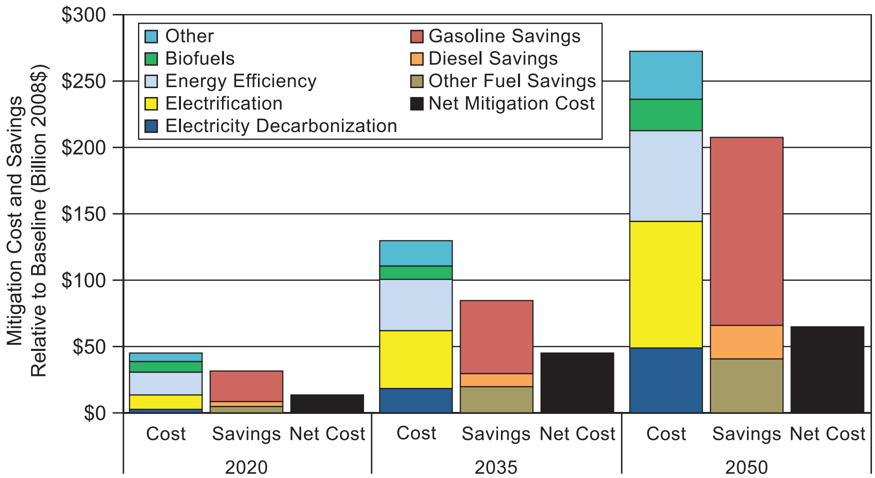


Fig. 4. Mixed-case net cost by mitigation type in 2020, 2035, and 2050. For each year shown, the left column shows incremental mitigation costs in excess of baseline costs, the center column shows incremental savings relative to baseline fuel costs, and the right column shows net cost (the difference between cost and savings). "Other" mixed-case costs include measure implementation costs not associated with EE, electrification, generation decarbonization, or biofuels. "Other" savings include jet fuel and natural gas purchases for direct use (e.g., heating). Net costs are $15 billion in 2020, $45 billion in 2035, and $65 billion in 2050. This is equivalent to $320 per capita or 0.5% of the statewide GSP in 2020, $910 per capita or 1.2% of the statewide GSP in 2035, and $1200 per capita or 1.3% of the statewide GSP in 2050.

costs of these policies equitably (*7*, *48*). Given the political challenges of achieving comprehensive federal climate legislation, it is worth further exploring decentralized electricity governance as a climate policy mechanism.

Assuming plausible technological advances, we find that it is possible for California to achieve deep GHG reductions by 2050 with little change in life-style (although the potential for life-style change deserves further study). The logical sequence of deployment for the main components of this transformation is EE first, followed by decarbonization of generation, followed by electrification. This transformation will require electrification of most direct uses of oil and gas. In California, no single generation technology (renewable energy, nuclear, or CCS) can be used to decarbonize all electricity; a mixed generation portfolio is required. If it is true that the low-carbon path features electricity, then the question is how best to mobilize investment and coordinate R&D and infrastructure rollout to achieve this end, and what climate policy modalities will be most effective. If the oil economy is replaced by the electric economy, it is instructive to consider the implications of the price of a decarbonized kilowatt hour replacing the price of a barrel of oil as a benchmark for the overall economy.

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36. Average carbon prices by measure type in 2020 and 2050 are shown in tables S21 and S22. Because measure selection in our model was based on policy and technical feasibility rather than marginal abatement curves, we cannot report a shadow marginal price for carbon comparable to those in price-based optimization models. However, our model does show penetration levels of EE, decarbonization, and electrification that are broadly rational in economic terms. The highest penetration levels in 2020 are EE measures with the lowest average cost, followed by decarbonization of generation, followed by electrification, which is much more expensive in this period. As may be true in other

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states, the timing of technology adoption in California is driven by policy as much as by markets, leading to the adoption of high-cost options (e.g., rooftop PV) concurrently with low-cost options (e.g., EE).
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Subparticle Ultrafast Spectrum Imaging in 4D Electron Microscopy

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Single-particle imaging of structures has become a powerful methodology in nanoscience and molecular and cell biology. We report the development of subparticle imaging with space, time, and energy resolutions of nanometers, femtoseconds, and millielectron volts, respectively. By using scanning electron probes across optically excited nanoparticles and interfaces, we simultaneously constructed energy-time and space-time maps. Spectrum images were then obtained for the nanoscale dielectric fields, with the energy resolution set by the photon rather than the electron, as demonstrated here with two examples (silver nanoparticles and the metallic copper–vacuum interface). This development thus combines the high spatial resolution of electron microscopy with the high energy resolution of optical techniques and ultrafast temporal response, opening the door to various applications in elemental analysis as well as mapping of interfaces and plasmonics.

Substantial progress has been made in the imaging of matter at the smallest length scale and shortest time response, using a range of optical and electron-based methods. Recent developments in electron microscopy have enabled studies of nanostructures with remarkable spectral and spatial resolution (*1*–*4*). However, a single nanoparticle-probing method with simultaneously high spatial, temporal, and spectral resolution has not hitherto been reported.

Here, we report ultrafast spectrum imaging (USI), with subparticle spatial resolution, in electron microscopy. The electron beam is focused down to the nanometer scale, the electron packet has femtosecond duration, and the energy resolution, optically induced, is in the millielectron-volt range; the energy and temporal resolutions are no longer limited to those of conventional microscopy imaging. At every probe position across a nanoparticle, or at an interface, the electron energy-gain spectrum can be acquired as a function of the time delay between femtosecond optical and electron pulses, and imaging is complete when the focused probe is simultaneously scanned.

We conducted two sets of experiments to demonstrate the potential of the technique. For plasmonic Ag particles, we observed the polarized electric field distribution, the femtosecond dielectric response, and the nanometer spatial localization of a single particle. For the Cu metal–vacuum interface, we determined the effective decay length (nanometer scale) and the evolution (femtosecond resolution) of the plasmonic field, and identified the strong and weak regions of the field by scanning the probe away from the interface. We anticipate a broad range of applications of USI because of the dimensions it simultaneously enables for imaging in space, time, and energy.

Knowledge of the dielectric response of materials and biological systems to an optical excitation is essential to the determination of the strength and extent of interaction between electromagnetic waves and systems under study. For example, bulk materials' reflection and absorption are dictated by such responses at the incident wavelengths. At the nanoscale, where the boundaries can have a marked effect on the way light manifests itself, the response can include spatially localized plasmonic fields (*5*, *6*). It follows that an understanding of the dynamics at the microscopic level, with combined spatial, spectral, and temporal resolutions, would be indispensable, both at the fundamental level and for various applications.

For bulk systems, there exist various optical techniques for measuring the dielectric response; these include ellipsometry, Fourier transform infrared spectroscopy, and Raman spectroscopy. In the frequency domain, these techniques can readily reach the energy resolution necessary to differentiate vibrational and rotational modes in molecules (meV and sub-meV) and collective vibrational excitations in solids (phonons). In the spatial domain, however, these techniques are limited by diffraction effects, and hence they exhibit a typical resolution of several hundred nanometers at the visible wavelengths. Modern optical methods have enabled improvement of resolution (*7*–*9*) beyond the diffraction limit in certain circumstances, but they cannot provide the spatial resolution of

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