SEPTEMBER 2017
R: 16-06-A

REPORT

AMERICA'S CLEAN ENERGY FRONTIER: THE PATHWAY TO A SAFER CLIMATE FUTURE

AUTHORS
Vignesh Gowrishankar
Amanda Levin

Authors and Acknowledgments

Authors: Vignesh Gowrishankar, Amanda Levin

E3 team: Ben Haley (now at Evolved Energy) and Jim Williams (now at University of San Francisco), with support from Amber Mahone and Fritz Kahrl.

External reviewers: Daniel Kammen (University of California, Berkeley), John Larsen (Rhodium Group)

We also received crucial feedback from a number of colleagues at other organizations.

The authors would like to acknowledge the invaluable contributions of a number of NRDC colleagues: Sneha Ayyagari, Vartan Badalian, Tom Barkley, Merrian Borgeson, Kaitlin Brazill, Sheryl Carter, Ralph Cavanagh, Han Chen, Jennifer Chen, Pierre Delforge, David Doniger, Lara Ettenson, Geoffrey Fettus, Rob Friedman, Nathanael Greene, Ashok Gupta, Lawrence Haseley, David Hawkins, Mary Heglar, Roland Hwang, Katherine Kennedy, Francine Kershaw, Virginia Lee, Ben Longstreth, Amy Mall, Elise Marton, Matthew McKinzie, John Moore, Briana Mordick, Jackson Morris, Simon Mui, Derek Murrow, Helen O'Shea, George Peridas, Pat Remick, Marybeth Reynolds, Sue Rossi, Jake Schmidt, Kevin Steinberger, Christina Swanson, Jake Thompson, Luke Tonachel, and Starla Yeh.

About NRDC

The Natural Resources Defense Council is an international nonprofit environmental organization with more than 2.4 million members and online activists. Since 1970, our lawyers, scientists, and other environmental specialists have worked to protect the world's natural resources, public health, and the environment. NRDC has offices in New York City, Washington, D.C., Los Angeles, San Francisco, Chicago, Montana, and Beijing. Visit us at nrdc.org.

NRDC Chief Communications Officer: Michelle Egan
NRDC Deputy Directors of Communications: Lisa Goffredi and Jenny Powers
NRDC Senior Editor, Policy Publications: Mary Annaïse Heglar
NRDC Policy Editor, Policy Publications: Tim Lau
Design and Production: www.suerossi.com

Cover image: © NASA

Table of Contents

Glossary

ACEEE	American Council for an Energy-Efficient Economy
AEO	Annual Energy Outlook
CCS	carbon capture and storage
CHP	combined heat and power
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
COP	Conference of the Parties
DDPP	Deep Decarbonization Pathways Project
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
E3	Energy + Environmental Economics, Inc.
EERS	energy efficiency resource standard
EIA	U.S. Energy Information Administration
EJ	exajoule
EPA	U.S. Environmental Protection Agency
EV	electric vehicle
FERC	Federal Energy Regulatory Commission
GDP	gross domestic product
GHG	greenhouse gas
GW	gigawatt
GWh	gigawatt-hour
HDV	heavy-duty vehicle
HFC	hydrofluorocarbon
IPCC	Intergovernmental Panel on Climate Change
ISO	independent system operator
kWh	kilowatt-hour
LBNL	Lawrence Berkeley National Laboratory
LDV	light-duty vehicle
LED	light-emitting diode
LNG	liquefied natural gas
LPG	liquefied petroleum gas
MCS	U.S. Mid-Century Strategy for Deep Decarbonization
MDV	medium-duty vehicle
mpg	miles per gallon
MMT	million metric tons
MW	megawatt
MWh	megawatt-hour
NDC	nationally determined contribution
NEMS	National Energy Modeling System
NEO	New Energy Outlook
NGO	nongovernmental organization
NRC	Nuclear Regulatory Commission
NRDC	Natural Resources Defense Council
NREL	National Renewable Energy Laboratory
PHEV	plug-in hybrid electric vehicle
PPA	power purchase agreement
R&D	research and development
RGGI	Regional Greenhouse Gas Initiative
RPS	renewable portfolio standard
RTO	regional transmission operator
solar PV	solar photovoltaics
TWh	terawatt-hour
UNFCCC	United Nations Framework Convention on Climate Change
VMT	vehicle-miles traveled
ZEV	zero emission vehicle

I. Executive Summary

© Shun Kambe

To stave off the worst impacts of climate change, the world must limit warming to no more than 2 degrees Celsius above preindustrial temperatures. The Intergovernmental Panel on Climate Change (IPCC) says this will require developed countries—especially the United States as the world's second-largest emitter—to cut their greenhouse gas (GHG) pollution by at least 80 percent by 2050, relative to 1990 emissions levels.[1,2] The Natural Resources Defense Council (NRDC) partnered with the internationally recognized consultant group Energy + Environmental Economics (E3) to determine whether, and how, the United States could achieve this target.

NRDC's groundbreaking analysis demonstrates clearly that with bold action on energy efficiency, renewable energy, electrification of vehicles and buildings with clean power, and electric grid enhancements, the United States can reach its 80 percent by 2050 climate goal. Moreover, we can get there at a much lower cost than any comparable study predicts.

Between 2015 and 2050, our plan's costs are just 1 percent more than current U.S. energy costs, but deliver benefits 7 times greater than these costs. This translates to average costs of $22 billion a year and more than $154 billion a year in environmental benefits—in extreme weather, heat waves, and climate-induced illnesses avoided. If we include resulting additional health advantages, the net benefits would be even greater. It's notable that NRDC's pathway incurs low additional costs cumulatively by 2050 compared to a scenario in which no action is taken, but costs less in 2050, and may be the lowest-cost option beyond 2050. The additional expense arises from more up-front capital investments in clean and efficient power, appliances, and vehicles. But these technology investments result in significant and growing fuel savings that help offset the incremental costs over time. In fact, our scenario costs $30 billion less in 2050 than a no-action scenario. Lastly, while we did not model post-2050, our approach may be the least-cost option beyond 2050, thanks to the continuing fuel savings. Furthermore, there is no need for technological breakthroughs—we have the tools now. The United States can cost-effectively reduce GHG emissions with proven clean energy solutions, most of which are deployed at commercial scale today.

While other studies also conclude that an 80 percent emissions reduction by 2050 is feasible, our report breaks new ground by combining more aggressive—but achievable—assumptions on the potential to scale up energy efficiency, renewable energy, and clean electrification, with a more robust technical analysis incorporating grid reliability impacts. Our modeling also maximizes the co-benefits of energy efficiency (e.g., consumer bill reduction, reduced stress on the electricity grid, reduced air and water pollution, and fewer land use impacts). The modeling in other reports relies more on costlier or riskier technologies such as biomass or nuclear, or those currently deployed at a much lower scale like carbon capture and storage (CCS), to help meet U.S. climate objectives.[3,4] NRDC's study reveals new insights into what we believe to be a better, safer way to achieve America's deep decarbonization goal, strengthening our grid and economy.

Since we began our analysis, President Trump announced his intention to withdraw the United States from the global Paris Climate Agreement, which pledges to limit the increase in global warming to well below 2 degrees (Celsius) while making best efforts to keep it beneath 1.5 degrees. Even if the federal government defaults on climate action for a period of time, it is essential that we continue to pursue aggressive emissions reductions to rein in runaway climate change. The efforts of state and local governments and businesses are even more crucial now, and fortunately there has been encouraging progress on that front.[5,6]

KEY FINDINGS

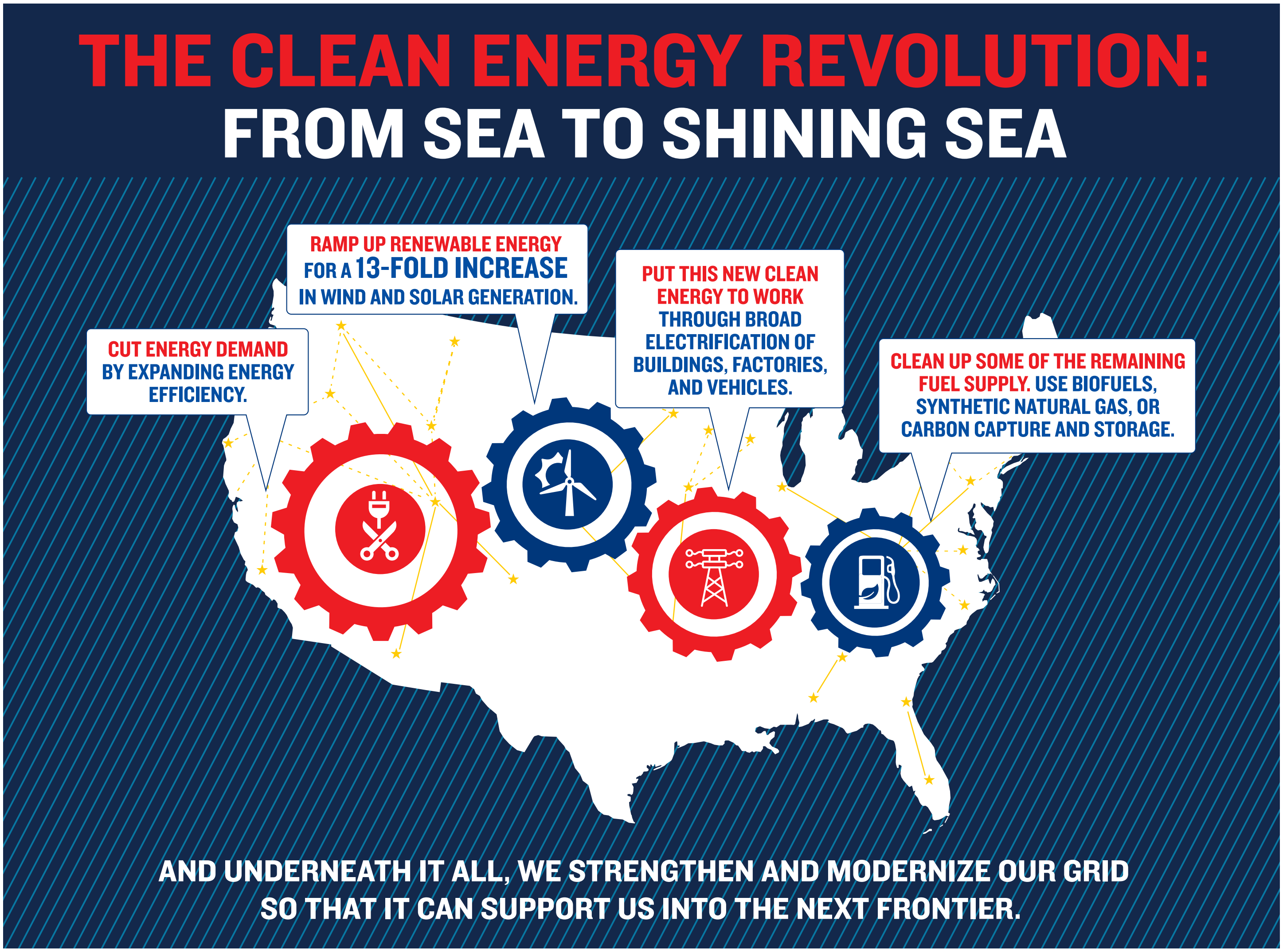
Our analysis shows that expanding **proven clean energy solutions—most of which are already deployed at commercial scale—can reduce U.S. GHG emissions across the entire economy by 80 percent by 2050**. Under our NRDC Core Scenario, the United States will:

1. **Implement energy efficiency technologies and system-wide approaches to reduce total U.S. energy demand by 40 percent** (compared with our reference case in which America's energy system evolves as it has historically). These reductions are achieved by aggressive efficiency improvements in buildings, factories, appliances, and vehicles based on what multiple, peer-reviewed sources have determined is feasible. New homes and office buildings would conform to much more stringent building energy codes, existing buildings undergo energy-saving improvements, the efficiency of appliances and equipment continues to increase, and the United States universally adopts light-emitting diode (LED) lighting in the buildings sector, helping consumers save energy and money while reducing the nation's carbon footprint. The industrial sector also must make significant investments in efficiency, ultimately achieving sector-wide energy savings in line with those already attained by some leading industrial players. Lastly, passenger vehicles continue to become more efficient, with the gasoline vehicle fleet achieving an average fuel economy of around 80 miles per gallon (mpg) by 2050 (exceeding 100 mpg in gasoline equivalents if electric cars are included). This is accompanied by about 25 percent reduction in annual average passenger vehicle-miles traveled (VMT). These levels of energy efficiency require multiple, complementary efficiency investments that can be driven by federal, state, and local policies and standards, in coordination with businesses and communities.

2. **Significantly expand renewable energy, like wind and solar, to generate more than 70 percent of our electricity supply by 2050**, compared with today's 8 percent from wind and solar. This will require a sizable increase in large-scale renewable energy facilities. Distributed (locally generated) renewable power production also can play a significant role. While ambitious, this expansion is achievable given the dizzying pace of U.S. renewable energy development amid steep price declines. For example, the costs of solar modules, the building blocks of photovoltaic panels, have declined by 80 percent in less than a decade, and average long-term power purchase contracts for wind have plummeted from $70 per megawatt-hour (MWh) in 2009 to less than $20 per MWh in 2016.[7] Even as the federal renewable energy tax credits phase out, analysts expect solar and wind to become the lowest-cost form of new power by 2023 and to be less expensive than even existing fossil generation by 2027 nationwide.[8] (It is already cheaper in some U.S. locations.[9]) This buildout also is in line with other peer-reviewed modeling and government reports.

3. **Employ the resulting near-zero-carbon electricity to the greatest practical extent to directly displace fossil fuels in transportation, residential and commercial buildings, and industry.** By 2050, electricity produced largely from renewable resources could supply up to 45 percent of U.S. energy needs, up from just one-fifth today. Although this transformation is in its early stages, recent progress includes more than a half-million electric or hybrid cars on America's roads.[10] While our analysis electrifies a substantial portion of the economy, customer preferences and technological hurdles also were incorporated. This results in a scenario with more minimal electrification of some items, such as gas stoves, long-distance freight trucks, and the most energy-intensive industries. Electrification technologies result in an additional 10 percent reduction, approximately, of overall energy demand, bringing the total energy demand reduction to about 50 percent.

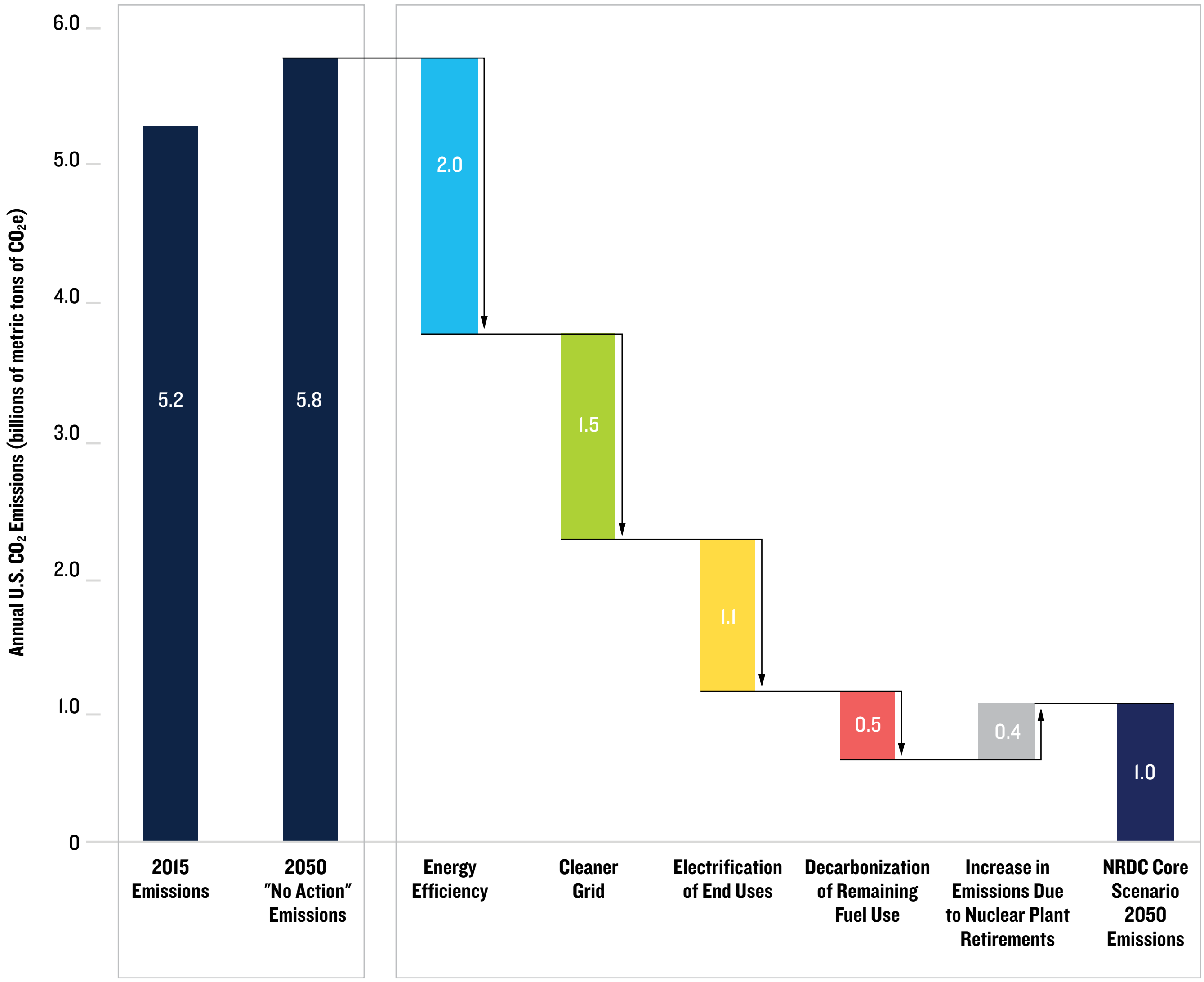
4. **Decarbonize some of the remaining fuel use**, mainly in transportation and industry. For applications that would be difficult to directly electrify (e.g., airplanes or long-haul trucks), we will need to replace oil or natural gas with decarbonized alternative fuels, derived from sustainable biomass or synthetic gas, and utilize carbon capture technologies to reduce the emissions footprint of these sub-sectors.[11] Such strategies will contribute a vital 10 percent of emissions reductions.



Our analysis demonstrates that the projected level of renewable energy resources can be reliably integrated into the U.S. electricity grid, but it is critical that we modernize and expand it. The grid needs to be updated no matter what the future U.S. energy system looks like, as most of it was built more than 40 years ago and it is vulnerable to extreme weather events. Prioritizing grid investments that better accommodate large-scale renewable energy generation, distributed energy resources, storage technologies, and flexible demand patterns will ensure the biggest bang for our buck. Achieving a clean electric grid will require transmission and distribution infrastructure investments, expanded grid-oversight regions, reforms to energy market rules and operations, improved operational practices, advanced forecasting, and demand-side upgrades, as well as mechanisms that better utilize and value these clean energy solutions.[12] These investments also can better optimize energy supply and demand, mitigating the incremental costs of an expanded clean electric transmission system by hundreds of billions of dollars.

Our four clean energy drivers, supported by a modernized grid, would reduce emissions to 1 billion metric tons compared to the approximately 5.8 billion metric tons anticipated if no action is taken, as shown in Exhibit ES-1.

EXHIBIT ES-1: ACHIEVING NRDC'S EMISSIONS REDUCTIONS IN 2050



Our analysis also incorporates estimated feasible reductions in all greenhouse gases beyond carbon dioxide, including methane emissions from oil and gas operations and the meat industry, nitrous oxide from the agricultural industry, and hydrofluorocarbons (HFCs) from refrigeration and cooling equipment. Reducing these GHGs is critical to achieving the overall U.S. emissions reduction target.

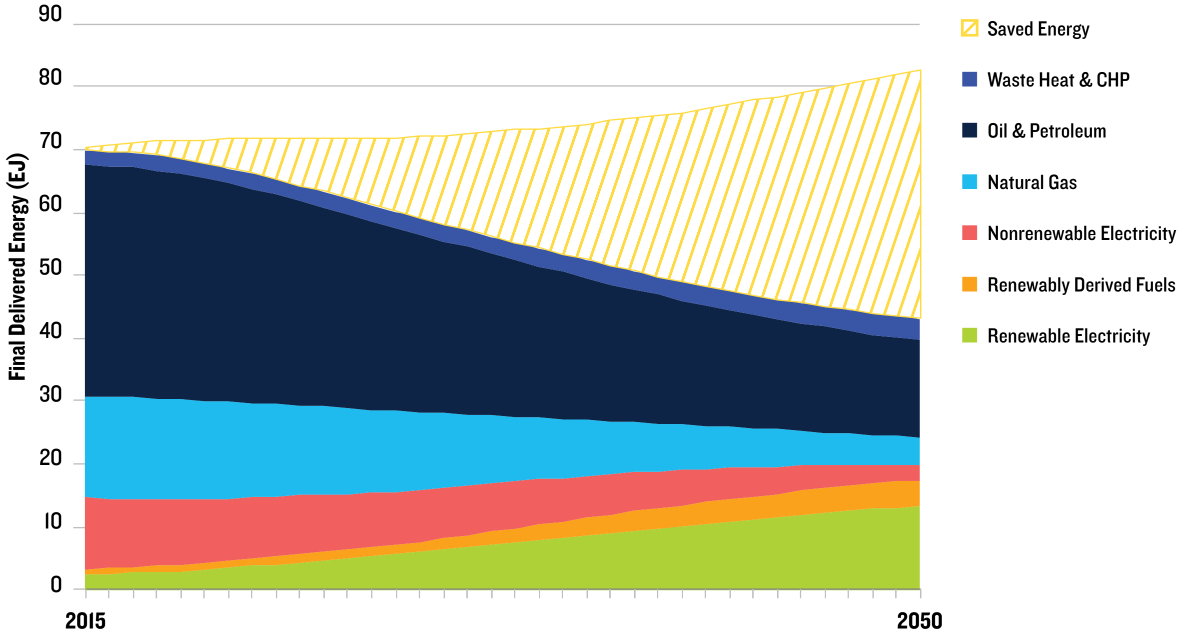
NRDC's pathway would reduce fossil fuel use by 70 percent in 2050, as shown in Exhibit ES-2. Among other actions, with additional shifts in higher- to lower-carbon fossil fuels and the use of carbon capture technologies, total GHG emissions can be cut by 80 percent, meeting our 2050 goal. Fossil fuels are the current main contributor to U.S. GHG emissions.

NRDC's Core Scenario relies on a broad, diverse portfolio of resources and technologies to achieve a decarbonized energy system, which allows for a more practical and lower-cost pathway forward. Exhibit ES-2 also shows how total energy demand drops by nearly half, while clean electricity use increases to enable shifts in ways energy is used (e.g., electric instead of gasoline cars). This break from fossil fuels will mitigate myriad health and environmental concerns related to their extraction, transportation, and consumption, and achieve a massive reduction in U.S. GHG emissions.[13]

NRDC's pathway would reduce fossil fuel use by 70 percent in 2050.

The energy shift will vary considerably by industry, region, and fuel type, depending on available infrastructure and technologies, and the comparable costs of possible solutions. For example, coal use declines by 90 percent from current levels under our scenario. Natural gas consumption declines by about two-thirds as there may be some gas use to replace fuels with higher carbon emissions, like coal and oil, in the industrial and transportation sectors.

EXHIBIT ES-2: ENERGY USE BY ENERGY SOURCE IN THE NRDC CORE SCENARIO



Total energy demand drops by nearly half. Fossil fuel usage declines sharply, while clean electricity use increases to enable modal shifts.

Technologies like efficiency and renewable energy already exist. Nonetheless, robust support for research and development (R&D) will remain crucial to improving them and decreasing the costs of moving to a lower-carbon energy system. Continual innovation, such as manufacturing and design refinements, can help further reduce costs as well as the potential operation and integration challenges of transitioning to a much cleaner system. Furthermore, innovation almost certainly will produce improved technologies by 2050 that we cannot even anticipate now.

However, failure to achieve the required clean energy deployment levels we know are possible will contribute to enormous climate disruption, or reliance on approaches that are costlier or riskier or currently deployed at a smaller scale to achieve our emissions target—or both. Strategic R&D investments to improve options like nuclear, biomass, and CCS could provide a hedge in the event that we wind up needing more of them because of insufficient clean energy investments.

Finally, the benefits of our plan will far exceed the costs. Even with conservative cost assumptions, the NRDC Core Scenario only costs about 1 percent more, or about $22 billion a year on average, than the Reference Case (in which the U.S. energy system evolves as it has historically). But the climate benefits—like avoided property and crop damage from extreme weather, fewer heat waves, and less climate-induced illnesses—would total more than $154 billion in additional benefits a year. That is 7 times greater than the costs, and does not include additional health benefits from reductions in ground-level smog and ozone.[14] While there are modest energy costs over the 35-year period arising from clean energy-related capital investments, these costs decline over time due to the considerable fuel savings from reduced energy demand and growing renewable power. In fact, in 2050, NRDC's pathway costs $30 billion less than the Reference Case thanks to these fuel savings from clean energy investments. These cost savings are likely to continue or grow after 2050, which could make the NRDC Core Scenario less expensive overall than the Reference Case over a period that extends beyond 2050, though the post-2050 timeframe was not modeled.[14] In sharp contrast, our modeling shows that delayed implementation by up to a decade would cost 10 to 15 percent more annually than the Reference Case by 2050.

Our Core Scenario also would drive substantial employment growth in clean energy sectors such as wind and solar, alternative fuels and vehicles, and energy efficiency manufacturing and construction. The clean energy economy today employs 2.8 million Americans—more than twice the number working in the fossil fuel industry—and would continue to increase. Clean energy also brings economic activity and has positive tax revenue implications at the local and state levels. Continued investment now will allow the United States to remain a global leader—and perhaps strengthen its position—in a sector that will only expand considerably and rapidly.

The clean energy economy today employs 2.8 million Americans—more than twice the number working in the fossil fuel industry—and would continue to increase.

OUR MODELING APPROACH

NRDC's analysis used E3's PATHWAYS model, which shares a common architecture with the U.S. Energy Information Administration's (EIA) National Energy Modeling System (NEMS), which was used to generate annual projections of energy production, demand, imports, and prices. However, the PATHWAYS model incorporates a more detailed representation of America's energy resource portfolio, the electricity sector, and grid operations and expansion. The data, costs, and other pertinent assumptions used in our modeling are largely from the EIA's Annual Energy Outlook (AEO) 2013 in order to facilitate an apples-to-apples comparison with other deep decarbonization reports using the same information. However, since 2013, there have been unforeseen rapid and continuing cost declines for wind and solar energy, and natural gas prices have plummeted, which means our cost projections may be higher than the most recent data indicates.

POLICY IMPLICATIONS

Finally, this report considers the policy implications of the NRDC Core Scenario and discusses high-level recommendations that can be taken at the federal, state, and city levels to meet the goal of an 80 percent reduction in emissions by 2050. They are based on these principles:

- To stave off the worst effects of climate change, we need an immediate, orderly, economy-wide transition to a clean energy system, which demands a **comprehensive approach leveraging effective policy frameworks and powerful market drivers to unleash the necessary investments**.
- Until the federal government resumes leadership on addressing climate change, **numerous actions can be taken at the regional, state, and city levels and by businesses and communities**. However, a national economy-wide approach is required for ultimate success.
- To meet the 2050 goal at the lowest cost, **policymakers and market participants should proactively accelerate widespread deployment and expansion of proven clean energy technologies** to avoid reliance on riskier and more expensive options.
- **Policies should provide forward-thinking guidance** to avoid undermining long-term emissions goals and creating stranded assets in the form of power plants, pipelines, or infrastructure no longer needed or desired. In the absence of sound, long-term planning, progress will be uneven and could fall short in the long-term.
- To achieve deep decarbonization, **all GHG emissions must be reduced**.

With these principles in mind, a range of tailored policies can drive the rapid and widespread deployment of proven clean energy technologies. To start, federal and state governments should expand and accelerate the adoption of performance-based standards for energy use and carbon pollution for vehicles, power plants, buildings, and appliances and equipment. Renewable energy portfolio standards, tax incentives, and other federal and state policies can continue to drive renewable energy progress forward. To reduce emissions from the transportation sector, we need to expand access to healthier, cleaner, more affordable, and faster transit alternatives. Since cars and trucks are a major part of the sector, clean vehicle and fuel economy standards will play a critical role. Policies that spur the adoption of mass transit, biking, or electric vehicles will also be vital.

Utilities should continue to play a central role in supporting this clean energy transition. State regulators must work with utilities to reform their business models to incentivize more investments in cost-effective energy efficiency and renewable energy. In particular, utilities need to take bolder steps to target the industrial sector, building decarbonization, and electric vehicles. Utilities can also be key players in upgrading our grid to facilitate the deployment and integration of clean electricity and emerging demand-side technologies (e.g., electric vehicles and rooftop solar). Policies must support the modernization of the power grid—its infrastructure, oversight, and operations.

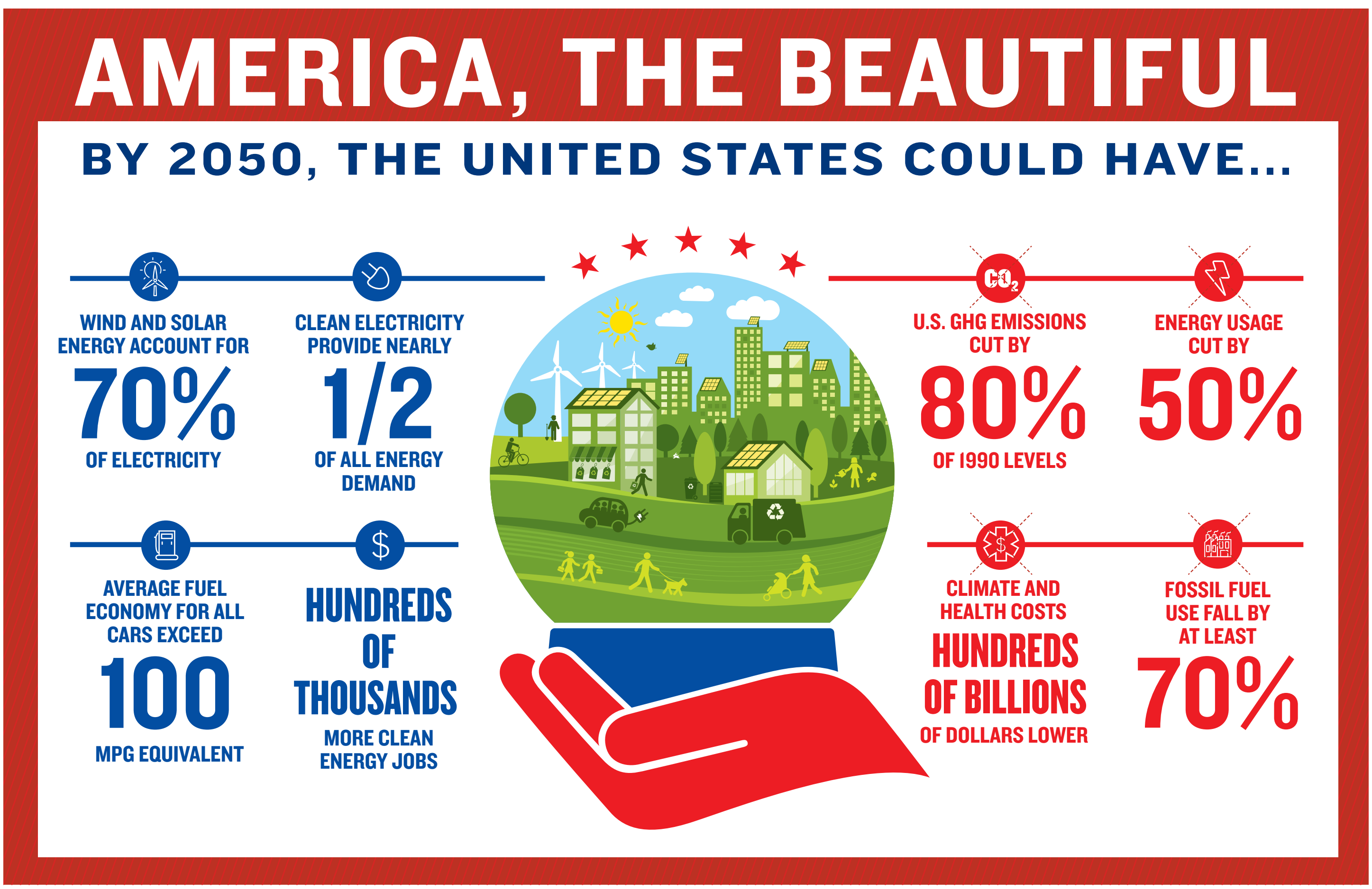
Investments in fossil fuel infrastructure, like power plants and natural gas pipelines, should be critically assessed to reduce the risk of stranded assets and the overall costs of transitioning to a decarbonized energy system. Meanwhile, innovation can lower the cost and environmental impact of current technologies, improve their integration into the energy system, and open doors to new options that could make it even easier to meet or exceed our 2050 goal.

Finally, policymakers should work with affected communities to ensure the clean energy transition is equitable and just, and that it maximizes the benefits of climate action. All Americans should have access to the benefits of clean energy, regardless of region or income. We can and should build this economy to benefit all communities, particularly those that have been adversely affected by the fossil fuel industry. Policies should also recognize and mitigate economic and employment impacts in regions and portions of the workforce that currently depend more on fossil fuel energy and reserves.

CLEAN ENERGY: THE NEXT AMERICAN FRONTIER

With the looming threat of worsening climate change, America's energy system must now evolve even more quickly to a cleaner energy future. The timing is urgent—and standing idle is not an option. Strategic and bold investments in energy efficiency, renewable energy, clean vehicles, and a stronger electricity grid will keep us on the right path. But if we collectively fail to act, we will lock ourselves into a dirtier energy system and may not be able to thwart the most dangerous impacts to our environment and our health.

This is an all-hands-on-deck moment. All levels of government must summon the political will to work with communities and businesses to adopt the policy framework and market structures that can guide investments in our long-term clean energy future. As NRDC's analysis shows, a clean energy transition is achievable at low cost and with today's technology. Success will enhance the safety and reliability of our energy system while putting Americans to work, lowering energy costs, curbing dangerous climate change, and protecting communities and natural resources. This transition will not be without challenges, but the choice is clear.



Executive Summary Endnotes

1 The White House, "Fact Sheet: U.S. Reports Its 2025 Emissions Target to the UNFCCC," March 31, 2015, https://obamawhitehouse.archives.gov/the-press-office/2015/03/31/fact-sheet-us-reports-its-2025-emissions-target-unfccc.

2 Intergovernmental Panel on Climate Change (IPCC), IPCC Fourth Assessment Report: Climate Change 2007, "Working Group III: Mitigation of Climate Change." See Chapter 13.3.3.3 Implications of regime stringency: linking goals, participation and timing. https://www.ipcc.ch/publications_and_data/ar4/wg3/en/ch13-ens13-3-3-3.html.

3 J.H. Williams et al., *Pathways to Deep Decarbonization in the United States*, revision with technical supplement, Energy and Environmental Economics, Inc. (E3), November 16, 2015, http://deepdecarbonization.org/wp-content/uploads/2015/11/US_Deep_Decarbonization_Technical_Report_Exec_Summary.pdf.

4 The White House, *United States Mid-Century Strategy for Deep Decarbonization*, November 2016, https://unfccc.int/files/focus/long-term_strategies/application/pdf/us_mid_century_strategy.pdf.

5 Climate Mayors, "359 US Climate Mayors Commit to Adopt, Honor and Uphold Paris Climate Agreement Goals," June 1, 2017, https://medium.com/@ClimateMayors/climate-mayors-commit-to-adopt-honor-and-uphold-paris-climate-agreement-goals-ba566e260097. Inslee, Jay. "United States Climate Alliance Adds 10 New Members to Coalition Committed to Upholding the Paris Accord," June 5, 2017, http://governor.wa.gov/news-media/united-states-climate-alliance-adds-10-new-members-coalition-committed-upholding-paris.

6 Henry Fountain and Hiroko Tabuchi, "Bucking Trump, These Cities, States and Companies Commit to Paris Accord," *New York Times*, June 1, 2017, https://www.nytimes.com/2017/06/01/climate/american-cities-climate-standards.html?hp&action=click&pgtype=Homepage&clickSource=story-heading&module=b-lede-package-region&region=top-news&WT.nav=top-news.

7 U.S. Department of Energy, *2016 Wind Technologies Market Report*, August 2017, https://energy.gov/eere/wind/downloads/2016-wind-technologies-market-report.

8 Bloomberg New Energy Finance, *2017 Sustainable Energy in America Factbook*, January 2017, https://data.bloomberglp.com/bnef/sites/14/2017/02/BCSE-BNEF-2017-Sustainable-Energy-in-America-Factbook.pdf. Bloomberg New Energy Finance, *New Energy Outlook 2017*, June 2017, https://about.bnef.com/new-energy-outlook/.

9 U.S. Department of Energy, *2016 Wind Technologies Market Report*, August 2017.

10 Bloomberg New Energy Finance, "EV Data Hub," accessed August 14, 2017 (data updated quarterly), subscription service access only.

11 U.S. Energy Information Administration, "Power-to-Gas Brings a New Focus to the Issue of Energy Storage from Renewable Sources," July 24, 2015, http://www.eia.gov/todayinenergy/detail.php?id=22212.

12 Trieu Mai, et al., *Renewable Electricity Futures Study*, National Renewable Energy Laboratory, 2012, http://www.nrel.gov/docs/fy12osti/52409-1.pdf.

13 Union of Concerned Scientists, "The Hidden Costs of Fossil Fuels," last revised August 2016, http://www.ucsusa.org/clean-energy/coal-and-other-fossil-fuels/hidden-cost-of-fossils#.WO-_-WnysdU.

14 Between 2015 and 2050, the total environmental benefit of carbon pollution avoided in the NRDC Core Scenario is $5.6 trillion (2011$), and the estimated cumulative health benefit is $557 billion. Cumulative impacts reflect the annual social cost of carbon values associated with each year between 2015 and 2050, starting at $33.63 per metric ton in 2010 and rising to $74.86 in 2050 (2011$). Interagency Working Group, "Technical Update on the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866," May 2013, https://obamawhitehouse.archives.gov/sites/default/files/omb/inforeg/scc-tsd-final-july-2015.pdf. The forecast non-climate costs of coal and gas generation (not including upstream impacts) reflecting the health costs of associated non-CO_2 pollution at the smokestack are drawn from the National Research Council. National Research Council, *Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use* (Washington, D.C.: The National Academies Press, 2010), http://www.ourenergypolicy.org/wp-content/uploads/2012/06/hidden.pdf.

1. The Global Climate Context

The scientific consensus is nearly unanimous: the earth is warming, the climate is changing, and it's overwhelmingly due to the burning of fossil fuels. To restrain dangerous, human-driven climate change, we must limit the average warming of the planet to well below 2 degrees Celsius above preindustrial levels, and strive to limit it to 1.5 degrees to further reduce risk.[1] The Intergovernmental Panel on Climate Change (IPCC) has concluded that limiting warming to a 2-degree threshold will require significant reductions in greenhouse gas (GHG) emissions by the middle of this century—and net zero emissions globally by century's end.[2] We need global collaboration to accomplish this, and each individual country must act to reduce its own emissions. If the world's countries fail to meet the midcentury targets, keeping temperatures below 2 degrees Celsius through the end of the century will likely require the deployment of more nascent technologies such as atmospheric carbon dioxide removal or other, yet-unknown methods.

In 2014, almost 36 billion tons of carbon dioxide were emitted globally.[3] The four largest emitters were China, the United States, the entire European Union, and India, in that order.[4] Together these nations contributed to almost two-thirds of all carbon dioxide emissions that year. Historically (cumulative contributions from 1850 to 2010), however, China and India are responsible for only 10 and 6 percent of the current level of global warming, respectively. On the other hand, the United States and the European Union contributed 23 and 17 percent, respectively.[5] The United States, as one of the largest emitters of global GHGs, both currently and historically, must aggressively reduce its emissions. In addition, the United States must use its powerful position as a global leader to work with other developed and developing economies to ensure that they also hit GHG reduction goals in a timely manner.

In December 2015, the United Nations Framework Convention on Climate Change (UNFCCC) convened world leaders in Paris for the 21st Conference of the Parties (COP21). There, more than 190 nations, including all of the world's largest polluters, signed what is now known as the Paris Agreement. By doing so, they pledged to limit global average temperature to well below 2 degrees Celsius above preindustrial levels and to pursue efforts to limit the increase to 1.5 degrees.[6] The Paris Agreement entered into force on November 4, 2016, with each signatory submitting a nationally determined contribution (NDC) that detailed how, where, and by when it would cut emissions in the next few years and initial steps toward realizing the pledge.[7] As part of its NDC, the United States set an emissions reduction target of 26 to 28 percent by 2025 (relative to 2005 levels).[8] The IPCC has found that developed countries, including the United States, need to achieve at least 80 percent GHG emissions reductions below 1990 levels by 2050 to keep warming below 2 degrees Celsius.[9]

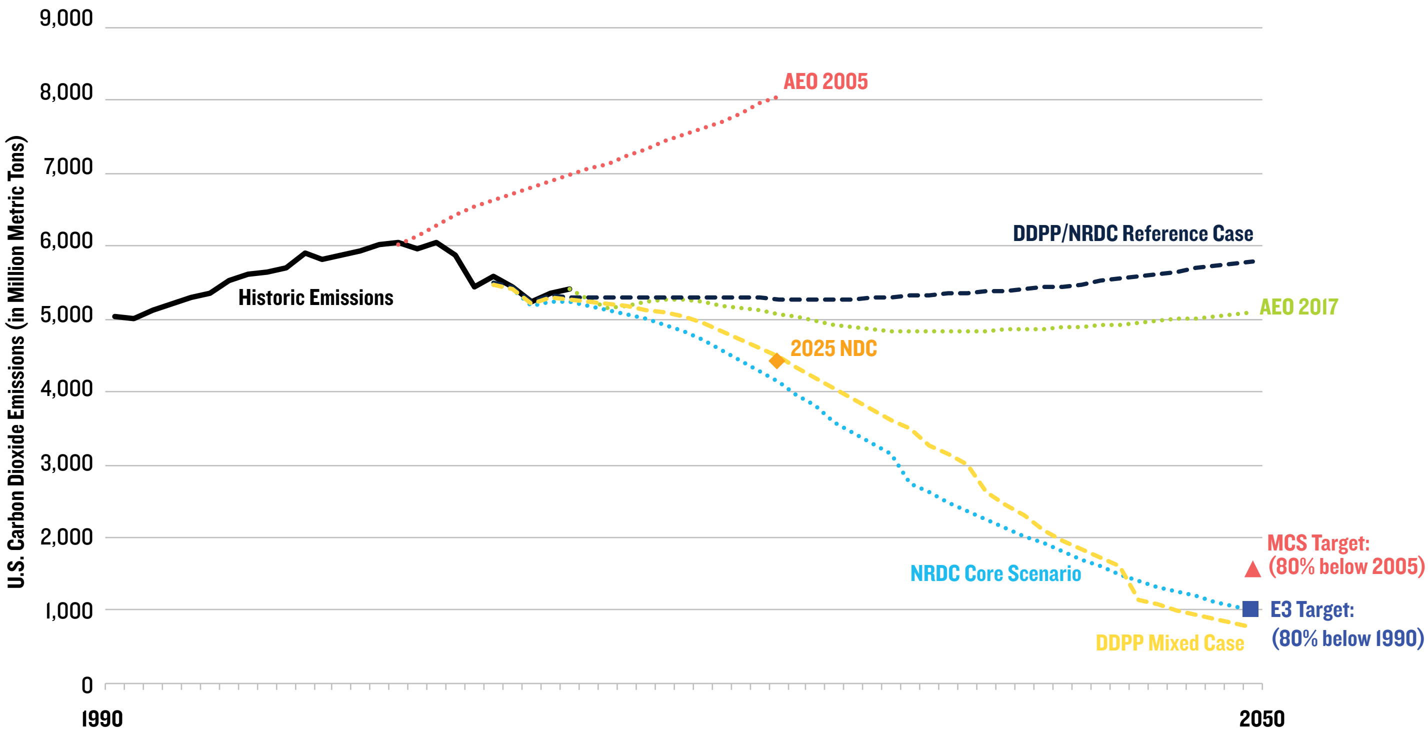
In June 2017, President Trump announced his decision to withdraw the United States from the Paris Agreement.[10] The process of officially abandoning the Agreement will take at least until 2020, and ultimately a new administration may reverse this decision. Even if the federal government defaults on climate action for a period of time, it is essential that the United States continues to pursue aggressive reductions to rein in runaway climate change in the interim. For this reason, the efforts of state and local governments and businesses become even more crucial, and there has been encouraging progress on that front. Immediately after the Trump administration's announcement, more than 350 cities and states—and counting—have come together in support of the Paris Agreement's goals and pledged to take action. Separately, the business community and universities, in combination with state and local governments, have reaffirmed the goals of Paris and are seeking to submit to the United Nations a joint commitment to reduce emissions in line with the Paris Agreement.[a]

a See Section 3.1 for more details. Climate Mayors, "359 US Climate Mayors Commit to Adopt, Honor and Uphold Paris Climate Agreement Goals," June 1, 2017, https://medium.com/@ClimateMayors/climate-mayors-commit-to-adopt-honor-and-uphold-paris-climate-agreement-goals-ba566e260097. Inslee, Jay. "United States Climate Alliance Adds 10 New Members to Coalition Committed to Upholding the Paris Accord," June 5, 2017, http://governor.wa.gov/news-media/united-states-climate-alliance-adds-10-new-members-coalition-committed-upholding-paris.

U.S. EMISSIONS TRAJECTORIES AND NRDC'S SCENARIO

Exhibit 1 depicts the trajectories of carbon dioxide emissions in the United States under different scenarios.[b,11] The U.S. Energy Information Administration's (EIA) Annual Energy Outlook (AEO) for 2005 assumed that carbon dioxide emissions would rise steadily over the next several decades to support economic growth.[12] This projection, however, has proved inaccurate. Until the mid-2000s, electricity-related GHG emissions and electricity demand grew in line with economic growth. Since then, while gross domestic product (GDP) has continued to grow, electricity use has declined slightly and emissions have fallen steeply, driven by increased renewable energy and natural gas use. In fact, between 2005 and 2016, U.S. carbon dioxide emissions fell by 14 percent and energy use remained flat.[13] At the same time, the U.S. economy grew by 17 percent (in chained dollars, accounting for inflation).[14]

EXHIBIT 1: TRAJECTORIES OF U.S. CARBON DIOXIDE EMISSIONS FROM 1990 TO 2050 IN DIFFERENT SCENARIOS



The DDPP/NRDC Reference Case is based on AEO 2013. E3 used a reduction goal of 80 percent by 2050 based on 1990 levels. MCS stands for Mid-Century Strategy, which was decarbonization modeling completed by the Obama administration following the Paris accord; MCS used a goal of 80 percent by 2050 based on 2005 levels.

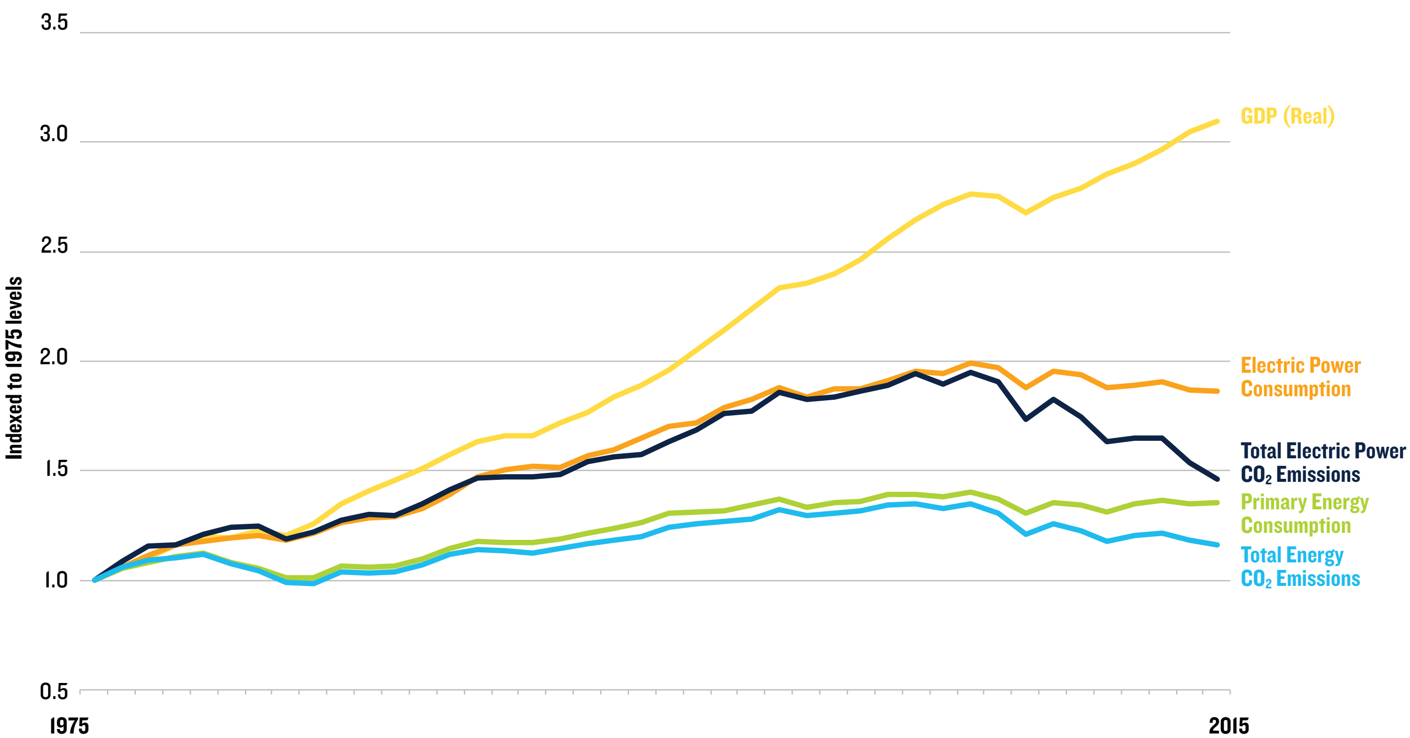
The changing relationships among carbon dioxide emissions, energy demand, and GDP have been driven by a combination of economic, policy, and technological factors. These include improvements in fuel efficiency in the transportation sector; growth in natural gas, wind, and solar in the power sector due to policy action and falling costs; decreasing energy intensity (the amount of energy it takes to produce a certain product or good) in the industrial sector; and improved energy efficiency across the economy.[15] The electricity sector has seen the most significant alterations in relationships among emissions, energy demand, and economic growth (See Exhibit 2).

b While GHG emissions reductions will require reductions of both CO_2 and non-CO_2 gases, CO_2 is the primary GHG, constituting more than 80 percent of all GHGs, and is most strongly correlated with long-term warming. Therefore, an analysis of its emissions trajectory alone can provide a good sense of the overall emissions reduction need.

The EIA's most recent forecast (noted as AEO 2017 in Exhibit 1) now projects that carbon dioxide emissions will decline to around 4.8 billion metric tons by 2030 and then rise slightly to 5 billion metric tons in 2047 without additional policy drivers.[16,17] However, much deeper carbon reductions are needed to meet both the shorter-term 2025 target indicated in the U.S. NDC and the longer-term 2050 target. This will require strengthening federal, state, and local clean energy policies. Note that there are two distinct 2050 targets. Both NRDC and the U.S. scenario for the Deep Decarbonization Pathways Project (DDPP) used an 80 percent reduction *from 1990 levels*. The Obama administration's Mid-Century Strategy report (MCS) used an 80 percent reduction *from 2005 levels*, which was the peak year for annual U.S. GHG emissions.[c]

The two sharply declining trajectories (DDPP Mixed Case and NRDC Core Scenario) in Exhibit 1 illustrate how deep decarbonization can manifest between now and 2050. They are both derived using the PATHWAYS model by Energy + Environmental Economics (E3). NRDC Core Scenario[d] is based on NRDC's scenario that is discussed in detail in Section 2. The DDPP Mixed Case is based on the analysis of researchers for the United States as part of DDPP.[18] The NRDC/DDPP Reference Case serves as the reference case for both pathways and is based on AEO 2013.[e]

EXHIBIT 2: THE CHANGING RELATIONSHIP BETWEEN U.S. CARBON EMISSIONS, ENERGY USE, AND GDP



c See Appendix F for further discussion about the differences in baseline years and modeling between these analyses.

d The NRDC Core Scenario exceeds the 2025 NDC goal. It achieves a 30 percent carbon dioxide reduction from 2005 levels by 2025.

e The Reference Case reflects AEO 2013 projections. E3 also used AEO 2013 as a reference case for its work on the U.S. scenario as part of the Deep Decarbonization Pathways project. NRDC and the DDPP scenario for the United States use the same reference case, which allows direct comparison between the two. The full AEO 2013 report is available at http://www.eia.gov/outlooks/archive/aeo13/. Further details on the E3 model and assumptions are provided in Appendices A and C, respectively.

2. Key Findings of the NRDC Deep Decarbonization Analysis

The PATHWAYS model developed by E3 has gained national and international recognition as a trusted model for analyzing economy-wide GHG emission scenarios.[19] NRDC commissioned its own study using E3's PATHWAYS model because we wanted to do the following:

- Establish and stress-test the feasibility of reducing U.S. emissions by 80 percent or more by 2050 compared with 1990 levels, based primarily on clean energy technologies and strategies. This includes an emphasis on the benefits of energy efficiency, renewable energy, electrification of buildings and vehicles, decarbonization of fuels, and a more limited reliance on biomass;
- Better understand the mix of technologies and practices—as well as the necessary rates of deployment—needed to achieve the emissions target;
- Examine different scenarios for cutting emissions by 80 percent or more and the consequences of shortfalls or implementation delays in certain sectors and measures; and
- Help identify important long-term policy themes and short-term policies that can help put us on the path outlined by our analysis, highlighting those that can be implemented at the state and local levels. (However, policies were not modeled within PATHWAYS.)

E3 has conducted similar analyses with the PATHWAYS model for several government agencies, including the United States' Pathways to Deep Decarbonization report, which was submitted to the United Nations, and the California State Agencies' Pathways Project.[20] Using an independent consultant and an established analytical platform in this manner enabled us to compare our results on an apples-to-apples basis and undertake a more rigorous effort than would have been possible otherwise.

Finally, this report stands out in terms of both the level of detailed underlying technical analysis and the achieved clean energy outcome. It combines aggressive but achievable assumptions on the potential to scale up energy efficiency, renewable energy, and electrification with a more robust technical analysis that incorporates grid reliability impacts. While the decarbonization study for the United States used the same model, its constructed scenarios focused much more heavily on carbon capture technologies, biomass, and nuclear.

U.S. 2050 CARBON REDUCTION GOAL IS ACHIEVABLE AND COST-EFFECTIVE WITH EXISTING CLEAN ENERGY TECHNOLOGIES

Our fundamental finding is that U.S. GHG emissions can be reduced, cost-effectively, by 80 percent by 2050[f] using proven clean energy solutions, most of which are deployed at commercial scale today. To achieve the necessary carbon dioxide emissions reductions, the United States will need to rapidly expand and deploy clean energy solutions that fall into four broad categories: energy efficiency; renewable electricity; electrification of end uses, using clean electricity; and decarbonization of some remaining fuel use. This reduction will also require an integrated and coordinated electricity grid that supports renewable electricity and flexible demand-side energy resources.

1. **Implement energy efficiency technologies and system-wide energy efficiency approaches to directly reduce energy demand by 40 percent** (compared with the Reference Case).
   - Cut energy demand through more efficient buildings, appliances, factories, and vehicles while conserving additional energy in buildings through operational and behavioral changes.
   - Reduce passenger vehicle miles driven by approximately 25 percent by 2050.

2. **Generate cleaner electricity primarily through the significant expansion of renewable energy resources, like wind and solar power**.
   - Scale up solar and wind capacity to provide 70 percent of *electricity* demand, an approximately 13-fold increase in total annual non-hydro renewable electricity generation from 2016. (This is a five-fold increase from the Reference Case.)[21]

f From 1990 levels, including all GHGs. Significant carbon dioxide emissions reductions represent a majority of these GHG emissions reductions and are the focus of this report.

- Install carbon capture and storage (CCS) on remaining limited fossil fuel–fired electricity generators. Under our scenario, a little more than one-tenth of electricity is generated from fossil fuels in 2050. Of this, around two-thirds is generated by plants with CCS installed.

3. **Employ this near-zero carbon electricity, to the greatest practical extent, to directly displace the use of fossil fuels in transportation, buildings, and industry.** By 2050, electricity supplies 45 percent of all energy needs, up from one-fifth today. (In this report, "electrification" refers to the switch from direct fuel use to low- and zero-carbon electricity.) Due to the greater thermodynamic efficiency of these technologies, electrification also results in an additional 10 percent reduction, approximately, in overall energy demand on top of energy reductions due to efficiency measures, bringing the total energy demand reduction to about 50 percent.
   - Electrify 75 to 100 percent of space and water heating in the residential and commercial sectors, and electrify more than 40 percent of boilers and process heat in the industrial sector.[g]
   - Electrify large portions of the vehicle fleet via electric light-duty automobiles (such that electric vehicles account for 60 percent of car vehicle-miles traveled [VMT] by 2050) and some electric medium-duty vehicles (MDVs), as well as greater electrification of passenger rail and, to a lesser extent, freight rail.

4. **Decarbonize some of the remaining fuel use**, mainly in transportation and industry. This could include synthesizing diesel fuel from sustainable biomass, switching to lower-carbon fuels, and using clean electricity to produce synthetic lower-carbon fuels. The following strategies contribute to cutting emissions by a vital 10 percent:
   - Replace fuels used mainly in transportation and industry with biodiesel produced from truly net-zero, sustainable biomass.[h]
   - Switch to less carbon-intensive fuels in the industrial sector (e.g., use gas instead of coal or oil) and in the transportation sector (e.g., use blended synthetic liquefied natural gas [LNG] instead of petroleum in long-haul heavy-duty trucks).
   - Produce synthetic natural gas (i.e., power-to-gas[i,22]) and/or hydrogen using renewable electricity to partly decarbonize fuels used in the industrial and transportation sectors.
   - Install CCS for industrial processes that still rely on fossil fuels, such as steel-producing blast furnaces, refineries, and cement plants.

OUR RESULTS COMPARED WITH PREVIOUS FINDINGS: ENERGY EFFICIENCY MATTERS

Several other recent reports have also determined that an 80 percent reduction in GHG emissions by 2050 is possible.[23] Those analyses rely more heavily on biomass, nuclear, and CCS technologies. Our scenario, on the other hand, relies most heavily on renewable resources and energy efficiency. Our more aggressive, but well-supported assumptions, on energy efficiency and renewables allow us to achieve our 2050 emissions goals without relying heavily on other technologies that are costlier or riskier or currently deployed at a smaller scale.[j] NRDC's analysis brings a new perspective to the rich discussion on deep decarbonization that can be found in existing literature.[24]

For the U.S. scenario as part of DDPP, researchers worked with E3 using the PATHWAYS model and relied on the same baseline assumptions.[25] In fact, NRDC chose to use the same data, technology cost and performance assumptions, and reference case so that we could directly compare the costs and implications of the NRDC scenarios to those done for the United States as part of DDPP. Both the NRDC and DDPP (Mixed Case) scenarios cut GHG emissions by 80 percent from 1990 levels by 2050 through a combination of energy efficiency, renewable resources, electrification across all sectors, and decarbonization of remaining fuel supply. However, there are notable and important differences. Primarily, the NRDC Core Scenario adopts a much higher, but achievable, level of energy efficiency, leading to 25 percent less primary energy demand than in the DDPP Mixed Case. This allows our scenario to rely much less than the DDPP Mixed Case on technologies that are riskier or costlier or currently deployed at a smaller scale, including nuclear, bioenergy and biofuels, synthetic fuels, and CCS. Our method also maximizes the co-benefits of energy efficiency (e.g., consumer bill reduction, reduced stress on the electricity grid, reduced air and water pollution, and fewer land use impacts). Consequently, while efficiency is the greatest contributor to emissions reductions in the Core Scenario, it is a much smaller contributor in the DDPP Mixed Case. There are other differences as well.

g An alternative to electrification of these end uses is to use decarbonized natural gas derived from renewable electricity or truly net-zero biomass; however, this alternative was not modeled. The availability of sustainable biomass and the economics of synthetic gas make this alternative more challenging than electrification. Nonetheless, the most cost-effective pathway may include a combination of electrification and fuel decarbonization. See section 2.3 for a discussion.

h An alternative approach to reducing emissions is to use biomass for aviation biofuels, but we did not model that approach.

i For example, renewable electricity can be used to produce natural gas that has low or zero life-cycle carbon emissions. Renewable electricity can be used to split water molecules to provide hydrogen and oxygen. The oxygen can be sold for industrial use or simply released into the atmosphere. The hydrogen can be combined with captured carbon dioxide to generate synthetic methane (synthetic gas, or "power-to-gas"), or the hydrogen can be burned directly or used in fuel cells.

j At the same time, the presence of a much reduced amount of nuclear energy, and relatively small amounts of carbon capture technologies, and low-carbon and bio-derived fuels, reduces the overall cost of achieving the emissions reduction goal.

As part of the UNFCCC's 22nd Conference of the Parties (COP22) in Marrakesh, the White House released the United States Mid-Century Strategy for Deep Decarbonization (MCS) in November 2016.[26] This report did not use the PATHWAYS model and examined a slightly different emissions target: 80 percent emissions reduction from 2005 levels when U.S. emissions peaked—rather than lower 1990 levels—by 2050. The MCS report's energy efficiency assumptions are similar to those of the DDPP Mixed Case. However, the MCS case relies more heavily on oil and natural gas due in large part to lower natural gas-price expectations. It also relies more on nuclear energy and CCS due to the MCS's much more optimistic assumptions about the future costs of these technologies. The MCS report provides useful insight into the potential value of research and development (R&D) as it weighs the potential outcomes of cost reductions, performance improvements, and new technological breakthroughs. NRDC's assumptions around technological innovation, on the other hand, are far more conservative. The NRDC scenarios also use a more conservative estimate for carbon sinks that reflect the estimated amount of carbon emissions that plant matter can absorb from the atmosphere and sequester in soil or other geological formations, which necessitates substantially greater reductions in smokestack and tailpipe emissions to meet emissions goals.

A more detailed comparison of these two analyses with the NRDC analysis is provided in Appendix F.

E3-NRDC MODELING APPROACH

NRDC's analysis used E3's PATHWAYS model, which is built on a bottom-up representation of the U.S. energy system and reflects how each component changes over time. It shares a common architecture with the U.S. Energy Information Administration's (EIA) National Energy Modeling System (NEMS), which is used to generate the administration's annual projections of energy production, demand, imports, and prices. However, the PATHWAYS model incorporates a more detailed representation of the electricity sector, adding to a granular and accurate picture of the energy resource portfolio. PATHWAYS can also assess grid reliability on an hourly basis using storage, flexible load, and thermal resources to ensure that demand and supply always match. PATHWAYS is a "scenario" model, meaning that portfolios of measures, such as the electricity supply mix and the makeup of transportation fuels, are selected by the user. The model then evaluates and deploys all available resources over time and identifies pathways to deeply decarbonize the U.S. energy system. Our analysis included two main scenarios: the Core Scenario and the Delay/Secondary Scenario. The model provides detailed projections of energy supply, demand, resource mix, and costs by sector and category of end use (e.g., appliance use in the residential sector) for census regions and the nation overall. Further details are in Appendix A.

While most emissions reductions, and consequently much of this report's discussion, focus on carbon dioxide, we did assume necessary reductions of other GHGs such as methane and hydrofluorocarbons (HFCs), as described in Appendix D and briefly in Section 2. Unlike other energy economy optimization models, PATHWAYS does not minimize the overall cost of energy supply or maximize social utility subject to imposed constraints; its objective was to achieve emission reduction goals. However, cost data can be overlaid on the results to calculate the costs of the scenarios. Data, costs, and other pertinent assumptions used by the model are largely from the EIA's Annual Energy Outlook (AEO) 2013. We chose to use this data to facilitate an apples-to-apples comparison with other deep decarbonization reports. We believe that our cost assumptions are likely conservative, given the recent and rapid cost declines for wind and solar, which are expected to continue for some time; energy efficiency cost assumptions that largely match actual observations; and near-term natural gas prices in the range of expected volatility. Although not modeled, it is also plausible that current powerful societal trends—for instance, urbanization and the sharing economy—will play a large and positive role in promoting decarbonization.

While the modeled solutions cost-effectively cut U.S. emissions through proven technologies, our Core Scenario calls for faster, broader, and more integrated clean energy deployment than has been achieved historically for some technologies. Our model does not explicitly consider issues like labor and capital availability, political support, and supportive policies and mechanisms. That said, recent trends and successes offer many reasons for optimism regarding the feasibility and viability of our scenarios.

NRDC POST-MODELING ANALYSIS

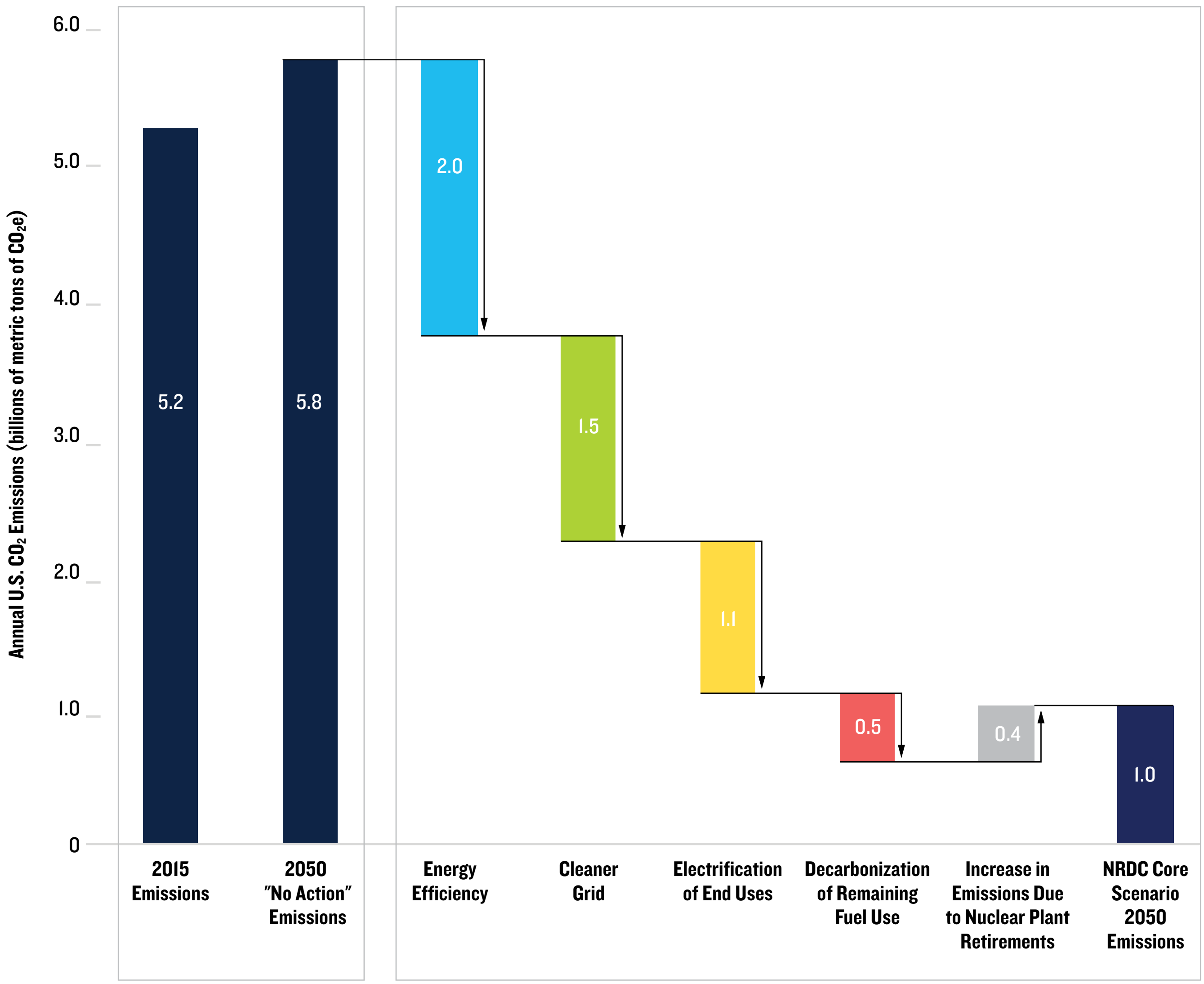
In addition to our collaborative work with E3 and its PATHWAYS model, NRDC conducted a post-modeling analysis with the same data to disaggregate the model's emissions reduction output data and attribute those reductions to specific strategies and drivers (e.g., energy efficiency, renewables, electrification and fuel-switching, and bio-derived and synthetic fuels).[k] Exhibit 3 provides a sense of the relative pace and emissions reduction contributions from these key clean energy drivers.

Exhibit 4 summarizes 2050 carbon dioxide emissions reductions by clean energy driver and sector, according to our post-modeling analysis.[l]

k The methodology for this post-modeling analysis is provided in Appendix B. The E3 model outputs—including absolute emissions levels by source and sector, energy use by source and sector, and absolute reductions in emissions or energy levels between the cases—are definitive and precise; NRDC's post-modeling attribution of both emissions and energy reductions to specific measures is not a precise estimate, but NRDC believes its methodology and estimates are reasonable and appropriate.

l For a summary of emissions reductions by driver for 2030, please see Appendix E.

EXHIBIT 3: ACHIEVING NRDC'S EMISSIONS REDUCTIONS IN 2050



Shown on the left are emissions in 2015 and in 2050 with "No Action." Shown on the right is a breakdown of emissions contributions in 2050 from the four key clean energy drivers.

EXHIBIT 4: SUMMARY OF CO_2E EMISSIONS REDUCTIONS IN 2050 BY CLEAN ENERGY DRIVER AND SECTOR

DRIVER OF EMISSIONS REDUCTIONS		SECTOR				Total MMT CO_2e reduced by driver (compared with Reference Case)
		Residential	Commercial	Industrial	Transport	
1. Energy efficiency (technologies and system-wide approaches)	More-efficient appliances and lighting, building shells, factories, and vehicles, including behavioral changes	550	465	374	441	1,830 (38.1%)
	Reduced vehicle miles traveled (light-duty vehicle fleet only)	-	-	-	173	173 (3.6%)
2. Cleaner grid	Widespread renewables	369	454	455	33	1,311 (27.3%)
	CCS with natural gas–fired and coal-fired generation	62	80	78	6	226 (4.7%)
	Nuclear plant closures*,[m]	−111	−121	−131	−9	−372 (−7.8%)
3. Electrification of end uses	Electrification of buildings, transport (light-duty vehicles, rail, and some medium-duty vehicles), and industry	225	122	264	481	1,092 (22.8%)
4. Decarbonization of some remaining fuel use	Production of biofuels, such as biodiesel	-	-	26	240	266 (5.5%)
	Fuel switching in industry and transport (freight and some medium-duty vehicles)	-	-	61	122	183 (3.8%)
	Production of synthetic gas (power-to-gas) and hydrogen	<1	6	37	14	57 (1.2%)
	CCS on industrial processes	-	-	32	-	32 (0.7%)
Total MMT CO_2e reduced by sector (compared with Reference Case)		**1,095 (22.8%)**	**1,006 (21.0%)**	**1,196 (24.9%)**	**1,501 (31.3%)**	**4,798**

*As the negative sign indicates, nuclear plant closures are not a driver of emissions reductions, but they have been included here for completeness.

The emissions reductions are in millions of metric tons of CO_2 equivalent, as compared with the Reference Case. The post-modeling analysis was undertaken separately by NRDC on the basis of E3 model outputs.

m As a modeling assumption, most nuclear plants were retired at the end of their 60-year license periods in the NRDC Core Scenario. This resulted in the loss of emissions benefits (i.e., net emissions increases) of 111, 121, 131, and 9 million metric tons of CO_2 in the residential, commercial, industrial, and transportation sectors, respectively, compared with the Reference Case. The lost benefit of zero-carbon generation from nuclear is primarily compensated for by increased renewables deployment.

2.1 ENERGY EFFICIENCY: DOING MORE AND WASTING LESS

As many authorities have pointed out, energy efficiency is cleaner, less expensive, and typically faster than building new energy production facilities, and thus it is a particularly important element of the NRDC Core Scenario.[27] We assume an aggressive, but technically achievable, deployment of energy efficiency across the U.S. economy based on recent studies of energy efficiency potential in the buildings, industrial, and transportation sectors.[n] Overall, these studies indicate greater energy savings from energy efficiency than do similar economy-wide deep decarbonization studies. Due to energy efficiency technologies alone, our Core Scenario results in an economy-wide energy demand reduction of 40 percent by 2050 compared with the Reference Case, and 17.5 percent by 2030.[o] This translates to roughly a 1.5 percent average annual reduction (compounded) across the entire U.S. economy between 2015 and 2050 compared with the Reference Case. Such an early and deep deployment of energy efficiency restrains growth in electricity demand, reducing the amount of renewable generating capacity needed and lowering the overall costs of shifting to a low-carbon energy system.

We assume an aggressive, but technically and economically achievable, deployment of energy efficiency across the U.S. economy based on recent studies of energy efficiency potential in the buildings, industrial, and transportation sectors.

2.1.1 RESIDENTIAL AND COMMERCIAL BUILDING ENERGY EFFICIENCY

Our energy efficiency assumptions reduce total energy demand by 32 percent by 2030 and 46 percent by 2050 for the buildings sector. This is 1.7 percent average annual reduction compared with the Reference Case. The 2030 reduction is consistent with the 25 to 30 percent overall energy efficiency reduction potential found in the National Academies report *Real Prospects for Energy Efficiency in the United States*.[28] Other reports have modeled larger potential energy reductions in buildings.[29] In addition to energy efficiency, the electrification of buildings presents additional energy savings due to thermodynamic gains from switching to electric end-use appliances. (By 2050, overall energy use in buildings falls by around 60 percent in total because of both energy efficiency and electrification, compared to the Reference Case. Around three-quarters of these savings come from energy efficiency measures; the other quarter is due to electrification.)

To achieve these energy savings, the building sector, on average, invests an additional $150 billion in efficient electric appliances and efficient building materials per year from 2015 to 2050, relative to the Reference Case. Average annual energy cost savings are marginally higher than this, producing net cost savings for the building sector during this period.

For building shell efficiency assumptions, NRDC relied primarily on the 2012 American Council for an Energy-Efficient Economy (ACEEE) report *The Long-Term Energy Efficiency Potential: What the Evidence Suggests*.[30] This report modeled various scenarios, including an Advanced Scenario and a Phoenix Scenario, and found that a 70 percent or 90 percent savings in heating and cooling needs could be achieved in new building shells by 2050 compared with 2012 standards. Our Core Scenario assumes 70 percent savings—but also assumes it could be achieved earlier than 2050. Our Core Scenario uses a 5 percent reduction per year in heating and cooling needs from new building shells, improving efficiency by 70 percent by 2037. NRDC assumed no additional gains in shell efficiency post-2037. For existing buildings, the ACEEE study estimated that a 40 to 60 percent savings in heating and cooling energy needs could be realized by improvements to the building shell by 2050 through retrofits

n Details and sources on our energy efficiency assumptions can be found in Appendix C.

o Total energy demand increases by about 15 percent between 2015 and 2050 in the Reference Case. In sharp contrast, energy efficiency–related demand reductions result in a decrease of approximately 30 percent from 2015 levels by 2050.

and other measures. NRDC more conservatively assumed that the existing building stock would see a 30 percent reduction in heating and cooling needs by 2050 via building retrofits.

For appliances, we assume a 2 percent annual improvement rate, on average, across all appliances. This is consistent with historical rates of efficiency gains for refrigerators, clothes washers, and dishwashers—all of which have improved at annual rates ranging from 2.3 to nearly 6 percent (televisions have seen even higher efficiency gains).[31,32] The 2 percent annual improvement rate reduces new appliance energy use by 50 percent by 2050, which is consistent with the ACEEE study's Phoenix Scenario for residential and commercial appliances. For lighting specifically, the NRDC Core Scenario assumes a universal adoption of LED lighting by 2050 (same as in the DDPP study) and additional reductions from lighting controls and daylighting twice as large as those in DDPP.[p]

As mentioned earlier, overall efficiency can be further improved through the electrification of appliances, which is inherently more efficient than direct natural gas use. Heat-pump water heaters are 2.5 to 3 times as efficient as electric resistance or natural gas water heaters.[33] Electric space heating is also three to four times as efficient as natural gas heating.[34] We assume nearly full electrification of heating and cooling by 2050 (see Appendix C for more details). Furthermore, electric appliances can help eliminate carbon pollution when powered by renewable electricity.

2.1.2 TRANSPORTATION ENERGY AND SYSTEM-WIDE EFFICIENCY

The transportation sector, which accounts for one-third of U.S. carbon emissions, has tremendous opportunity to reduce emissions through higher fuel efficiency, electrification and other fuel switching, and reduced travel demand. Our Core Scenario results in a 50 percent reduction in total transportation energy demand by 2050 compared with the Reference Case. For light-duty vehicles (LDVs), the energy demand reduction is almost 75 percent; nearly half of that comes from vehicle fuel efficiency, while about a quarter each comes from reduced vehicle-miles traveled (VMT) and electrification.[q]

There is tremendous untapped potential for increased fuel efficiency of conventional vehicles that use internal combustion engines. The national program for GHG emissions and fuel economy standards for passenger vehicles, established by the U.S. Environmental Protection Agency (EPA) and U.S. Department of Transportation (DOT), call for the new vehicle fleet in model year 2025 to reduce tailpipe carbon dioxide emissions by an estimated 40 percent compared with 2012 model year vehicles—equivalent to increasing fuel economy to 54.5 miles per gallon (in laboratory testing).[r, 35] In our Core Scenario, we assume that new conventional passenger vehicles (those that are powered by internal combustion engines, including hybrids) continue to improve, achieving 95 miles per gallon (mpg) by 2050. This assumption is based on another report from the National Academies that found feasible technology pathways for new passenger vehicles to achieve 75 mpg by 2030 and 100 mpg by 2050 (not including electric vehicles).[36] This results in an average on-road fuel efficiency for the entire gasoline-powered passenger vehicle fleet (including all model years) of around 40 mpg by 2030 and approximately 80 mpg by 2050.

To estimate the potential for policies to reduce passenger VMT, we adapted an analysis developed by the EIA for AEO 2014. In our Core Scenario, VMT drops 24 percent below the Reference Case 2050 forecast and emissions are reduced by 173 million tons of carbon dioxide in 2050.[37,s,t]

Overall vehicle efficiency can also be improved through electrification, which has an inherently higher energy efficiency than internal combustion engines and can eliminate carbon pollution when renewable electricity is used. Energy-efficient electric vehicles convert about 59 to 62 percent of the electrical energy from the grid to power at the wheels,[u] while conventional gasoline vehicles convert only about 17 to 21 percent of the energy stored in gasoline to power at the wheels.[38] ln the NRDC Core Scenario, 60 percent of all miles traveled by passenger vehicles are powered by clean electricity in 2050. This requires sales of new electric vehicle (EV) and plug-in hybrid electric vehicles (PHEV) to ramp up quickly, expanding from 1 percent of annual sales in 2015 to 4 percent by 2020, about 30 percent by 2030, and nearly 85 percent by 2050.[v] This is in line with the scenarios developed for studies by the National Academies.[39] Other details of electrification expansion in the transportation sector in our Core Scenario are discussed in Section 2.3.

p See Appendix C for details and supporting materials on these assumptions.

q It was difficult to compute a similar breakdown for other forms of transportation.

r In real-world driving conditions, this translates to an estimated average of 40 miles per gallon for the model year 2025 fleet. Center for Climate and Energy Solutions, "Federal Vehicle Standards," http://www.c2es.org/federal/executive/vehicle-standards (accessed October 27, 2016).

s In AEO 2014, the Energy Information Administration published a Low VMT sensitivity case. The AEO 2014 Low VMT case assumed that per capita passenger VMT growth was reduced by 0.5 percent compared with the reference, resulting in a 0.2 percent annual increase in per capita VMT. (As AEO 2013 and 2014 project only up to 2040, we linearly extrapolated using the same annual growth rates between 2012 and 2040 to project 2050 VMT levels.) The AEO 2014 Low VMT case essentially holds total VMT constant at today's levels because it relies on a substantially lower level of "business as usual" VMT growth, a 0.9 percent growth rate for the AEO 2014 reference case versus 1.2 percent annual growth rate for the AEO 2013 reference case.
We instead applied the same percentage reduction potential (24 percent) to the AEO 2013 reference case VMT.

t Maintaining total VMT at roughly today's level is equivalent to approximately a 15 percent reduction in per capita VMT by 2040 and a 20 percent reduction by 2050. This would result in per capita VMT declining from today's 10,700 miles to 8,460 miles by 2050.

u Percentage of energy converted to "power at the wheels" simply indicates what fraction of starting energy is converted to actual energy used to move the car; the rest is wasted energy. Electric vehicles are roughly three times as efficient as gasoline vehicles at converting initial/input energy to power at the wheels.

v We note that some automakers are also pursuing electric vehicles powered by hydrogen fuel cells. A hydrogen fuel cell pathway was not included as a significant driver in this analysis but could potentially substitute for other electric-drivetrain technologies.

For medium- and heavy-duty trucks, we rely on a mix of electric-drive trucks, ultraefficient diesel, and ultraefficient natural gas trucks running on renewable electricity, renewable-based diesel, and biogas. A recent study by the International Council on Clean Transportation points to how these technologies cut fuel consumption by more than 50 percent from 2010.[40,w,x] We assume a full implementation of technologies based on the DOE SuperTruck program, which would double the average new vehicle fuel efficiency from 6 mpg to 12 mpg and cut fuel consumption from new vehicles in half.[41]

Finally, aviation and shipping will need advances in both fuel efficiency and clean fuels to reduce their carbon emissions. Targeted R&D by corporations and the federal government, along with U.S. standards and international goals, can help spur progress in these areas. In our scenario, efficiency represents the primary means of reducing energy use in aviation, which is consistent with other analyses.[42,y] There has also been significant effort to reduce emissions from ships, including switching to low-carbon biofuels and low-sulfur fuels. There may be lessons to be learned from efforts to switch to more efficient engines in China. Our scenario assumes reduced shipping emissions from cleaner diesel along with modestly improved efficiency.

In total, the Core Scenario requires substantial investments in electric and efficient vehicles. Our projections require the transportation sector to spend approximately $115 billion more on electric and hybrid vehicles and trucks annually from 2015 to 2050. This would save nearly $200 billion on average per year in net energy costs, growing to nearly half a trillion dollars in net energy cost savings in 2050 alone.

2.1.3 INDUSTRIAL ENERGY EFFICIENCY

As is true elsewhere, the industrial sector has tremendous potential to reduce energy demand through efficiency, operational improvements, and electrification. Our Core Scenario results in a total reduction in energy demand of 33 percent by 2050 from both energy efficiency and electrification, equivalent to a 1.1 percent average annual reduction compared with the Reference Case. The industrial sector also adds another 200 gigawatts (GW) of new industrial combined heat and power (CHP) capacity by 2050.[z]

The industrial efficiency assumptions are consistent with findings from a 2009 McKinsey study and the 2010 National Academies *Real Prospects for Energy Efficiency in the United States* report, which found that cost-effective energy efficiency potential was 14 to 22 percent over just one decade.[43,44] Importantly, the latter identified that additional efficiency investments could become cost-effective through R&D. Longer-term assumptions are also consistent with an analysis by the Rocky Mountain Institute.[45] In fact, many companies have already achieved or have committed to achieving appreciable, sustained energy intensity reductions in line with, or in some instances in excess of, our assumptions. For instance, 3M, General Motors, Hanes Brands, PepsiCo, and Toyota have achieved average savings greater than 2 percent per year over five years or more. Other companies have achieved savings greater than 3 percent per year.[46] Under the DOE's Better Buildings, Better Plants Program, participants have saved an average of 2.1 percent annually.[aa] Participating companies as disparate as Arby's, eBay, HARBEC, Nissan, Haverty's, Cummins, and Schneider Electric have all sustained between 2 and 4 percent annual energy intensity gains over multiple years.[47]

w In the time since our modeling assumptions were finalized, the cost and technology feasibility of certain options has changed. Numerous new and existing manufacturers have begun to announce projects or products in the medium- and heavy-duty truck market. For example, Tesla Motors and BYD, two of the world's largest electric vehicle and battery manufacturers, are planning to introduce products in medium- to heavy-duty categories from Classes 3 through 8, while companies like Toyota and Nikola are pursuing fuel cell–based Class 7 and 8 trucks, which were not included as options in the modeling.

x A caveat: The modeling did not include regional and local constraints on criteria emissions and air quality. In parts of the country, such as California, additional controls on criteria emissions would likely necessitate larger deployment of zero-emissions technologies operating on renewable-based electricity. Indeed, recent studies—buoyed by battery cost declines and innovation in longer-distance transportation—have projected that almost one-third of new bus sales could be all-electric by 2020. This could further reduce the transportation industry's carbon footprint at a lower cost and allow us to redirect the limited supply of sustainable biofuels to aviation and shipping. In general, the large uncertainty in the modeling assumptions and results should be treated generally as pointing to the need for ultraefficient power trains in trucks and very low carbon fuels to meet the goals, whether electric, hydrogen, natural gas, or diesel based.

y While airplanes can use biofuels, the supply of truly sustainable biofuels is constrained, once life-cycle impacts are considered (see footnote af). Aviation is the portion of the transportation sector with the fastest-growing carbon dioxide emissions, but aviation carbon emissions are not yet regulated. Still, the industry has set commendable goals to shrink its carbon footprint. These goals include capping its carbon emissions by 2020 and reducing its emissions by 50 percent of 2005 levels by 2050. NRDC has been tracking the industry's progress toward greening its fleet since 2013 in our Aviation Biofuel Scorecards.

z See Appendix C for a list of assumptions. This assumption was drawn from the previous DDPP analysis completed by the U.S. DOE and E3, which also assumed that an additional 200 GW of CHP capacity in the industrial sector was feasible by 2050.

aa The program's goal is for "industrial partners to reduce their energy intensity by at least 2.5 percent per year over a 10-year period. DOE data indicates that this is an aggressive, but achievable target." So far, the program has achieved average annual savings of 2.1 percent, with many partners achieving much greater savings. More information is available from DOE, "Better Plants Program: Frequently Asked Questions", https://energy.gov/eere/amo/downloads/better-plants-program-frequently-asked-questions (accessed July 28, 2017).

The industrial sector is vast, stretching from food to manufacturing and from clothing to construction. It also represents about one-quarter of U.S. energy use and emissions. Emissions reduction strategies vary greatly among subindustries, but a combination of operation and maintenance improvements and equipment upgrades could improve efficiency across the board. In energy-intensive industries such as cement, iron and steel, pulp and paper, chemicals, and refining, most of the efficiency gains lie in improved efficiency in manufacturing processes, as well as more efficient boilers. In non-energy-intensive industries, greater efficiency in buildings and motors can contribute more to energy savings.[48] For even deeper and lasting energy (and materials) efficiency, there are innovative strategies that could more fundamentally alter and improve the full spectrum of manufacturing processes.[49] Innovation can reimagine manufacturing methods and bring about holistic process redesigns and improvements.[50] The technical potential for energy efficiency improvements in many industries is between 35 and 71 percent. While the full potential may not always be accessible affordably through retrofits, these improvements may be incorporated cost-effectively at new or "greenfield" sites.[51] There are also substantial opportunities for greater efficiency in the entire industrial supply chain.[52] Reflecting observed successes at major corporations over the past few years (as discussed above), along with the technical potential for significant long-term improvements, our Core Scenario assumed near-term annual energy intensity improvements of 3 percent, falling to 1 percent by 2050.

As with the other sectors, electrifying as much as possible will improve overall energy efficiency. Many manufacturing subindustries that are less energy intensive—including food manufacturing, transportation equipment manufacturing, and computer and electronics manufacturing—have large opportunities to electrify many of their processes, allowing them to capture considerable energy and carbon savings (see Appendix C for our assumptions).

2.2 RENEWABLE ENERGY: CLEANING UP OUR ACT

In our Core Scenario, more than one-quarter of GHG emissions reductions are due to an expansive deployment of renewable electricity, which both directly and indirectly displaces fossil fuels. Increased levels of renewable electricity result in direct displacement and reduction of fossil fuel generation. An example of indirect displacement would be using renewable energy to produce synthetic natural gas that is burned as needed, instead of burning natural gas extracted from the ground to serve the same need.

In our Core Scenario, 70 percent of electricity comes from wind and solar energy by 2050, up from 8 percent in 2016. Wind and solar electricity-generation capacities grow by an annual average of 14.3 GW and 24.4 GW, respectively, between 2017 and 2050. Fossil fuel–fired electric plants with CCS provide about 7 percent of the electricity mix. The rest is supplied by hydropower (9 percent, divided fairly equally between small-scale and conventional), nuclear (3 percent), natural gas without CCS (4 percent), industrial CHP (5 percent), and geothermal (1 percent).

Reflecting market trends at the time of modeling, our Core Scenario is wind-dominated.[ab] We rely on large transmission investments to integrate and transmit onshore wind generation from the Midwest and Great Plains states and offshore wind from the coasts. The PATHWAYS model also utilizes other means to match energy demand with energy supply across all time periods, including shifting customer demand, distributed energy storage (such as water heaters and EV batteries) that holds excess renewable energy, and power-to-gas that converts excess renewable energy to another fuel. A solar-dominated system, especially one with more distributed and on-site generation, would require different types and levels of transmission investments, as well as grid-balancing measures that address midday excess generation.[53]

It is important to note that in our Core Scenario, just over 70 percent of electricity comes from non-hydro renewables (including geothermal), requiring about a 13-fold increase in non-hydro electricity generation from current levels.[54] The model provides estimates of how much onshore wind power, offshore wind power, and solar power will be needed to achieve U.S. climate goals by 2050 (approximately 39, 16, and 15 percent of total electricity generation in 2050, respectively). However, the specific proportion of each type of renewable resource is less important than the total, proportion from renewable power. In other words, onshore and offshore wind as well as large-scale and distributed solar are rather interchangeable from an emissions reduction perspective. However, capacity factors, geographical availability, load profiles, integration requirements and strategies, land use requirements, and ultimately costs will differ. Accordingly, the model provides a high-level guidepost of the scale and nature of renewables and grid needs. The actual mix of renewables, and the resulting transmission build-out and market services, will depend on costs, supporting policies, and regional opportunities and constraints.[ac] A robust and diverse mix of renewable energy technologies will also be valuable to meet regional needs and reflect differing regional renewable energy resources. More in-depth and region-specific modeling

ab Most decarbonization modeling tends to rely more heavily on wind than on solar, due at least partially to better capacity factors. Wind has also been a more mature technology historically. However, solar has seen large cost declines (greater than assumed by our modeling). If our modeling reflected the more optimistic cost forecasts for solar (such as Bloomberg New Energy Finance's NEO 2017), it is reasonable to expect more solar than projected by our Core Scenario. However, wind would still likely be a dominant part of the renewable portfolio, albeit less than projected by the Core Scenario.

ac As a result of more rapid cost declines than expected in renewable technologies in recent years, the current cost of renewables and the future expectations of costs are lower than what the model assumed for all years (2010–2050). In the near term, the model also did not include extensions to the Production Tax Credit for wind and the Investment Tax Credit for solar.

will be required—and may need to be regularly updated—to assess cost-effective energy and storage solutions, completed energy system upgrades and expansion, environmental needs, and evolving grid requirements.

While the absolute levels of build-out required by our Core Scenario have not yet been seen consistently over sustained periods of time, U.S. wind and solar have undergone unprecedented growth over the past 10 years, with annual growth rates of 23 percent and 60 percent, respectively.[55] In 2016, incremental solar capacity additions exceeded 14 GW.[56] Annual wind capacity additions have approached 15 GW in the past five or so years.[57] In fact, in the past decade, more than half of all cumulative power-generation capacity added has been in the form of renewables.[58] This has been accompanied and enabled by deep price declines.[59] Solar module prices have seen an 80 percent decrease in less than a decade; analysts expect solar to become the lowest-cost form of new power (unsubsidized) in the United States by 2023 and to be less expensive than even existing fossil generation by 2027 across the country (it is already cheaper at certain locations).[60] At the same time, the average wind power purchase agreement (PPA) has fallen from $70 per MWh in 2009 to $20 per MWh in 2015, according to the DOE.[61] March 2017 saw a record 10 percent of U.S. power come from solar and wind.[62] Even more encouraging, longer-term projections indicate that the current growth in renewable energy is not an aberration but a lasting paradigm shift in the U.S. electric sector.[63] In addition, the build-out of renewable capacity in the NRDC Core Scenario is in line with other deep decarbonization modeling (see Appendix F for more details). However, higher levels of energy efficiency make possible a higher fraction (penetration) of electricity coming from renewables like wind and solar.

Indeed, if solar installations continue at the pace seen last year and expected in the next few years, solar will likely exceed the levels necessitated by our model. Annual solar installations are expected to reach 15 GW by 2019 and to surpass 20 GW by 2021, which would exceed the average annual solar deployment required by the NRDC Core Scenario.[64] GTM Research and the Solar Energy Industries Association (SEIA) estimate that more than 100 GW of solar (utility and small-scale) will be installed in the United States by 2020.[65] In NRDC's Core Scenario, the United States reaches this level of solar 10 years later, in 2030. Furthermore, the 2017 Bloomberg New Energy Outlook (NEO 2017) projects average annual solar growth of 20 GW between 2025 and 2040, in line with the model's projected needs, based on historic reductions in solar costs and anticipated cost reductions in the future.[66]

The PATHWAYS model considered only utility-scale electric generation capacity. However, distributed generation can play a meaningful role in decarbonizing the U.S. electric system. Distributed solar generation comprises a variety of small-scale solar installations such as those on homes, on commercial buildings, on hospitals, and even in manufacturing centers. A recent study by the National Renewable Energy Laboratory (NREL) found that cost-effective rooftop solar deployment could represent between 200 and 275 GW of U.S. capacity by 2050, depending on future technology costs and policies.[67] This is equivalent to approximately half, or more, of all solar capacity projected by the Core Scenario. At that rate, we would either need significantly less annual utility-scale solar additions to meet the total level of solar projected by the Core Scenario, or it could be possible to exceed that total level.

To reach the levels of wind power required by 2050 in our Core Scenario, wind capacity would need to grow by 23.8 GW each year. That breaks out to additions of 16.4 GW of land-based wind and 7.4 GW of offshore wind annually. To reach the levels required under the Core Scenario, rapid development of both offshore and onshore wind power will be needed. The multi-GW annual levels of recent onshore wind expansion (see Exhibit 5b) have come close to the required levels of land-based wind power indicated by our Core Scenario. The U.S. offshore wind industry was just launched with the December 2016 start of commercial operations of Deepwater Wind's 30 megawatt Block Island Wind Farm in Rhode Island state waters.[68] Today 14 offshore wind projects are in the planning phase, and the DOE sees the potential for 22 GW of offshore wind by 2030.[69] But these current projections fall short of the annual 7.4 GW offshore wind capacity additions called for by the NRDC analysis. Technology refinements, capacity factor improvements, and projected price declines will help pick up the pace.[70] But clearly, aggressive long-term policy support, appropriate incentives, and substantial private sector investment will be needed to scale up offshore wind capacity to the required levels. Stronger-than-expected growth in other renewable technologies such as distributed solar could also reduce the wind requirements indicated in our Core Scenario. Exhibits 5a and 5b show the historical growth of wind and solar (and expected near-term trends), compared with our model's projections to meet our 2050 goal.

EXHIBIT 5: COMPARISON OF OBSERVED AND PROJECTED BUILD RATES OF WIND AND SOLAR IN NRDC CORE SCENARIO

EXHIBIT 5A

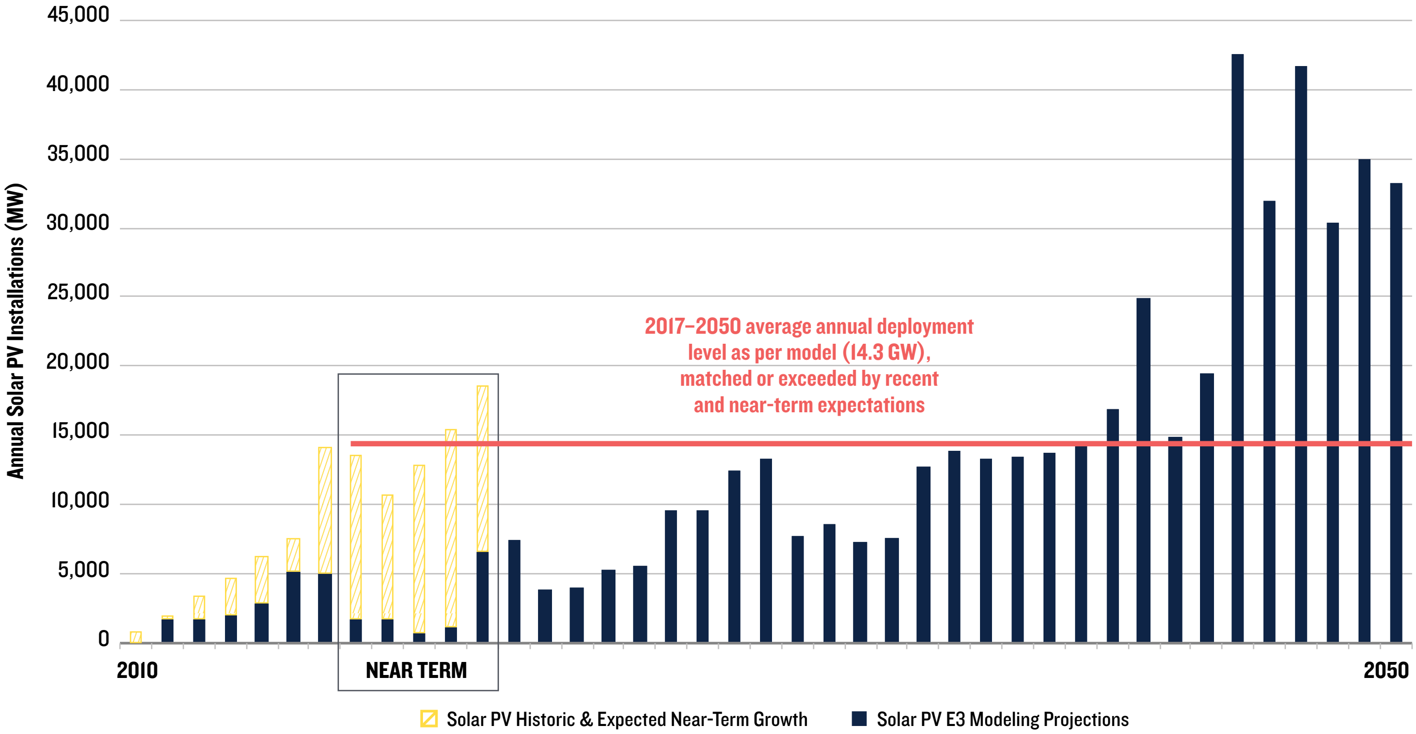
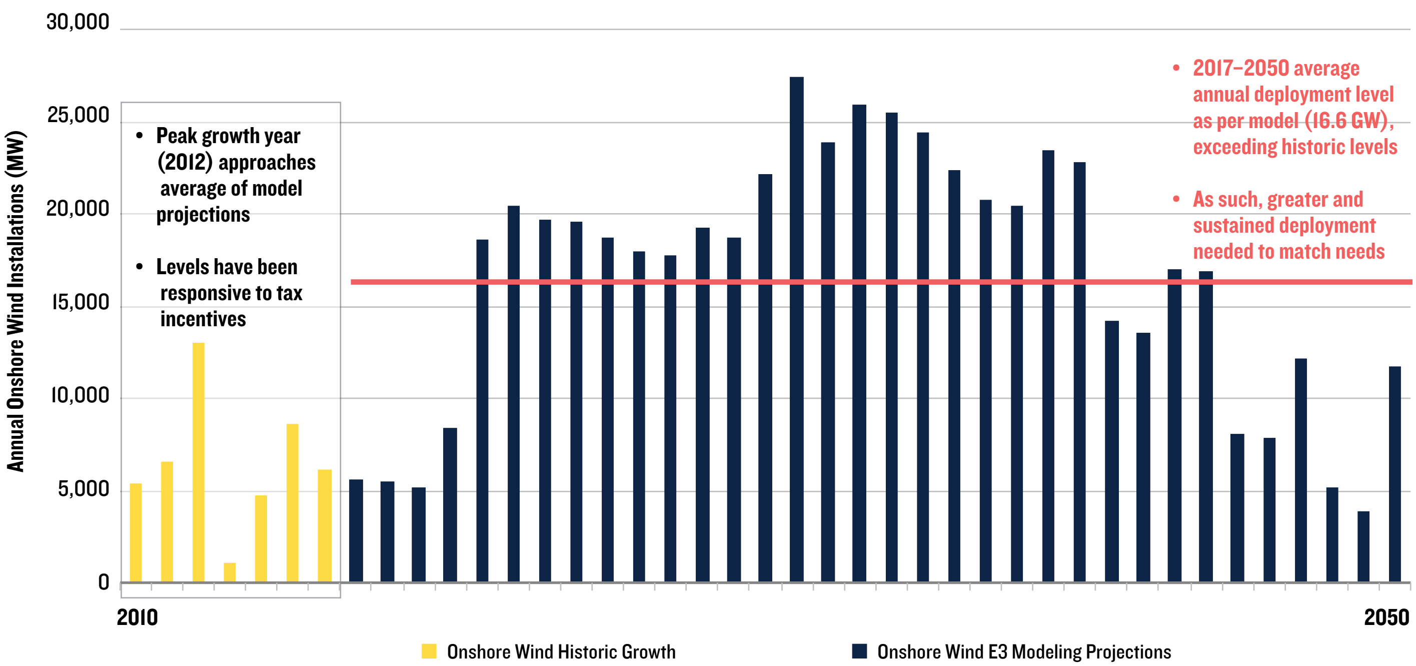


EXHIBIT 5B



Exhibits 5a and 5b. The graph of Exhibit 5a (top) shows how recent installations and near-term market expectations of solar photovoltaic (solar PV) installations exceed average annual deployment levels as per the model. Exhibit 5b (bottom) shows that although recent installation levels are impressive, onshore wind installations need to be increased and sustained beyond these levels.

© Dennis Schroeder/NREL

2.3 ELECTRIFICATION: PUTTING CLEAN ENERGY TO WORK

The NRDC Core Scenario capitalizes on the rapid decarbonation of the electricity grid by converting many end uses that currently rely on fossil fuels (e.g., vehicles, space heaters, water heaters) to electricity. In a crucial paradigm shift, we project that by 2050, electricity will supply about 45 percent of all end-use energy, up from about one-fifth in 2015. Given this broad electrification of the U.S. economy, total electricity consumption in 2050 is about 25 percent more than in 2015. Importantly, though, due to energy efficiency, it is 14 percent lower than the Reference Case for 2050 (even though the Reference Case has smaller levels of electrification).[ad] While the NRDC analysis does electrify a substantial portion of the U.S. economy, not everything is electrified. Customer preferences and technological hurdles were incorporated in the modeling, resulting in more minimal electrification of things like gas stoves, long-distance freight trucks, and the most energy-intensive industries. Electrification is associated with nearly one-quarter of emissions reductions (see Exhibit 4). Electrification also has the additional benefit of inherently improving overall efficiency; in our accounting, energy demand reductions due to electrification also contribute toward its emissions savings.

As discussed earlier, in the NRDC Core Scenario, 60 percent of the passenger VMT is powered by clean electricity, which assumes about 85 percent of new vehicles sold to be electric by 2050.[71] Including electric cars the entire passenger vehicle fleet has a gasoline-equivalent fuel economy greater than 100 mpg in 2050. The NRDC Core Scenario is matched by near-term market expectations, which have been driven by a more expansive set of EV model options and steep battery cost declines.[72] According to Bloomberg New Energy Finance, 55 EV models were available at the end of 2016, almost 20 percent more than one year earlier, and there are more than a half-million electric or hybrid cars on America's roads.[73] In July 2017, Volvo became the first mainstream automaker to signal a full transition away from internal combustion engines.[74] Prices for the lithium-ion batteries that are typically used in EVs have fallen by more than 70 percent since 2010, due to technology improvements, learning by doing, and improved economies of scale.[75] Reports indicate that Toyota is working on a battery technology that can power longer driving ranges while charging in just minutes.[76] Post-2030, however, these baseline market forecasts estimate much smaller increases than our analysis requires. This suggests a promising opportunity for policies and incentives to make a significant difference by fomenting budding market forces.

ad As a clarification, it is important to note that the contributions of electrification and renewable electricity work hand in glove. However, for accounting purposes, such as for Exhibit 4, the GHG reduction contributions need to be attributed to one or the other. Our methodology attributed emissions savings to electrification when switching an end use to electricity from another fuel (e.g., replacing a natural gas space or water heater with an electric heat-pump heater). However, when a source is powered by electricity (e.g., televisions or dishwashers), the emissions savings are attributed to a cleaner grid.

There is substantial potential to electrify both passenger and freight rail, as was assumed in our analyses. Modal shifts from passenger vehicles and air travel to passenger rail, and from heavy-duty trucking to freight rail, provide further opportunities to reduce economy-wide emissions. For example, the International Road Transport Union (IRU) estimates that 40 to 45 percent of long-haul road transport needs to run on electricity by 2050.[77] In China's own deep decarbonization report for the United Nations, the country assumed it could electrify 90 percent of all passenger rail by 2050. Mexico assumed 100 percent of intra-urban rail could be electrified. [78] It also assumed up to 80 percent of freight rail could be electrified by 2050—helping the country smartly reduce transportation emissions as it shifts 25 percent of its current freight trucking to freight rail by 2050 to meet emissions targets.

While the technologies are known, there are market barriers to rapid adoption of building electrification, such as low consumer awareness, limited contractor expertise, and higher up-front costs for high-efficiency products as compared with less efficient models. Space and water heating present some of the largest energy-saving opportunities in the building sector. Space heating typically constitutes the greatest portion of household energy use and tends to influence fuel choice for other domestic appliances such as water heaters, stoves, and clothes dryers. To reach the decarbonization levels prescribed by the NRDC Core Scenario, about 90 percent of U.S. residential and commercial buildings would need to use electric space- and water-heating appliances, up from just under half today. On average, around 49 percent of U.S. homes still use gas or oil for space heating, with slight declines in recent years.[79]

Critically, as we push for increased electrification and more clean energy to supply that electricity, we must also tackle the issue of direct fossil fuel consumption. Various parts of the residential, commercial, industrial, and transportation sectors directly burn fossil fuels, such as natural gas, gasoline, or diesel. Improving the efficiency of these end uses should be the first strategy for reducing their emissions (as discussed in Sections 2.1 and 3.2). Next, emissions should be further cut by either (a) electrifying the end uses with clean electricity or (b) decarbonizing the direct use of fuel.[ae] Strategic navigation between these two routes is necessary. Given sector-specific constraints and available, cost-effective technologies, the optimal solution will almost certainly be different across sectors. For example, the residential and commercial sectors are more amenable to electrification, while certain industrial subsectors may continue to burn some direct fuels.

Along these lines, despite extensive electrification of most sectors, there are some limitations to full electrification with available technologies. For instance, industrial facilities may need to burn gas for some high-heat applications, and ships and planes currently still need to use liquid fuels. Our analysis, however, replaces some of this remaining fuel use with low- or zero-carbon alternatives, such as bio-derived fuels or synthetic fuels derived from excess renewable electricity and captured carbon. Since the supply of truly sustainable, low-carbon biofuels such as biodiesel or renewable diesel are limited, we also rely on other lower-carbon fuels, such as blended fuels with synthetic or bio-derived components and synthetic natural gas derived from renewable electricity.[80,af]

Finally, the alternatives to electrification may hit GHG reduction targets at very different costs. Power-to-gas approaches, for example, are currently available at scale but are very expensive, and sustainable biomass-derived natural gas is limited in supply. Given this, electrifying end uses with clean electricity is generally more affordable than direct fuel decarbonization. For this reason, our analysis did not over-rely on these fuel decarbonization technologies as they are more expensive and less proven at scale. Also, as the goal of our analysis was limited to 80 percent emissions reduction by 2050, there was not a need to further decarbonize fuels or substitute for fossil fuels in the Core Scenario.

Expanded deployment of clean energy resources cuts fossil fuel usage by about 70 percent in 2050 compared with the Reference Case.

ae An electric heat pump water heater (using heat exchange rather than resistive heat) is an example of the former; using biomass-derived natural gas and replacing gasoline with biodiesel in a truck are examples of the latter.

af For more details on our principles on sustainable biomass, see our Forests Not Fuel and Money to Burn? reports.

2.4 REMAINING FOSSIL FUELS: GETTING CLOSE TO ZERO

As noted earlier, in our Core Scenario, expanded deployment of clean energy resources cuts fossil fuel usage by about 70 percent in 2050 compared with the Reference Case. Coal consumption falls by 80 percent, mainly from the power sector; natural gas consumption falls by around 65 percent, largely from the power and buildings sectors; and petroleum consumption falls by 65 percent, mainly from changes in the transportation sector.[ag,ah] This considerably reduces the severe environmental, public health, and ecosystem impacts caused by fossil fuel extraction, production, transportation, and use.[81] (See box on Perils of Natural Gas.)

For the vestigial remaining fossil fuel usage, further emissions reductions can be achieved by switching to less emissive fossil fuels. For example, the construction industry transitions away from diesel and gasoline and relies on natural gas. Likewise, the cement industry partially switches to natural gas and biodiesel, while still using coke and coal. In other instances where fossil fuels are required, such as in industrial facilities including steel, chemicals, refining, and cement plants, we assume CCS technology is installed. Due to these measures, emissions reductions are larger than what the 70 percent decline in fossil fuel usage might suggest.

Significantly, the steep declines in fossil fuel usage in our Core Scenario, enabled by significant increases in energy efficiency and renewable energy, highlight the need for rigorous scrutiny of any additional fossil fuel infrastructure. Over-investing in fossil fuel infrastructure could lead to stranded assets and higher economic and environmental costs, making it more difficult for the United States to achieve its climate goals.

PERILS OF NATURAL GAS

The exploration and production of oil and natural gas come with significant public health and environmental impacts.[82] These impacts are well documented, including those from hydraulic fracturing, or fracking. They include but are not limited to:

- Emissions of GHG pollutants;[83]
- Contamination of drinking water sources;[84]
- Use of chemicals that are harmful to human health, including known carcinogens;[85]
- Toxic air pollution, including chemicals that can cause asthma, severe headaches, childhood leukemia, cardiac problems, and birth defects;[86]
- Generation of large amounts of waste that can be toxic or otherwise harmful;[87]
- Destruction of landscapes, including wildlands and vital wildlife habitat;[88] and
- Earthquakes caused by underground storage of oil and gas wastewater.[89]

Too often, this dirty industrial process is—literally—in backyards across America. More than 15 million Americans live within one mile of a fracking site.[90] Yet our laws, regulations and oversight are much too weak to protect families and communities from the dangerous air, water, and land impacts of this industry.[91] Oil, gas, and other fossil fuels come with grave consequences for our health and our future. Digging, processing, distributing, and burning these fuels turn people's homes, neighborhoods, and treasured wild places into industrial zones, causes climate change, and contributes to serious health problems.[92]

ag The percentage reduction in natural gas use in the electric sector is greater than that economy-wide. This is likely because it is easier to replace power-sector natural gas with other sources of electricity, such as wind, solar, and battery storage, than to do so where it is used as a direct fuel in other sectors, such as buildings or industry.

ah Comparing 2050 NRDC results with 2015 levels, coal use drops by about 90 percent, oil by about 55 percent, and natural gas by about 66 percent.

2.5 IMPROVING THE GRID: HOW IT ALL COMES TOGETHER

To underpin these solutions, a modernized power grid will be paramount, especially to support the expansion of renewable energy resources.[ai] As the United States integrates more renewables, electrifies the transportation sector, and decarbonizes the building sector, the electricity grid becomes both increasingly important and faces increasing limitations. We must invest in the right systems to alleviate congestion, integrate more renewable energy on the grid, and to obtain more real-time information about power flows on the transmission and distribution system from distributed energy. Otherwise, costs and adverse events due to congestion, power quality degradation, and system overload could increase.

An improved grid can enable and better utilize next-generation supply and demand resources, such as large-scale renewables, energy efficiency, and flexible demand-side distributed energy resources (e.g., rooftop solar, battery storage, thermal storage, and electric vehicles). It can also promote demand response—that is, technologies or actions that adjust electricity demand according to the real-time needs of the grid and consumers. These include smart thermostats that better optimize cooling when energy prices are very high, factories that moderate operations when the grid is under large strain, electric water heaters that charge during off-peak hours, and the utilization of EV batteries to store and release power to address short-term fluctuations in energy. Appropriately sited and adequate transmission and distribution investments will also be central to modernizing the grid.

But a modern grid also requires reconfigured management and operations. This includes greater coordination of resources and integration of power markets across larger regions of the country, which would improve utilization of available clean energy resources, manage their variability, and reduce overall cost.[93] Updated processes and operations at grid-management organizations that facilitate and integrate these next-generation clean energy resources are also essential. See Exhibit 6 for a vision of how a modernized grid may be different from today's and enable a range of clean energy technologies.

Together, real-time data, advanced forecasting methodologies, and transmission upgrades have allowed regions to integrate ever-increasing levels of wind and solar. Multiple local, state, and regional operators have now successfully integrated enough solar and wind power to meet more than 50 percent of all energy needs over short periods.[94,95,96] In the longer term, technical modeling of the U.S. power system demonstrates that well-planned transmission and distribution system upgrades can help the grid reach renewables penetration levels of 80 to 90 percent.[97]

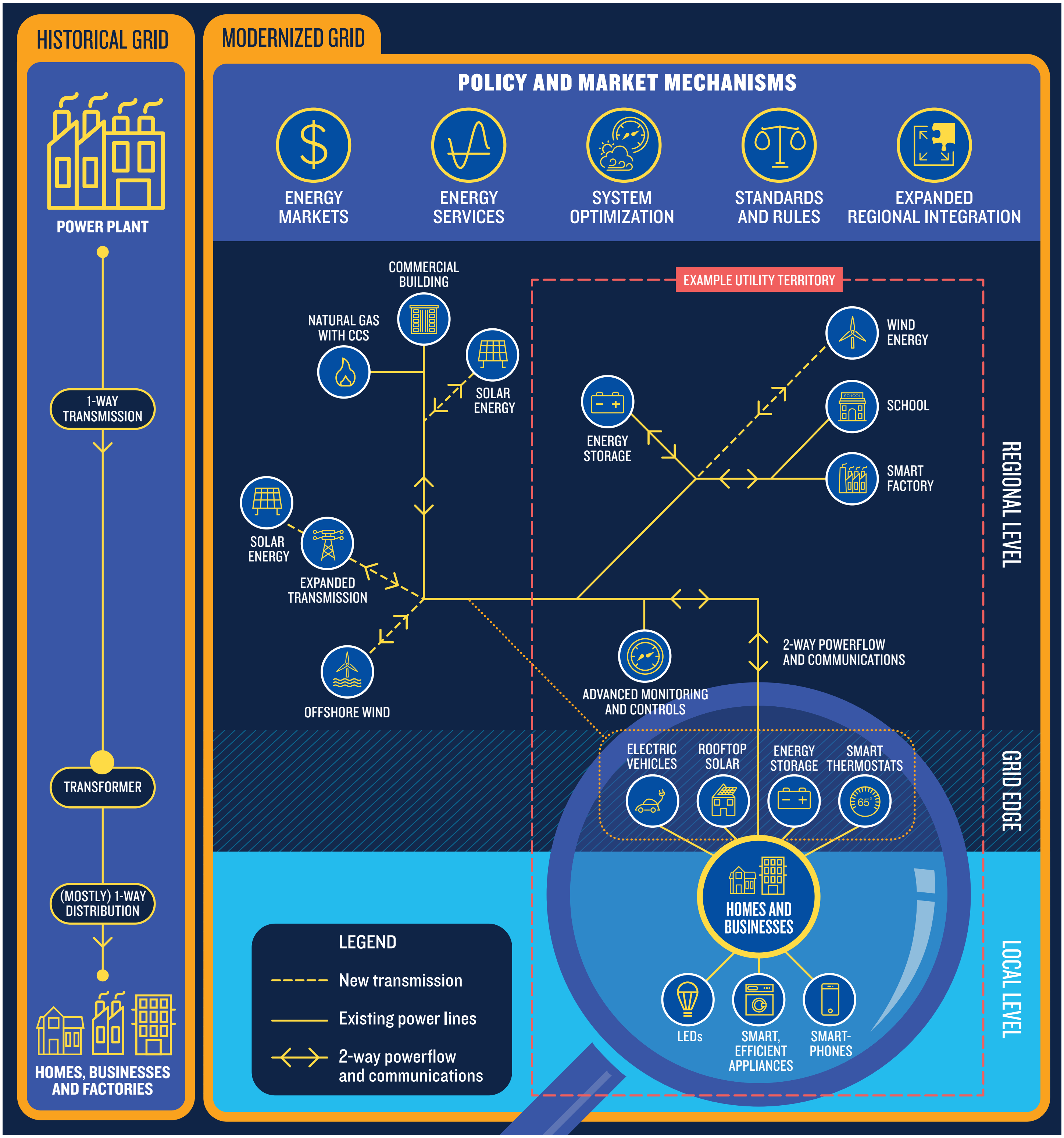
A modernized grid would also serve as a stronger shield against weather events, minimizing costly power outages.[98] Weather-related outages are estimated to have cost the U.S. economy an inflation-adjusted annual average of somewhere between $18 billion and $70 billion from 2003 to 2012.[99] With the changing climate and rising global temperatures, extreme weather events will become more frequent and more destructive—which could further impact and depress the U.S. economy, leaving us in the red and in the dark.[100]

The PATHWAYS model ensured that renewables and other technologies could be integrated into the grid with adequate and appropriate investments. The NRDC Core Scenario projects cumulative incremental transmission (high-voltage) system costs of $925 billion more than the Reference Case between 2015 and 2050. However, a more flexible transmission grid and improved load control reduce distribution (low-voltage) system costs by $660 billion over the same period. Net power grid infrastructure-related cost increases are, therefore, $265 billion. (This does not include the substantial fuel cost savings from increased renewable energy deployment.) To put this into perspective, the transmission and distribution costs of the Reference Case between 2015 and 2050 add up to $7.8 trillion—so a net increase of $265 billion is equivalent to 3.4 percent of reference costs.

Exhibit 7 provides a sense of the time line and key milestones for the deployment of the various clean energy measures in the NRDC Core Scenario.

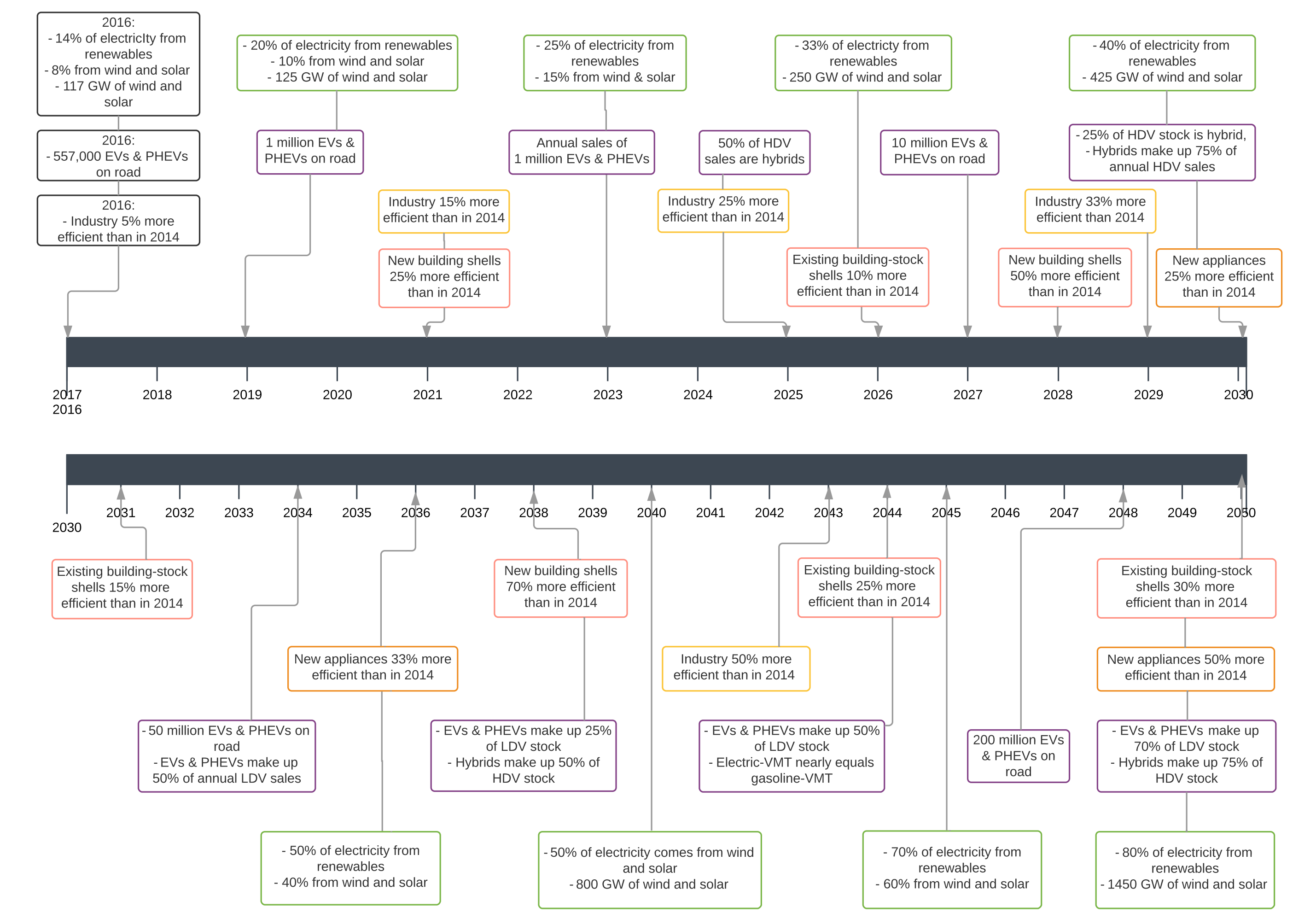
ai There are two main parts of the electric system: one supported by the high-voltage transmission grid that moves electricity across state lines and is ultimately regulated by the Federal Energy Regulatory Commission (FERC), and the other supported by the lower-voltage distribution grid, which is regulated by each state within its borders. There are currently three major transmission grids that straddle the United States (and parts of Canada and Mexico), called interconnections. Regional Transmission Organizations (RTOs) and Independent System Operators (ISOs) are regional grid operators that manage parts of the electricity systems in each of these three interconnections. Utilities are structured differently across the country, but typically they handle power distribution to customers and interface with state regulators and regional grid operators. They also manage the transmission grid in the parts of the country without RTOs and ISOs (primarily the Southeast and the West, apart from California). The hardware, organizational structures, and management processes continue to evolve to serve our changing power needs. However, the current configuration is influenced by the electric power system of the past, which has been dominated by centralized coal-fired, gas-fired, nuclear, and hydro power plants. Chang, Judy W. et. al. *Advancing Past "Baseload" to a Flexible Grid, How Grid Planners and Power Markets Are Better Defining System Needs to Achieve a Cost-Effective and Reliable Supply Mix*. Prepared for Natural Resources Defense Council. June 26, 2017.

EXHIBIT 6: AMERICA'S MODERNIZED GRID



A modernized grid is essential to meeting our clean energy needs, such as integrating solar and wind power, and helping unlock flexible demand-side distributed energy sources. At the most local level (a home or business), a range of equipment can help manage energy demand and supply, like solar panels, grid-enabled smart appliances, storage, and EVs. At the regional level, grid operators can take advantage of, for example, industrial demand response capabilities, energy storage technologies, advanced grid monitoring and control systems, renewables resources, and expanded transmission and distribution lines with two-way powerflow and communication, to maintain the reliability and resiliency of U.S. energy systems. Some technologies present in homes and businesses can also be aggregated to directly provide grid services, and thus sit at the "grid-edge." U.S. energy regulators, regional grid operators, state regulators, local utilities, and third-party aggregators can explore ways to expand coordination efforts to optimize the energy system, and reform energy markets to better value the energy and ancillary services that clean energy resources provide. Expanded regional integration has also demonstrated value and improved grid performance. This figure is simply illustrative and various other combinations of (clean) energy resources and their interactions are possible.

EXHIBIT 7: TIME LINE AND KEY MILESTONES FOR THE DEPLOYMENT OF THE PRINCIPAL CLEAN ENERGY RESOURCES UNDER THE NRDC CORE SCENARIO PATHWAY



With the right policies we can achieve or even surpass these goals. In the absence of adequate policies, while there may be meaningful progress, it will be uneven in sectors and regions, and will likely fall short in the long-term, while some near-term investments may prove to be distractions or impediments.

2.6 REDUCING U.S. RELIANCE ON NON-RENEWABLE LOW-CARBON RESOURCES: LOWERING THE RISK

Our Core Scenario's reliance on substantially expanded energy efficiency and renewable energy also significantly reduces U.S. dependence on other low-carbon technologies such as nuclear, fossil fuel generation with CCS, and unsustainable biomass. Decreased reliance on CCS technology and biomass brings many benefits. Presently, CCS is installed at a much lower scale and costs considerably more than renewable energy and energy efficiency.[101] Biofuels have risks associated with the limited availability of truly sustainable, carbon-neutral biomass.[102]

While nuclear energy is a low-carbon technology, the nuclear fuel cycle has a host of environmental and public health risks and impacts and is increasingly noncompetitive with other forms of electricity generation.[103,104] The reduced role of nuclear power in the NRDC Core Scenario, however, chiefly reflects the economic challenges facing the nuclear industry and the aging of the existing U.S. nuclear fleet. In our scenario, there are approximately only 20 GW of nuclear power plant capacity in operation by 2050, an 80 percent decline from present levels. Currently, the United States has 99 operating nuclear power plants, but early retirement plans have been announced for seven reactors at five plants largely because of economic pressures.[105] It is increasingly difficult for nuclear power plants to compete in the face of sustained low wholesale electricity prices.[106]

Nuclear power plants are licensed by the federal Nuclear Regulatory Commission (NRC). The initial license lasts for 40 years, and plant owners can then apply for 20-year license extensions. Because most of the United States' nuclear power plants were built in the 1960s, 1970s, and 1980s, these plants will have reached the end of their 60-year extended operating licenses by 2050. Only one nuclear power reactor has been completed and commenced operation in recent years (Watts Bar Unit 2 in 2016). Four more reactors are under construction (Summer Unit 2 and 3 in South Carolina, and Vogtle Unit 3 and 4 in Georgia), but schedule delays and cost overruns have made their futures uncertain.[107]

In our scenario, there are approximately only 20 GW of nuclear power plant capacity in operation by 2050, an 80 percent decline from present levels.

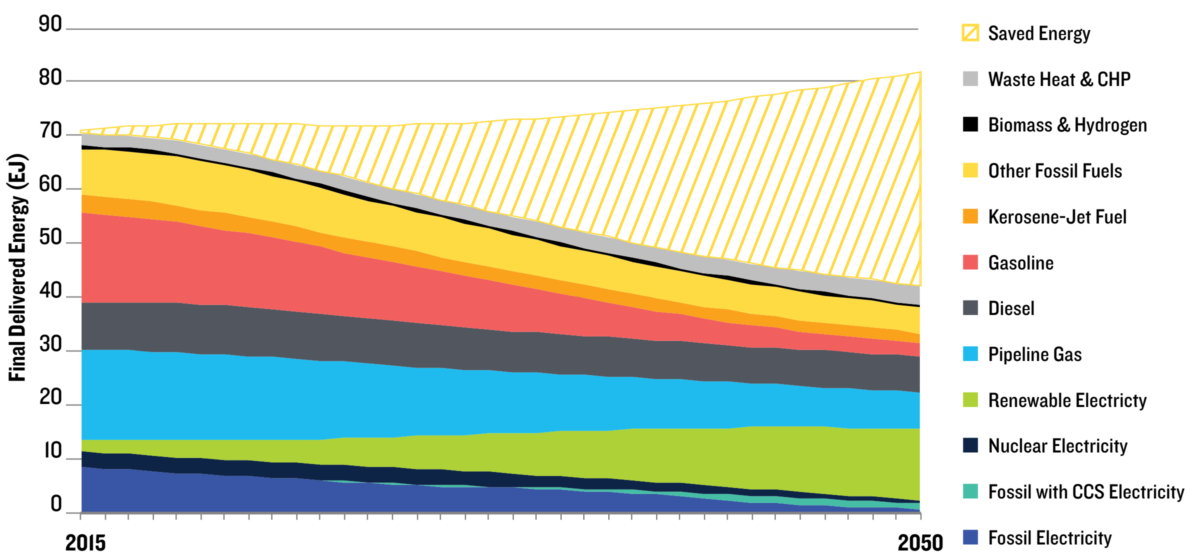
Due to the high cost of nuclear power plant construction and the current wave of premature retirements, NRDC assumed that, aside from those already under construction, no new nuclear facilities would be built. We also assumed that very few existing plants would operate beyond 60 years. That is a reasonable assumption because, to date, no plant has received a license to extend to 80 years, although the NRC is now considering it.[aj,108] The economics of keeping an aging reactor operating through a second 20-year relicense period would also be challenging.[109] No working prototypes of advanced (non-light-water) nuclear reactor designs or small modular reactor designs are firmly planned at this time. Therefore, the NRDC Core Scenario conservatively does not include prospective new nuclear technology. In the NRDC scenarios, increased renewables deployment primarily makes up for the lost zero-carbon benefit over time from nuclear generation.

NRDC'S STANCE ON NUCLEAR POWER

NRDC is not opposed in principle to nuclear power, and acknowledges its beneficial low-carbon attributes in a warming world but we take seriously the significant safety, global security, environmental, and economic risks that use of this technology imposes on society. These outstanding problems for nuclear energy are: environmental harms from uranium mining; safety and security of nuclear plant operations; nuclear weapons proliferation impacts; and spent nuclear fuel disposal. In addition, nuclear power is unproven to be economical compared to alternate forms of low-carbon electricity generation. This demands stringent regulation of the complete nuclear fuel cycle, beginning with the mining and milling of uranium and ending with the final disposal of radioactive wastes. Until these risks are properly mitigated, expanding nuclear power should not be a leading strategy for diversifying America's energy portfolio and reducing carbon pollution. NRDC favors more practical, economical, and environmentally sustainable approaches to reducing both U.S. and global carbon emissions, focusing on the widest possible implementation of end-use energy-efficiency improvements, and on policies to accelerate the commercialization of clean, flexible, renewable energy technologies.

Exhibit 8 depicts the major economy-wide energy trends and paradigm shifts in the NRDC Core Scenario.[ak]

EXHIBIT 8: ENERGY USE FROM 2015 TO 2050 IN THE NRDC CORE SCENARIO



Delivered energy excludes energy lost (i.e., wasted heat) during the generation, transmission, and distribution of the energy.

aj According to our assumptions, there would be approximately 15.5 GW of nuclear capacity in 2050 from currently operational plants. In addition, approximately 4.5 GW of capacity are in plants under construction. NRDC's nuclear assumptions and trajectory are in line with the AEO2013 Low Nuclear Case.

ak Some of the electricity generated in 2050 is used to create synthetic natural gas. This synthetic gas makes up 10 to 15 percent of the total gas supply in 2050 and is included in the pipeline gas wedge, not in the electricity wedge.

2.7 REDUCING OTHER GHGS: GOING BEYOND CARBON

While carbon emissions see the biggest reductions in our Core Scenario, deep decarbonization of the U.S. economy requires reducing all GHGs. Several non–carbon dioxide emissions are associated with fossil fuel consumption and certain production processes, such as coal and natural gas extraction, processing, and distribution. Therefore, carbon reduction strategies that directly reduce fossil use can indirectly reduce non–carbon dioxide emissions as well (e.g., reducing gas demand will, in turn, reduce methane from oil and gas operations).

While some non-carbon dioxide emissions can be reduced indirectly, direct non-carbon dioxide mitigation measures will be required to achieve an 80 percent reduction in total U.S. GHG emissions. Both of NRDC's scenarios considered emissions reductions of all non-carbon dioxide GHGs, primary among them being methane (such as from oil and gas operations, coal mines, landfills, and the meat industry), nitrous oxide (such as from agricultural soil and manure management, and chemical manufacturing), and HFCs (such as in refrigeration and cooling equipment). The NRDC scenarios used reasonable assumptions for possible non–carbon dioxide emissions reductions, based on a review of analyses completed by NRDC and by external parties.[al] For example, our scenarios assumed that the United States can implement measures to directly address and reduce methane leaks from both existing and new natural gas extraction and transmission systems (for more details, please refer to our joint report *Waste Not*, developed with the Clean Air Task Force and the Sierra Club). All told, our scenarios reduce non–carbon dioxide GHG emissions by close to 30 percent relative to 1990 levels and 50 percent compared with the Reference Case, which comes to approximately 300 million tons of carbon dioxide equivalent (CO_2e) by 2050.

Our Core Scenario would likely be the lowest-cost scenario over any period longer than about four decades.

2.8 THE COST-EFFECTIVE APPROACH TO CUTTING EMISSIONS: WEIGHING THE OPTIONS

Even with conservative cost assumptions, our Core Scenario would amount to only about 1 percent more than the Reference Case cumulatively between 2015 and 2050. This is primarily due to incremental capital outlays associated with the clean energy transition, which are almost entirely offset by reduced fuel expenditures from energy efficiency and renewables. By 2050, the annual cost of the Core Scenario is actually lower than that of the Reference Case, and it would likely become even less expensive after that point (although the post-2050 period was not specifically modeled). In fact, our Core Scenario would likely be the lowest-cost scenario over any period longer than about four decades. Furthermore, the potential health and climate benefits would far outweigh any temporary cost increases.

As shown in Exhibit 9, annual incremental net expenditures average around $422 billion between 2015 and 2050 (around 1.2 percent of average annual Reference Case energy spending over those 35 years). This is driven mainly by higher up-front costs for higher-efficiency appliances, electric appliances, and electric vehicles and increased electric transmission investments, which are partially offset by lower fuel and operating outlays due to efficiency and renewables. But by 2050, the NRDC Core Scenario costs $30 billion less than the Reference Case. Pre-2027 costs are also slightly lower than the Reference Case, thanks to lower-cost efficiency measures with very short payback periods. These include things like switching from incandescent lighting to LED bulbs, using occupancy sensors for commercial lighting, and making operational changes (e.g., switching electronics to sleep mode after shorter periods of inactivity), which very quickly yield savings that more than compensate for initial costs. To put these numbers in perspective, annual energy system expenditures in the Reference Case rise from $1.35 trillion in 2015 to $2.4 trillion in 2050.

Finally, if we were to include the environmental and health benefits of the NRDC Core Scenario, the benefits would far outweigh the costs, with a cumulative $5.6 trillion in environmental benefits, along with some additional health benefits, due to emissions reductions between 2015 and 2050 compared with the Reference Case.[110,111]

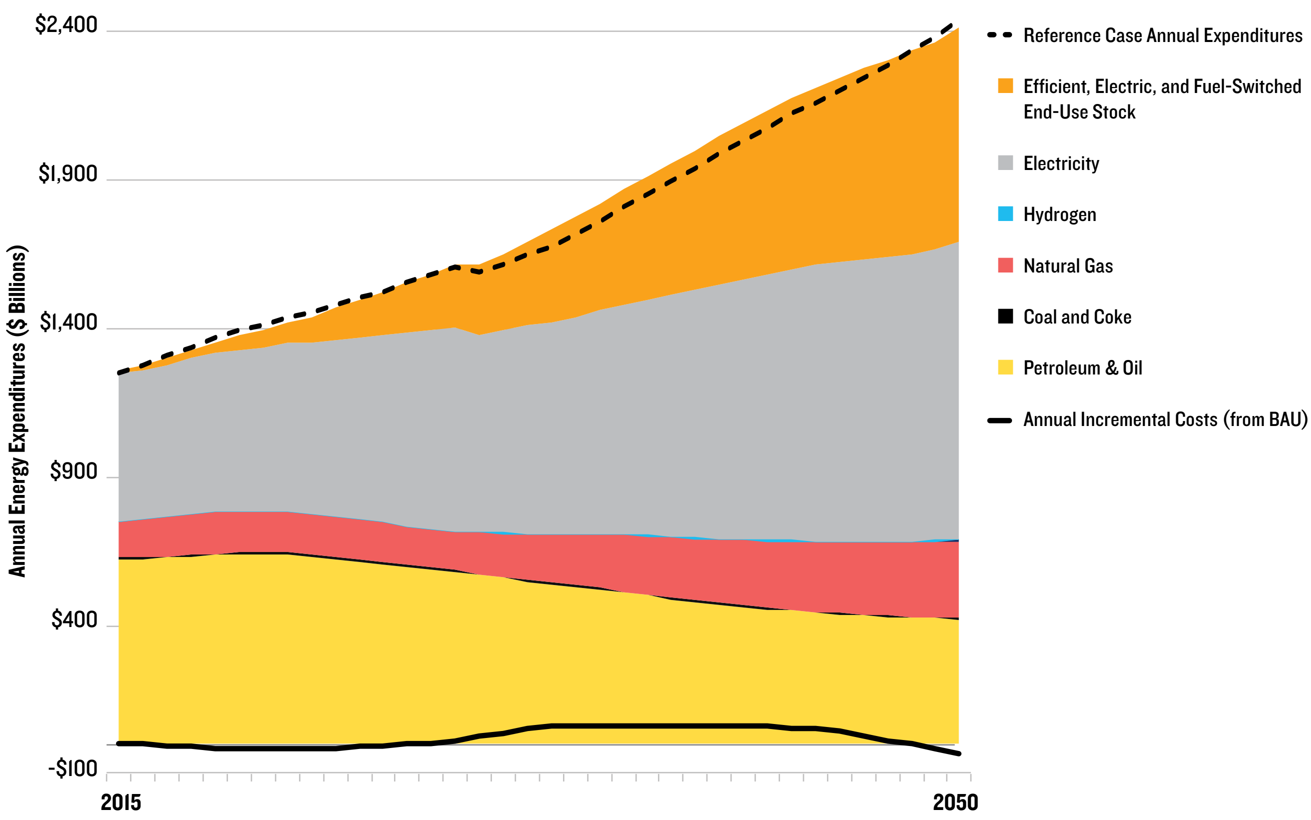
The NRDC Core Scenario also costs substantially less than the DDPP Mixed Case (see Appendix F), by about 10 to 15 percent. This is mainly due to more aggressive energy efficiency implementation, which reduces the need for more expensive clean energy technologies like nuclear and CCS. However, a delay in implementing energy efficiency and some electrification technologies would raise costs 10 to 15 percent above the Reference Case (similar to the DDPP Mixed Case), which will be discussed in Section 2.9.

al NRDC compiled data related to absolute GHG emissions reductions from 1990 levels in 2050, based on both E3's GCAM analysis completed for the DDPP report and NRDC's own internal analysis of potential non–carbon dioxide emissions reductions post-2020. NRDC used the higher estimate, or in a few select cases a median estimate, as the upper limit of feasible GHG reductions by 2050 for each non-CO_2 GHG source. The maximum possible reduction in non-CO_2 GHG sources was 554 MMT below 1990 levels. While the *absolute feasible emissions reduction limits* were established by taking the more aggressive of the numbers mentioned above, NRDC's modeled assumptions were more conservative, achieving only a 306 MMT reduction from 1990 levels—or about 55 percent of the identified possible emissions reductions. These reductions were nonetheless larger than those in the DDPP (Mixed Case), in part due to higher assumed reductions in methane and HFCs.

All told, our scenarios reduce non-carbon dioxide GHG emissions by close to 30 percent relative to 1990 levels and 50 percent compared with the Reference Case, which comes to approximately 300 million tons of carbon dioxide equivalent by 2050.

As context for our cost assumptions, cost data used in the model are taken largely from the EIA's AEO 2013. The Reference, NRDC, and DDPP cases are all based on AEO 2013, which allows for a direct comparison of costs between NRDC's and the DOE's own modeling. We believe that our cost assumptions are likely conservative, given the recent and rapid cost declines for wind, solar, and batteries that are expected to continue for some time. Although not modeled, it is also plausible that current powerful societal trends—for instance, urbanization and the sharing economy—will play a large and positive role in promoting decarbonization. Since the modeling was completed, costs and projections of energy resources have changed markedly, with renewable cost expectations falling drastically and lower natural gas price forecasts due to increased viable reserves. With current prices, the overall energy system costs in all the modeled scenarios would likely be lower, albeit not uniformly, and cost differences among them might be smaller. On balance, however, discussion about and a comparison of costs are still meaningful, even if imperfect.

EXHIBIT 9: BREAKDOWN OF ANNUAL ENERGY EXPENDITURES IN THE NRDC CORE SCENARIO



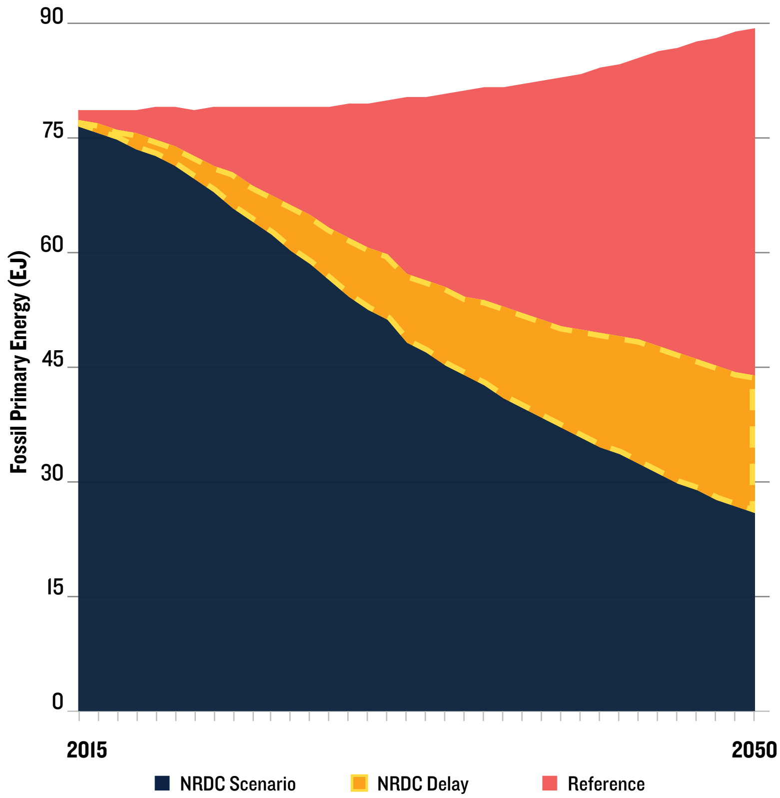
The dashed black line reflects annual energy expenditures in the Reference Case; the solid black line represents the annual incremental costs of the NRDC Core Scenario compared to the Reference Case. As illustrated, the NRDC scenario sees higher annual incremental costs between 2027 and 2050 but falls to $30 billion less than the reference in 2050. Cumulative incremental costs between 2015 and 2050 are just over 1 percent above the cumulative Reference Case.

2.9 THE COSTS OF DELAYED ACTION: TIME IS OF THE ESSENCE

If implementation of clean energy technology is delayed or insufficient, we could fall short of the 2050 emissions goal by 1 billion tons of carbon dioxide (about one-fifth of the necessary reductions), or more. As part of a Delay Scenario, we examined the implications of not deploying efficiency in all sectors and not electrifying the transportation and industrial sectors at the required scale and pace.[am] Reaching the emissions goal in this case would require much greater reliance on nuclear, biomass, natural gas, and CCS—technology pathways that are currently deployed at a smaller scale, carry greater environmental risks, or are more expensive. Specifically, our Delay Scenario results in about 10 to 15 percent higher costs, increased land use impacts due to higher biomass deployment, and heightened technological uncertainty.

The Delay Scenario costs on average about $140 billion more annually than the Reference Case and about $120 billion more than the NRDC Core Scenario. It requires 55 GW of nuclear (versus 20 GW under the NRDC Core Scenario, but still a decrease from today's level of 100 GW), three times the levels of CCS, and more than twice as much biomass (a level far higher than what NRDC believes can be sustainably sourced) as compared with the NRDC Core Scenario. Furthermore, higher energy demand across the economy would require approximately 150 percent more gas for direct use in industry and for power generation, as well as a modestly higher renewables build-out. These differences are summarized in Exhibit 10.

EXHIBIT 10: BREAKDOWN OF PRIMARY ENERGY USE AND DECLINE OF FOSSIL ENERGY



2050 Primary Energy Use (EJ)	NRDC Core Scenario	Delay/ Secondary Scenario	Reference Case
Coal	4.1	3.8	22.1
Natural Gas	11.6	28.2	34.6
Petroleum, Other	10.1	11.8	33.1
Total Fossil Use	**25.9**	**43.8**	**89.7**
BELOW DATA NOT IN ADJOINING GRAPH			
Renewables	16.1	18.6	3.9
Nuclear	0.6	1.6	3.1
Biomass	9.6	19.2	5.6
Fossil Feedstock*	3.6	5.3	5.3
Total Primary Use	**55.6**	**88.5**	**107.6**
Saved Energy	**52.0**	**19.1**	-

* Fossil feedstock does not represent an energy use per se but is included for accounting purposes in the model as EJ for "primary use".

The graph and table show the breakdown of primary energy use by energy resource in exajoules. Three scenarios are shown: Reference Case (red), NRDC Core Scenario (blue), and NRDC Delay/Secondary Scenario (orange).

am The consequences of delayed/insufficient implementation were realized by running a separate scenario with its own set of assumptions. For more details, please refer to the NRDC Delay/Secondary Scenario in Appendix C.

In addition, when households spend less on energy because of efficiency, they have more income available to spend on other goods or to save for large life events such as education, a home purchase, or retirement.

2.10 THE MACROECONOMIC BENEFITS OF CLEAN ENERGY

The macroeconomic benefits of clean energy were not analyzed by our modeling. However, there is ample evidence that clean energy has significant macroeconomic benefits.

Nearly 500,000 people are employed in clean energy sectors such as solar and wind, in jobs related to equipment manufacturing and electricity supply. Around two million workers are employed in jobs that directly or partially relate to the manufacturing, installation, and design of efficient appliances, lighting, and buildings.[112] And almost 300,000 workers are employed by the technologies that create cleaner cars.[113] By comparison, around 1.1 million people work in the fossil fuel sector—in extraction and refining, fuel transportation, pipeline construction, manufacturing of related equipment, and electricity generation from fossil fuels.[114] As we expand the clean energy sector, the economic benefits will only multiply.

© Dennis Schroeder

By investing in a 21st-century grid alone, according to the Edison Electric Institute, electric utilities currently spend more than $100 billion annually to build smarter energy infrastructure and to transition to even cleaner generation sources, doubling from just a decade ago.[115] Already planned investments in a smart grid are expected to employ 500,000 people across the country—as advanced metering and grid technologies support not only traditional power sector jobs, but also jobs in the computer and mathematical sciences to develop, optimize, and maintain software and network systems.[116] Further investments in a more advanced, resilient grid provide greater opportunities to build and strengthen America's STEM (science, technology, engineering, and mathematics) workforce.[117]

A clean energy economy can also bring greater local and state economic and employment benefits that can help currently fossil-dependent economies. For example, per MW of capacity, utility-scale renewable generation has been found to create two to five times more jobs than natural gas generation.[118] And small-scale (distributed) solar creates about twice as many jobs per MW of installed capacity as utility-scale solar—or roughly 10 times the number of jobs created by a new gas plant. Modeling of finalized carbon pollution standards has found that these carbon policies result in net employment gains.[119] In other words, at a national level, the gain in clean energy–related full-time employment more than outweighs the employment losses in the fossil sectors. While modeling suggests that carbon policies can produce net economic and employment benefits nationally, the impacts vary regionally. Accordingly, timely attention is needed to adequately address issues associated with displaced workers and affected communities

In addition, when households spend less on energy because of efficiency, they have more income available to spend on other goods or to save for large life events such as education, a home purchase, or retirement. In the future, increased investments in energy efficiency could create hundreds of thousands more jobs directly and indirectly.[120] The ACEEE estimates that each $1 million invested in energy efficiency supports 20 jobs in the U.S. economy, directly and indirectly. In comparison, the economy-wide average is 17 jobs supported per $1 million of investment, and the utility sector supports only 9 jobs per $1 million of investment, on average.[121] Finally, increased local economic activity increases the tax base that enables further investment in the well-being of the community.[122]

More than 2.8 million Americans were already employed in the renewable or energy efficiency sectors as of 2016.

3. Policy Implications of the NRDC Core Scenario: High-Level Themes

In this section, we discuss the policy implications of the NRDC Core Scenario and put forward a set of thematic policy recommendations that can be taken at the federal, state, and city levels, in partnership with the private sector and communities, to help keep the United States on track to meet its 2050 climate goals. Our suggested policy recommendations are high-level, rather than prescriptive or exhaustive, recognizing that the country's deep decarbonization goals can be met through a variety of policies and market actions and that the necessary approaches will change over time. No specific policies were included in the modeling analysis.

CORE POLICY PRINCIPLES

Underlying these policy recommendations are the following core principles:

- Policymakers and market participants should **prioritize accelerating widespread deployment and expansion of proven clean energy technologies**, as discussed earlier, that are critical to meeting long-term goals. While our scenarios call for faster, broader, and more integrated clean energy deployment than has been achieved historically for some clean energy technologies, recent energy efficiency and renewable energy growth trends indicate that the right mix of aggressive policies can achieve the needed scale at the needed speed. Proactive, near-term action is essential to ensure that the 2050 goal can be reached at the lowest cost. Failure to achieve rapid gains will necessitate reliance on riskier and more expensive technologies to meet emissions reduction goals.
- At the same time, policies should provide longer-term guidance to avoid stranded assets and undermining long-term emissions goals. Investments in fossil fuel infrastructure that will likely no longer be needed by 2050 should be avoided. Policies must facilitate an intelligent pathway to the electrification of end uses, differentiated by subsector and service provided. Modernization of the power grid—its infrastructure, oversight, and operations—will need to facilitate the integration of more and more clean electricity, rather than evolve as it has historically. With the right policies, these goals can be met or surpassed. In the absence of adequate policies, while there may be meaningful progress, it will be uneven in sectors and regions, and will likely fall short in the long term, while some near-term investments may prove to be distractions or impediments.
- Deep decarbonization cannot be realized by government or corporations or communities alone—these entities must all act, lead in their respective ways, and take action together when possible. We need an immediate, timely, and orderly economy-wide transition to a clean energy system, and this demands that all stakeholders **take a comprehensive approach that leverages effective policy frameworks and powerful market drivers to unleash necessary clean energy investments**.
  - **Federal action:** The prospects for the adoption of such a comprehensive approach are slim under the current federal leadership. Even so, there is opportunity for the federal government to move forward now on a bipartisan basis with many important supporting policies, such as adopting stronger efficiency standards, tax incentives, and funding for R&D.
  - **State action:** Generally speaking, states have primary jurisdiction over many key energy policy decisions, including regulating utilities, deciding on the components of the state energy mix, establishing renewable energy and energy efficiency portfolio standards, determining state incentives for development and deployment of clean energy technologies, and establishing state climate policy.
  - **City action:** City-level action will become increasingly important since such a large proportion of the U.S. population already lives in urban and near-urban areas and urbanization is only likely to increase.[123] Cities can play an important role in city planning, implementing local sustainability actions, and scaling up clean energy and energy efficiency via a variety of policies.
  - **Corporate action:** The business sector can take significant voluntary steps toward reducing GHGs and investing in clean energy, by improving the sustainability of their operations and their products and services, by engaging their customers, and by working with their local communities.[124] Environmental responsibility has both societal and business benefits.[125]

- **Community action:** Members of the public and communities can also take individual or collective action. This includes implementing energy efficiency and clean energy measures in their homes and offices, working with community groups and local nongovernmental organizations (NGOs), engaging their local governments and businesses, and holding elected representatives accountable.

- To achieve deep decarbonization, **emissions of all GHGs must be reduced.** Our report focuses mainly on reducing carbon dioxide emissions from the energy system, and that is also the focus of this policy section. Notwithstanding, policies to curb other GHGs will be important, as described in the two examples below.
  - Federal agencies should act promptly to reduce methane emissions from the oil and gas sector by half or more. Our recent analysis suggests that this level of reduction is possible in just a few years.[126] The previous presidential administration had a goal to cut methane emissions by similar levels by 2025.[127]
  - The United States should ratify the Kigali Amendment to the Montreal Protocol adopted in late 2016 by nearly 150 countries.[128] The amendment lays out a series of declining production and consumption levels for HFCs, which are climate-unfriendly chemicals used as refrigerants and in other related applications.

In the following section, we discuss our recommendations in more detail. In the following order, we will cover overall climate and clean energy policy, energy efficiency, renewables, modernizing the grid, the industrial sector, the transportation sector, nuclear energy, and energy access and equity.

3.1 OVERARCHING CLIMATE AND CLEAN ENERGY POLICY RECOMMENDATIONS

Recommendation 3.1.1: The federal government, states, and regions should push for comprehensive, economy-wide approaches to limiting GHG emissions.

Ultimately, we need a national, economy-wide approach that links many sectors and is market-based to realize our climate and emissions goals most cost-effectively. In the absence of a national economy-wide approach, sectoral approaches to controlling emissions—which can be very useful—would need to be expanded over time.

Some states have articulated economy-wide or near-economy-wide goals or implementation approaches. For example, in its Senate Bill 350, California has an economy-wide goal of reducing GHG emissions by 40 percent below 1990 levels by 2030.[129] Similarly, New York's State Energy Plan sets a goal to reduce GHG emissions by 40 percent below 1990 levels for the entire energy and transportation sector (not just emissions from generation), also by 2030. New York State is working to put a regulatory structure in place to effectuate that goal, and its Reforming the Energy Vision regulatory proceeding is intended to spur private sector innovation and investment to help achieve this objective.[130] Both these states would rely on 50 percent renewables by 2030. In 2008, Massachusetts signed into law a framework to achieve 25 percent emissions reductions below 1990 levels economy-wide by 2020, and at least an 80 percent reduction by 2050.[131]

An example of a sectoral approach is the nine-state Regional Greenhouse Gas Initiative (RGGI), which started in 2009 after an initial state commitment to create the program in 2005. RGGI established a regional, market-based carbon cap-and-trade program to reduce carbon dioxide emissions from power plants in northeastern and mid-Atlantic states.[132] Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, Rhode Island, and Vermont participate in RGGI, which has added more than 30,000 job-years and $2.9 billion in regional economic activity.[133] The EPA's national Clean Power Plan is also a sectoral approach, limiting carbon emissions from power plants.[134]

Congress has, in the past, come close to passing comprehensive climate legislation such as the 2009 Waxman–Markey and 2010 Kerry–Lieberman bills.[135,136]

Recommendation 3.1.2: Federal and state governments should continue to adopt and strengthen performance-based energy and carbon pollution standards.

Decades of energy and environmental policymaking demonstrates that performance-based standards can be a cornerstone of any successful policy framework to promote the adoption of new technologies. Carbon pollution emissions limits and energy efficiency standards are crucially important performance-based, technology-neutral standards that spur innovation and accelerate private sector clean energy deployment by providing longer-term market certainty. Examples include the EPA's GHG pollution standards for cars, trucks (and companion fuel economy standards), power plants, and oil & gas operations; appliance efficiency standards and building codes; and state and regional cap-and-trade systems. At the same time, governments should consider supporting specific clean energy technologies when it serves broader public policy benefits.

Recommendation 3.1.3: States, cities, and businesses all need to lead on climate and clean energy.

Cities and states have shown impressive support for the Paris Agreement from the very beginning, with many committing to actions via the Global Climate Action Agenda at the Paris Conference in 2015.[137] In the wake of the Trump administration's decision to abandon the Paris Agreement, cities, states, and the business community are once again stepping up to lead on climate change mitigation.

More than a dozen states have also come together to form the U.S. Climate Alliance, committing to continuing to reduce state-level GHG emissions even if the federal government reverses course.[138] States have been and can continue to be clean energy leaders. Texas, Oklahoma, and Iowa are leaders in wind energy.[139] The four states with the most installed solar capacity are California, North Carolina, Arizona, and Nevada.[140] Massachusetts and Rhode Island lead on energy efficiency, each requiring more than 2.5 percent annual improvement.[141] States can also extend their market power through regional cooperation, as in RGGI.

So far, mayors representing more than 350 U.S. cities and towns, with a total population of 54 million Americans, have moved to adopt and uphold the Paris commitments.[142] Cities can drive energy efficiency, such as by adopting stronger energy building codes and enacting local laws requiring or encouraging building benchmarking and energy efficiency retrofitting policies.[143] For instance, the City Energy Project, a joint endeavor of NRDC and the Institute for Market Transformation, works in 20 cities across the country to improve the energy efficiency of buildings while boosting local economies and reducing harmful pollution.[144] Cities can also encourage renewable energy by establishing and working toward goals, like the 100-plus cities that have committed to powering their communities with 100 percent clean energy.[145] These cities provide models for others.

The private sector, too, can play a vital role in achieving climate goals. A growing number of businesses are committing to procuring 100 percent of their energy from renewable resources.[146] Companies can take a variety of other measures such as adopting an emissions-reduction target, developing a corporate climate policy, and reporting emissions in public documents.[147] Companies can also submit their own climate-related pledges to the United Nations via the Non-State Actor Zone for Climate Action (NAZCA).[148]

Recommendation 3.1.4: Federal and state governments should fund R&D to spur innovation.

A focus on specific, critical technology pathways can accelerate innovation and the adoption of clean energy. Innovation in manufacturing, design, and deployment can reduce the cost of commercial clean energy technologies and improve the integration and adoption of new and emerging approaches. Historically, government support for R&D has been instrumental in the success of many of today's energy technologies, including solar PV, LEDs, and EVs.[149] The DOE's Energy Efficiency and Renewable Energy (EERE) and Advanced Research Projects Agency-Energy (ARPA-E) programs have been especially important in supporting early commercialization of clean energy.

In the Sunshot initiative, for example, the DOE set defined goals and clear metrics and then drove down costs for solar energy to make it more competitive and increase access. We can replicate this for other critical technologies such as offshore wind, energy storage, CCS, second-generation biofuels, advanced manufacturing, smart cities, and electric and autonomous vehicles. For example, the DOE should remain committed to spurring technological innovation in offshore wind and supporting first generation projects. The DOE's Advanced Manufacturing Office can help foster innovation in the industrial sector and help generate durable and deep energy efficiency and productivity gains via technology and process refinements in the long term.

Accordingly, the federal government must continue to provide national and global leadership in clean energy innovation, through cutting-edge research at national laboratories, universities, and other reputable organizations. It should also collaborate with corporations to steer private investment in R&D. States and utility regulators must also support and encourage R&D investments by utilities and state agencies, providing additional support for pilots, demonstrations, and market deployment of low-carbon technologies. Furthermore, research funds filter down to clean-tech incubators and start-ups across the country. These labs and incubators are jump-starting companies on the cutting edge of energy innovation and will keep America competitive at a time when the rest of the world—from China to Germany—is significantly surpassing our investments in clean energy.

Finally, although the scope of our analysis was limited to 80 percent GHG reductions by 2050, the globe must achieve net-zero emissions by the end of the century to keep warming below 2 degrees Celsius.[150] Therefore, innovation will be needed to develop technologies to reduce emissions even further than our 80 percent goal. And if we fail to meet our deployment targets for available technologies by mid-century, we will need innovation to identify new technologies to close any emissions gap prior to 2050.

3.2 KEY RECOMMENDATIONS FOR ENERGY EFFICIENCY

Recommendation 3.2.1: The federal government should establish stronger energy efficiency standards for appliances and commercial and industrial equipment and should expand the ENERGY STAR® program. States should establish energy efficiency standards for areas that federal programs do not cover.

The DOE should continue to meet or surpass congressionally mandated deadlines for establishing and strengthening energy efficiency standards for residential appliances and commercial and industrial equipment. Performance-based energy efficiency standards have proven highly effective at cutting energy use from our current appliances, buildings, and vehicle stock while also reducing customers' utility bills. The DOE adopts minimum efficiency standards for a range of appliances and equipment, such as central air conditioners, pool pumps, dehumidifiers, and refrigerators. These standards are often the result of negotiations between manufacturers and other stakeholders. Together, they reduced total U.S. household consumption by an average of 21 percent for electricity, 6 percent for gas and oil, and 14 percent for water in 2015.[151] These cuts translated to a total of $80 billion in utility bill savings in 2015 and could possibly reach $150 billion annually by 2030.[152]

The ENERGY STAR program is a voluntary labeling program that helps consumers and businesses select a more energy efficient model for an array of products including laptop computers, televisions, refrigerators, and freezers—usually among the top 25 percent most efficient in each category. All the consumer needs to do is look for models that have the blue ENERGY STAR logo; this means the manufacturer has voluntarily applied to the EPA for the label and that the product meets specific energy-saving requirements. The program has been extremely successful, saving more than $230 billion on utility bills and 1.7 billion tons of GHG emissions since the program's inception.[153] However, the number of ENERGY STAR–certified models varies widely by product type (laptops are currently among the most represented, while clothes dryers are among the least), and product uptake varies as well.[154] The EPA should ensure its specifications are kept up to date and work with utilities to incentivize manufacturers to certify more of their products and encourage consumer uptake. Congress should continue to provide robust funding for this successful program.

States should also adopt state-level energy efficiency standards for appliances and products that are not regulated by the DOE program.[an] The California Energy Commission's appliance efficiency standard program provides an excellent model for other states.[155]

For summaries of the success of efficiency standards, please refer to NRDC's *The $2 Trillion Success Story: Energy Efficiency Standards* and *Strong U.S. Energy Efficiency Standards: Decades of Using Energy Smarter*.

States should also consider adopting energy efficiency policies[156] that:

- Establish and periodically strengthen building energy codes for new construction or major renovations, while encouraging the use of energy-saving construction materials and hardware;
- Require buildings to provide periodic benchmarking assessments of energy use and require or encourage energy efficiency retrofits to reduce building energy use;
- Increase energy efficiency financing opportunities through the establishment of green banks and other finance tools; and
- Require or encourage utilities to offer incentive and market-transformation programs to spur greater adoption of and investment in efficient appliances and building design.

an Although federal preemption generally applies for efficiency standards for products that are regulated by the DOE, states can establish their own energy efficiency standards for products not covered by the federal program. States can also seek waivers from preemption under some circumstances. See generally 42 U.S. Code 6297.

Cities are also leading by adopting the same set of energy efficiency policies independently via local ordinances. Cities can also encourage the adoption of voluntary green building standards like LEED (Leadership in Energy and Environmental Design).[157]

For more details on scaling up energy efficiency, please refer to our reports *Scaling Up Energy Efficiency: Saving Money, Creating Jobs, and Slashing Emissions* and *Doing More and Using Less: Regulatory Reforms for Electricity and Natural Gas Utilities Can Spur Energy Efficiency*.

Recommendation 3.2.2: States should adopt policies to promote investment in all cost-effective energy efficiency.

States should establish energy efficiency resource standards (called EERS, and sometimes referred to as an energy efficiency portfolio standards), and should strengthen these standards over time, to promote investments in all cost-effective energy efficiency measures. Investments in energy efficiency should precede expansion of any new energy resources due to its lower cost and the opportunity it affords to avoid unnecessary infrastructure investments. A state-level energy EERS establishes specific, long-term targets for energy savings that utilities or nonutility program administrators must meet through customer energy efficiency programs. EERS can apply to either electricity or natural gas utilities, or both. As of January 2017, 26 states had adopted such energy efficiency resource standards.[158] The strongest EERS requirements exist in Massachusetts and Rhode Island, which require more than 2.5 percent new energy savings annually.[159] In fact, Massachusetts utilities achieved savings of around 3.3 percent of retail sales in 2016.[160] Other states with strong energy efficiency standards include Vermont, Arizona, Washington, and Maine.[161]

As of January 2017, 26 states had adopted such energy efficiency resource standards.

Recommendation 3.2.3: State regulators and utilities should work together to spur investments in energy efficiency by reforming regulation and utility business models.

State utility regulators should also establish best practices on utility regulation that will encourage utilities to broaden their energy efficiency investments and identify shortcomings in current efficiency programs. State utility regulators should adopt revenue decoupling provisions to remove utility disincentives from investing in energy efficiency (and distribute resources more broadly). As of June 2017, 29 states had adopted such policies for natural gas and/or electric utilities.[162] States must enable utilities and others to maximize cost-effective energy savings and explore emerging market or technology opportunities. This will require regulatory reforms that establish new utility business models that incentivize utilities to invest in and facilitate energy efficiency; rate design structures that encourage more-efficient use by customers; and market options that will spur utilities, businesses, and individuals to implement deep energy efficiency measures. (See *A Vision for the Future of the Electric Industry*, *Doing More and Using Less: Regulatory Reforms for Electricity and Natural Gas Utilities Can Spur Energy Efficiency*, and *Removing Disincentives to Utility Energy Efficiency Efforts*.)

Utilities should also be encouraged to develop new offerings that better address the needs of large commercial and industrial customers (see Section 3.5), municipal customers, and low-income or multifamily residential customers (such as weatherization programs and targeted incentives for landlords). Additionally, utilities should explore programs that encourage more-efficient consumer behaviors, including demand-response programs and dynamic rate offerings for residential and small commercial customers.

Recommendation 3.2.4: Policymakers should remove barriers to building electrification and encourage innovation.

Decarbonization in homes and buildings is still in its infancy. To promote growth in the near term, policymakers could update building codes and energy efficiency program designs to remove regulatory barriers and reform outmoded efficiency program rules that favor fossil fuels over cleaner, more efficient electric end uses. Funding for R&D to develop and improve low-carbon space- and water-heating technologies could have a significant impact. Programs that develop the market and make low-carbon alternatives more readily available could also be powerful. In addition, cities are particularly well placed to explore advanced technologies for district heating and cooling.[163] Recently there have been game-changing advances in this arena, as discussed in *Slashing Emissions from Fossil Fuels Burned in Buildings.*

Several regions have already made progress toward efficient electric appliances, such as heat pumps for space and water heating. In the Pacific Northwest, market transformation programs have already achieved 10 percent penetration of ductless heat pumps in single-family zonal electrically heated homes.[164] These same programs are making progress with heat pump water heaters as well. Some electric utility cooperatives now also offer innovative programs to tap into the thermal storage capabilities of electric hot water heaters, which can serve as a demand-side resource that assists with grid integration.[165] Others have developed financing programs to buy new heat pump technology.[166] Over the past decade, heat pump technology has made tremendous progress in efficiency, reliability, affordability, and variety. This clean energy solution now has the potential for large-scale market deployment, if supported by appropriate market transformation policies. (In our modeling, emissions savings from building electrification are captured in the third category of clean energy solutions related to electrification, as, for example, in Exhibit 4.)

3.3 KEY RECOMMENDATIONS FOR RENEWABLES

Recommendation 3.3.1: States should establish and strengthen renewable portfolio standards.

Renewable portfolio standards (RPS), which establish renewable energy deployment targets for states and regions, provide long-term, progressive guidance for renewable energy investment. Twenty-nine states and Washington, D.C., have already adopted RPS policies at varying levels.[167] Hawaii has established a 100 percent renewables requirement by 2045.[168] Vermont has established a 75 percent renewables requirement by 2032.[169] Oregon has established a 50 percent renewables requirement by 2040, in conjunction with a complete coal power phase-out by 2035.[170] Another eight states have nonbinding renewable energy goals.[171] Leading the larger states, California and New York have established 50 percent renewables requirements by 2030 and are considering higher requirements.[172] In fact, more than one-fifth of the U.S. population lives in a state with an RPS goal of at least 50 percent.[173] Going forward, all states should establish ambitious RPS goals and strengthen these goals over time. To catalyze the growth of particular renewable technologies that may need additional policy support, such as distributed solar or offshore wind, states should also consider reserved set-asides or "carve-outs"[ao] within the RPS for such technologies.

Recommendation 3.3.2: State regulators and utilities should work together to spur investments in renewable energy through business model reforms.

Local electric utilities will be needed as key partners in the significant expansion of renewable energy capacity. Utilities will need appropriate incentives to invest in large-scale renewables—either directly or through long-term power purchase agreements—and to facilitate investment in and interconnection of distributed renewable energy. With respect to the former, utilities must be motivated to invest in, or contract with, renewable energy instead of traditional fossil fuel assets. The contextual policy and market conditions would vary by state and utility, depending on whether the state's utilities are vertically integrated or in a competitive market. Just as with energy efficiency, state regulators must enable utilities to explore and implement new business models to unlock these investment opportunities, especially for distributed renewables. Decoupling and appropriate, well-designed rate structures can also align costs with the value of renewables, supporting both large-scale and distributed clean energy investment. (See *A Vision for the Future of the Electric Industry*.)

Net energy metering allows owners of small-scale, distributed generation systems, such as homeowners or small businesses, to receive credit based on the retail cost of electricity for the energy they provide back to the grid. This is a central policy typically implemented at the state level. "Value of solar" is a companion policy element that estimates the grid value of distributed solar systems so they may receive appropriate credit. The simplicity of net metering incentives provides an effective and efficient boost during the early stages of (regional) market development. As the market matures, it may make sense to explore more sophisticated crediting structures designed to compensate distributed resources, such as those based on the value of solar.

Finally, several region-specific market-design issues and regulatory and permitting hurdles should be eliminated, limited to certain circumstances, or otherwise ironed out to smooth the path for renewables. These hurdles include limits on third-party sales that hamper the economics of residential solar panels, and onerous interconnection requirements that make it cumbersome and costly to install renewable energy systems.[ap]

Direct investments in renewables by corporations, communities, and individuals should also be encouraged where appropriate. State regulators can play a key role in this regard. All customers, from low-income residents to corporations, should be able to procure clean energy at an appropriate and fair rate, through either the utility or a third party within reasonable limits.[174] These purchases should be supplementary to—and not substitutes for—RPS requirements. Cities are also well placed to develop clean energy investment opportunities for their residents beyond individual rooftops, exploring

ao RPSs can be structured in many ways. Most allow for a set of eligible technologies to meet the specified clean energy requirements. A set-aside or carve-out within an RPS typically specifies that only a particular technology (e.g., solar) satisfy a defined portion of the RPS. These can help boost the specified clean energy industries in the region.

ap Third-party sales allow entities other than utilities to sell or supply power to the grid. This allows owners of rooftop solar systems to optimally size their array and possibly partake in other incentives such as appropriate payments for net energy supplied. Limits to third-party sales undermine the prospects for and economics of residential solar panels and other distributed energy systems.

models such as community solar.[aq] Several cities have also announced 100 percent renewable energy goals.[175]

Recommendation 3.3.3: Federal and state siting and environmental review policies should ensure that large-scale renewable projects are planned "smart from the start."

To ensure long-term success, we must provide sufficient oversight, especially as it relates to environmental and ecosystem concerns. Siting and environmental review policies should ensure that large-scale renewable projects are implemented "smart from the start."[176] Developers should be incentivized, for example, to build projects in areas with low natural resource values and to avoid disturbing important or threatened wildlife habitat and wildlands. The Bureau of Ocean Energy Management (BOEM), which is charged with identifying ocean areas that are appropriate for offshore wind development and with permitting these projects, should continue to identify additional appropriate wind energy areas, award leases for development in these areas, and also support offshore wind with appropriate environmental review and mitigation measures to ensure that the responsible development of U.S. offshore wind is consistent with protecting oceans and marine ecosystems.

Recommendation 3.3.4: The federal government should maintain tax incentives for renewable projects.

Congress should maintain the existing renewable energy tax credits that were enacted in 2015, chiefly the Investment Tax Credit and Production Tax Credit for solar and wind, respectively.[177] Less mature renewable energy technologies such as offshore wind will likely require continued tax policy support after these credits expire or are phased down. Longer-term tax and market reform should be informed by market conditions and address identified market distortions. Tax subsidies for fossil fuel technologies should be eliminated.

3.4 KEY RECOMMENDATIONS TO MODERNIZE THE GRID

Recommendation 3.4.1: States, regulators, utilities, and independent system operators should expand energy markets.

Expanded regional energy markets, along with transmission upgrades and improvements in how the grid utilizes all available resources, would allow us to integrate even more renewables and distributed energy resources (DERs) into our power supply. In fact, NREL found that improved grid management practices could allow the western grid to integrate up

aq Community solar can refer to solar projects that are community-owned or to projects owned by a third party but shared by a community. Residents may not have the requisite roof space or financial capital to install solar panels on their homes, or they may simply prefer not to. But participating in a community solar project can allow them to share the electricity of a solar installation that may cost less than that from their utility.

to 35 percent renewable energy, on average, through the year, without extensive infrastructure expansion.[178] The western states are considering expanding the California Independent System Operator into a western integrated grid.[179] Creating a large western energy market with coordinated planning will require leadership from all levels of government, state regulators, grid operators, and utilities. Further, these entities will need to partner closely with labor groups, communities, and other interested parties.

Recommendation 3.4.2: Utilities and other developers should invest in grid modernization.

As stewards of the grid, utilities, with support from their state regulators, will need to invest substantially in appropriate transmission and distribution infrastructure, including new transmission technologies, advanced metering equipment, and electric vehicle charging infrastructure. At the same time, operational and market processes, typically under the purview of regional grid operators, need to be optimized to promote system flexibility. For instance, the compensation for and requirements placed on demand response, distributed energy resources, and energy storage resources need to be modified to better reflect their unique advantages and constraints vis-à-vis grid needs and should not be dictated by legacy protocols.

States will need to develop 21st-century utility business models that incentivize utilities to promote efficiency and clean energy generation by customers and third parties as opposed to higher energy sales for themselves. (See *A Vision for the Future of the Electric Industry*.) This includes innovative rate design, better utility and operator utilization of grid-connected devices, real-time monitoring and weather-related forecasting of distributed and large-scale renewable generation, and an improved understanding of customer energy-use patterns.

Strategic guidance on emerging needs and effective oversight from the Federal Energy Regulatory Commission (FERC) can help identify constructive wholesale energy and capacity market reforms, promote the adoption of new ancillary service products, and facilitate long-term regional and interconnection-wide electricity infrastructure planning.[180] Regional grid operators are well positioned to initiate many of these actions, subject to FERC review and approval.

Recommendation 3.4.3: Policymakers and market players should harness the full potential for distributed energy resources to increase the flexibility and reliability of the grid.

Distributed energy resources (DERs) can play a vital role in integrating high levels of renewable electricity and enhancing grid reliability.[181] Distributed storage can hold excess energy (when prices are low, for example), and certain kinds can inject power back into the grid when needed (e.g., battery power packs for homes). In fact, energy storage can often offer more flexible and faster grid service than traditional resources.[182] Automated demand response in buildings and industrial facilities can also cost-effectively shave peak loads or absorb excess power. At the residential level, grid-enabled water heaters, for example, can respond to signals from grid operators regarding when and how to draw power. In the industrial sector, energy-intensive manufacturing processes can be programmed to adapt to prices without affecting output. Many technologies, such as EVs and grid-enabled water heaters, can provide both demand response and energy storage. To better utilize the full range of grid-connected DERs, customers can use smart meters that provide utilities and power system operators with detailed data in real time, sophisticated algorithms that can analyze such data, and rate structures that convey actionable price signals to customers. Since utilities manage the electricity distribution network, they are best suited to integrate DERs into the grid, with complementary and supportive actions from FERC and independent system operators (ISOs).

Recommendation 3.4.4: Regulators should prevent over-investment in fossil fuel infrastructure.

As discussed earlier, over-investing in fossil fuel infrastructure can lead to stranded assets, and cause unnecessary expenditures, making it difficult to achieve our climate goals. Therefore, efficiency and other clean energy opportunities should be explored first to satisfy energy needs. Then plans and environmental review should account for full life-cycle costs and benefits of fossil fuel infrastructure proposals and different alternatives, including the environmental and health costs of associated pollution and the cost of stranded infrastructure in the case of over-investment. Prudent long-term planning on the part of local, state, and federal policymakers and regulators will be needed, in close coordination with businesses, communities, and NGOs.

3.5 KEY RECOMMENDATIONS FOR INDUSTRY

Recommendation 3.5.1: Utilities should invest in energy efficiency programs geared to the industrial sector.

Many states currently allow industrial customers to opt out of energy efficiency programs, and many existing programs are not effectively designed to meet industrial needs. This leaves a range of large, low-cost opportunities on the table, such as savings from regular maintenance, submetering and energy tracking, efficient lighting, process efficiencies, and insulation.

Accordingly, state regulators should provide the right incentives for utilities to better address the needs of industrial subsectors that have been historically neglected, through mechanisms like on-site waste heat capture, demand response, and strategic energy management programs.

Strategic energy management at industrial facilities puts decision makers in the right place at the right time with the right incentives.[183] Managers of industrial companies often treat energy as a fixed overhead rather than a controllable cost. Shifting the management structure to focus on energy savings can identify substantial overlooked savings opportunities. Therefore, on a continual basis, it leads to increased equipment and process efficiency and improved operations and behaviors. To be most effective, strategic energy management needs to adopt a customized approach that incorporates a variety of elements and processes that work within the particular organization or facility. Managers can refer to extensive guidance and documentation from organizations like the International Organization for Standardization.[184]

Recommendation 3.5.2: Federal and state agencies should train and assist industrial site managers.

Partners from government, NGOs, and the private sector can assist factory and facility managers, for instance, in implementing efficiency measures by generating greater awareness of available opportunities, developing repositories of efficiency tools, providing targeted training, organizing information exchanges among cohorts, and compiling a database of regional service providers. The DOE is well placed to coordinate these resources, building on its successes with the State and Local Energy Efficiency Action Network and its Combined Heat and Power Technical Assistance Partnerships.

Recommendation 3.5.3: The DOE should continue to strengthen minimum efficiency standards for industrial equipment and expand the types of equipment that are covered by standards.

Industrial equipment has significant potential for improvement, as discussed earlier. While this equipment is often customized, unlike many consumer appliances, the DOE can establish minimum efficiency standards for classes of equipment. It can promote further industrial energy reductions through expanded efficiency standards and incentives for mass-produced equipment such as transformers, blowers and fans, electric motors, walk-in refrigerators, and pumps.

3.6 KEY RECOMMENDATIONS FOR TRANSPORTATION

Recommendation 3.6.1: Federal agencies should maintain existing clean car and truck standards and strengthen them for future years.

The EPA and DOT should maintain existing passenger-vehicle GHG and fuel economy standards through the 2025 model year and strengthen standards for future years by at least 5 percent per year, a trajectory similar to that required by the current standards. Existing carbon pollution standards set by the EPA call for fleet-wide average new passenger-vehicle emissions of 163 grams of carbon dioxide per mile, equivalent to 54.5 mpg for 2025-model vehicles.[185] Unfortunately, in March 2017, the Trump administration announced that it will reopen the midterm evaluation of the EPA's standards for 2021 to 2025 model years, a first step to potentially weakening the rules. Especially in the absence of federal leadership, California should continue to move forward with its next phase of post-2025 carbon dioxide vehicle standards. Similarly, the EPA and DOT should maintain existing GHG and fuel efficiency standards for medium- and heavy-duty trucks through 2027 and strengthen standards for future years to require GHG reductions of at least 5 percent per year.

Recommendation 3.6.2: California and Clean Car states should strengthen the Zero Emission Vehicle program.

California's Clean Cars Program establishes tailpipe emissions standards for passenger cars and trucks in order to reduce smog-forming pollutants, soot (particulate matter), and GHGs. In addition, the program includes a Zero Emission Vehicle (ZEV) standard that requires manufacturers to sell an increasing mix of electric-drive vehicles over time, such as battery electric, plug-in hybrid electric (PHEV), and hydrogen fuel cell vehicles.

With its ZEV program, California is now a national leader in plug-in electric vehicle sales, accounting for nearly half of all national sales of such vehicles, and it will continue to make progress.

California, as the leader in plug-in electric vehicle sales, provides a shining example. With its ZEV program, California is now a national leader in plug-in electric vehicle sales, accounting for nearly half of all national sales of such vehicles, and it will continue to make progress. In 2015, 3 percent of new passenger vehicles sold in the state were plug-in electric vehicles. The current ZEV program will put an estimated 1.2 million electric-drive vehicles on the road by 2025, according to the California Air Resources Board.[186] This means 8 percent of all car sales in California between 2010 and 2025 will be electric-drive vehicles.[187] With additional sales spurred by complementary policies and incentives, the state is aiming to bring even more clean vehicles on the road by 2025 to help reach Governor Jerry Brown's goal of placing 1.5 million clean vehicles on the road by 2025. Twelve other states, referred to as Clean Car states, have adopted California's Low Emission Vehicle program, and nine of these states have adopted the ZEV program,[ar] which means that collectively about 28 percent of the U.S. market is poised to rapidly ramp up EV sales. We note that the national scenarios do not reflect regional distributions with the market; we expect the Clean Car states can go faster in adoption of electric-drive vehicles than the national numbers presented here.

Recommendation 3.6.3: Congress should extend tax credits for electric vehicles.

Federal tax credits of up to $7,500 are available to purchasers of new plug-in electric vehicles. The tax credits phase out on vehicle models as the manufacturer of that model reaches a cap on total plug-in electric vehicle sales. Some early entrants into the market—including General Motors, Nissan, and Tesla—are approaching their caps. We recommend that the caps be extended to maintain momentum in the nascent EV market. While EV costs are rapidly declining as battery costs come down, tax credits are still important to help overcome the current higher purchase price. Extending the tax credits until the costs are more comparable to non-EVs will help spur demand that drives further cost reductions; in the near term, it will help prevent the EV market from stalling in this early phase.

Recommendation 3.6.4: Utilities should invest in electric vehicle infrastructure and programs.

Utilities can partner with cities and states to remove barriers to EV adoption by expanding charging infrastructure while ensuring grid reliability. Promotion of EVs can also include targeted customer education, consistent and fair treatment of EV load, and appropriate rate structures that balance grid needs while incentivizing adoption. We need to develop new regional policies, utility rate structures, and power market protocols to provide the proper valuation of these services. For more details, please refer to *Driving Out Pollution* and *Supplying Ingenuity*.

To further accelerate EV deployment over the medium term, utilities should explore ways to harness the storage potential of EV batteries. EVs can be thought of as batteries on wheels, providing ancillary grid services when parked. This includes helping relieve grid strain by scheduling charging to coordinate with grid needs, as well as potentially providing power back to the grid as needed.

Recommendation 3.6.5: Cities and states should create low-carbon transportation choices and deploy demand management strategies to cut vehicle miles traveled by 25 percent below reference levels by 2050.

Reducing our overall transportation carbon footprint requires creating attractive, competitive, low-carbon alternatives, as well as demand management strategies to encourage a shift away from driving—particularly solo-driving. State and local governments must begin or continue to prioritize resources to create high-quality and convenient transit and transportation choices.

Lower-carbon modes of travel such as walking, biking, and public transportation are more competitive when state and local governments plan walkable neighborhoods and cities that incorporate a mix of activities and daily needs nearby. These transportation choices are lower-stress, healthier, cleaner, less expensive, and often quicker. By contrast, single-use, low-density, suburban development patterns force people to drive for every trip.

Innovative business models may also accelerate the transition away from solo drivers. Transportation network companies such as Lyft and Uber, as well as micro-transit companies such as Via and Chariot deploy on-demand technology and flexible routing to serve multiple passengers, reducing the need for personal vehicles. Policymakers should promote the adoption and use of emerging business models that can demonstrably reduce carbon pollution. The advent of autonomous vehicles and the rise of longer-range EV technology may portend additional opportunities, through the convergence of shared, autonomous EVs. Certain studies find the potential for great social and environmental benefit from this convergence. However, their impacts need to be monitored and guidelines may be needed to align these with our climate goals. For more information, see NRDC reports *A Plan for Cleaner Transportation* and *First and Last Mile Connections: New Mobility*.

ar In addition to California, these nine states are: Connecticut, Maine, Maryland, Massachusetts, New Jersey, New York, Oregon, Rhode Island, Vermont.

In addition to creating new, lower-carbon transportation choices, empirical evidence from other cities around the world show that demand-management strategies are the most effective to discourage the use of inefficient single-occupancy vehicle travel and achieve uptake and use of low-carbon transportation choices. Congestion charging mechanisms in London and Stockholm cut the number of vehicles entering their cordoned charging areas by up to 20 percent. They also documented 7 to 11 percent increases in the use of public transportation, walking, and cycling.[188] These changes happen in the very near-term and hold over time, creating durable options for curbing carbon pollution. Policymakers and market players should adopt demand management strategies, including pricing mechanisms, which align with government infrastructure investments to achieve our climate goals in a timely manner.

The VMT reductions assumed in our model will depend on the implementation of the policies outlined above. These can and should both reinforce and maximize ongoing demographic and social trends. According to the EIA, reducing VMTs "assumes an environment in which travel choices made by drivers result in lower demand for personal vehicle travel, consistent with recent trends in VMT per licensed driver."[189] The EIA notes that VMT will continue to be influenced by economic and demographic factors, but also by telecommuting, travel options, e-commerce, and spatial development patterns. The Rocky Mountain Institute has also explored levers for reducing VMT.[190] These latter factors can be influenced by policy at all levels of government. While more-precise estimates of VMT reduction are beyond the scope of this report, recent studies clearly demonstrate there is tremendous potential to reduce VMT, in line with our per capita VMT reduction assumptions discussed earlier (approximately 25 percent below reference levels). A study by Fehr and Peers estimated the potential for reducing per capita VMT to 15 percent below 2007 levels by 2040, which corresponds to about 9,800 miles of annual per capita travel in 2040.[191] California's policies under its landmark SB375 Sustainable Communities legislation are projected to reduce per capita GHG emissions by 15 percent below 2005 levels by 2035.[192] Finally, an internal NRDC study of 30 metropolitan areas around the country found that a level of reduction similar to California's may be possible in those cities as well.

NRDC'S REGIONAL EFFORTS TO REDUCE VMT

Vehicle use (measured in VMT) in the United States has almost tripled over the past 45 years, and is expected to continue without interventions, meaning the transportation system is becoming less efficient each year. NRDC's Urban Solutions program is working to reverse this trend by focusing on ways to get people, goods, and services around more conveniently and cheaply, and with fewer climate impacts. We are advocating for systems that link decisions and funding to performance-based metrics that include efficiency and climate pollution. We are also working with leadership in cities to reduce driving by: providing clean transportation choices other than driving that are attractive and competitive; providing real-time information about the availability of these options via smart-phone apps and websites; and by aligning financial incentives and other regulatory structures with lower carbon transportation choices. Cities that have taken these steps have lowered their vehicle use by 10 to 20 percent immediately upon implementation.

3.7 KEY RECOMMENDATIONS TO ADDRESS THE AGING NUCLEAR FLEET

Recommendation 3.7.1: Regulators should explore approaches for replacing retiring nuclear units with zero-carbon resources and protecting the livelihoods of workers and host communities.

As our current nuclear power fleet ages, reaches the end of licenses or license extensions, and/or becomes increasingly uneconomical in today's wholesale electricity markets, growing numbers of reactors are likely to be retired (see Section 2.6). Regulators and other stakeholders will need to avoid abrupt closures, which could result in carbon emissions increases from replacement generation, and instead plan for shutdowns with sufficient lead time to ensure that power is reliably replaced with zero-carbon energy resources, power needs are reduced by energy efficiency, and that the livelihoods of workers and nearby communities are protected. The Joint Proposal to replace California's only remaining nuclear power plant, the two Diablo Canyon reactors in San Luis Obispo, provides a model of an appropriate transition plan. The Joint Proposal, negotiated by PG&E, Friends of the Earth, NRDC, and labor stakeholders, calls for closing Diablo Canyon by 2025 and replacing its power with lower-cost, zero-carbon options led by additional energy efficiency and renewable energy resources. The Joint Proposal also includes significant labor and community protections, such as provisions for worker retention and retraining and compensation for severance and community impacts.[193,194] Some parts of the Diablo Canyon proposal are specific to California's utility regulatory model and its advanced clean energy characteristics. However, other states can learn from and incorporate many aspects of this approach.

Recommendation 3.7.2: The EPA, NRC, and the states should address existing nuclear safety and fuel issues.

The federal government should take action to address the unresolved problems regarding safety, security, waste, and nuclear weapons proliferation risk associated with nuclear power. The EPA and NRC should adopt stronger regulations to address the environmental impacts of uranium mining as well as the safety and security risks associated with nuclear power plant operations. The federal regulations governing the decommissioning of nuclear power reactors are being fundamentally overhauled. This rulemaking must provide a robust roadmap, overseen by the NRC, to decommission reactors safely, and state and local government and host community must have input over radioactive cleanup and other impacts. The federal government should develop a science- and consent-based siting process for one or more deep geologic repositories to isolate spent nuclear fuel from the environment for millennia. Accordingly, Congress should amend the Atomic Energy Act of 1954 to remove its express exemptions of radioactive material from environmental laws, thus creating a role for the EPA and the states in nuclear waste disposal.

Recommendation 3.7.3: The federal government should continue to fund research into nuclear energy.

Long-term federal investment in energy technologies is a key aspect of federal energy policy, including DOE programs that support R&D for nuclear fuel cycle and reactor designs. Federal spending on advanced nuclear R&D must prioritize the analysis of severe accident scenarios and security vulnerabilities. While cost estimates for advanced nuclear designs should be rigorously examined early in their R&D cycle, the cost and reliability assessments can only be realistically understood based on the performance of an advanced nuclear prototype and a first-of-a-kind commercial reactor. Highly expensive projects should be pursued as a public-private partnership to affirm market viability for a given advanced nuclear design. Nuclear weapons proliferation impacts should also be addressed early in the R&D cycle; advanced nuclear designs that require a closed nuclear fuel cycle to reprocess spent nuclear fuel should be rejected outright given the associated proliferation risk.

For some basics of nuclear policy, please refer to our policy primer Nuclear Energy.

3.8 KEY RECOMMENDATIONS TO ENSURE CLEAN ENERGY BENEFITS ALL

Recommendation 3.8.1: States and cities should ensure that access to and benefits of clean energy are available to all citizens.

A successful clean energy revolution will provide opportunities for everyone, but states and cities need to take special care to protect and empower low-income communities to ensure that they have full access to affordable clean energy. Standards or programs aimed at promoting clean energy and reducing carbon pollution should be accompanied by complementary policies to address and mitigate any impacts on vulnerable groups. Any successful clean energy policy should ensure energy remains affordable for all Americans and its benefits accessible to both urban and rural low-income and overburdened communities. Possible measures include bill assistance for low-income customers and expanded low-income energy efficiency and weatherization programs.[195] Programs such as community solar will allow urban and rural low-income residents to share in clean energy investment. Low-cost clean energy financing for low-income and poor-credit customers can also help promote clean energy and energy efficiency investments, as can innovative financing approaches (e.g., on-bill financing). Furthermore, state and city governments can explore local and private partnerships to spur clean energy investment opportunities and grow their region's clean energy economy.

The transition to the clean energy economy must strive to create jobs and wealth opportunities for all Americans, across regions and social strata.

WHAT IS A JUST TRANSITION?

As we move from fossil fuels to a clean energy economy, a just transition will require that we shift workers from polluting industries to a sustainable economy through policies designed to ensure they are retained, retrained, and reemployed in local, sustainable, and emerging industries. In a just transition, coal miners, for instance, are not left behind when their mines close. Instead they are retrained and ushered into the clean energy industry. This concept grew out of the labor and environmental movements of the 1970s, when it became necessary to advocate for workers' rights in conjunction with environmental reforms so that communities and workers had a voice in planning for a more sustainable future. The specifics of a just transition depend on collaboration with impacted workers and their communities to ensure that their needs and local knowledge are fully integrated.[196]

Specific programs that target worker-retraining help affected workers and communities take advantage of clean energy employment and economic opportunities. Such programs can be designed to fit the needs of specific communities, industries (e.g., sustainable building construction, advanced manufacturing, wind and solar energy), and populations (e.g., veterans, unemployed/dislocated adults, youths, workers with limited English skills). The U.S. Department of Labor has found that unemployed workers who take advantage of these retraining programs tend to find employment faster, are more likely to retain work, and see an average salary bump of $2,500 per quarter, relative to those without retraining.[197] For example, a Colorado program to retrain unemployed and dislocated workers as wind technicians helped 77 percent of those who completed the training find employment in the wind industry, with 90 percent retaining their jobs in the following year.[198] In a Tennessee program focused on solar energy and carbon fiber industries, more than 80 percent of those who finished training found jobs in those industries, with 95 percent retaining employment over the next year.[199]

Recommendation 3.8.2: Federal and state authorities should provide opportunities for the fossil fuel workforce to benefit from the clean energy transition.

States and federal agencies should adopt policies aimed at ensuring that fossil fuel industry workers have an opportunity to transition to jobs building a cleaner and more efficient energy system. Effective programs that support this kind of shift will be vitally important. The process will be challenging and will require thoughtful and targeted assistance. The transition to the clean energy economy must strive to create jobs and wealth opportunities for all Americans, across regions and social strata.

Federal and state governments should consider policies that will generate awareness of in-demand trades or skills, provide effective vocational retraining, strongly incentivize companies to prioritize this newly trained worker pool, provide economic development support for local businesses, and help revitalize affected communities. States should also consider direct revenue assistance to communities to make up for lost local tax revenue from declining coal plants and mines.

4. An American Revolution: Clean Energy Today for a Safer Tomorrow

Our analysis shows that a more aggressive pursuit of energy efficiency, renewable energy, electrification of end uses, and an enhanced power grid can indeed put the United States on the path to cutting its GHG emissions by 80 percent by 2050. In most cases, these technologies are already proven and commercially deployed. We already know how to ramp them up and get them to scale and onto the electricity grid. They are likely to pose lower overall risk and fewer environmental impacts than other, less proven approaches. Critically, this clean energy future is cost-effective and, by 2050, will be cheaper than taking no action. Simply put, if we want a better 2050, we need a bigger and faster—and smarter—approach to building a clean energy system.

Models and scenarios do not determine the future. Rather, they highlight the benefits, risks, uncertainties, and limits of different energy pathways to illuminate the choices we face as a country. Unforeseeable events and trends as well as the predictable consequences of affirmative policy decisions will shape the actual pathway. Still, we have come to the next American frontier. The timing is urgent—and inaction is not an option. Smart and timely investments in energy efficiency, renewable energy, clean vehicles, and a stronger electricity grid will lead us to a safer future if we continue to scale them up. By the same token, if we fail to act, we will lock ourselves into a dirtier energy system and leave ourselves vulnerable to the most dangerous impacts of climate change.

All levels of government must summon the political will to work with communities and businesses to adopt the policy framework and market structures that can guide investments in our long-term clean energy future. A clean energy transition will enhance the safety and reliability of our energy system while putting Americans to work, lowering energy costs, curbing dangerous climate change, and protecting communities and natural resources.

Our proposal, to be fair, is nothing less than a revolution. But since when have Americans been afraid of revolutions?

ENDNOTES

1 International Panel on Climate Change (hereinafter IPCC), *Climate Change 2014*, *Synthesis Report*, Section SPM 3.4, 2014, http://ar5-syr.ipcc.ch/ipcc/ipcc/resources/pdf/IPCC_SynthesisReport.pdf.

2 IPCC, IPCC Fourth Assessment Report: Climate Change 2007, "Working Group III: Mitigation of Climate Change." See Chapter 13.3.3.3 Implications of regime stringency: linking goals, participation and timing. https://www.ipcc.ch/publications_and_data/ar4/wg3/en/ch13-ens13-3-3-3.html.

3 J.G.J. Olivier et al., *Trends in Global CO_2 Emissions: 2015 Report*, PBL Netherlands Environmental Assessment Agency, 2015, http://edgar.jrc.ec.europa.eu/news_docs/jrc-2015-trends-in-global-co2-emissions-2015-report-98184.pdf.

4 IPCC, *Climate Change 2014, Synthesis Report.* Globally, based on most recent data (for 2010), about 49 billion tons (±4.5 billion) of GHGs were emitted that year, with carbon dioxide representing 76 percent of the total, or about 38 billion tons (±3.8 billion).

5 D.S. Ward and N. M Mahowald, "Contributions of Developed and Developing Countries to Global Climate Forcing and Surface Temperature Change," *Environmental Research Letters* 9, no. 7 (2014), http://iopscience.iop.org/article/10.1088/1748-9326/9/7/074008/pdf.

6 United Nations, *Paris Agreement* , December 12, 2015, "Opening for Signature," C.N.63.2016.TREATIES-XXVII.7.d, February 16, 2016, https://treaties.un.org/doc/Publication/CN/2016/CN.63.2016-Eng.pdf; "Issuance of Certified True Copies," C.N.92.2016.TREATIES-XXVII.7.d, March 17, 2016 https://treaties.un.org/doc/Publication/CN/2016/CN.92.2016-Eng.pdf.

7 United Nations Framework Convention on Climate Change, "Paris Amendment: Status of Ratification," http://unfccc.int/paris_agreement/items/9444.php (accessed October 28, 2016).

8 The White House, "Fact Sheet: U.S. Reports Its 2025 Emissions Target to the UNFCCC," March 2015.

9 Ibid.

10 The White House, "Statement by President Trump on the Paris Climate Accord," June 1, 2017, https://www.whitehouse.gov/the-press-office/2017/06/01/statement-president-trump-paris-climate-accord.

11 U.S. Environmental Protection Agency (hereinafter EPA), *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2014*, April 15, 2016, https://www.epa.gov/sites/production/files/2016-04/documents/us-ghg-inventory-2016-main-text.pdf.

12 U.S. Energy Information Administration (hereinafter EIA), *Annual Energy Outlook 2005*: "Market Trends—Carbon Dioxide Emissions," 2005, http://www.eia.gov/forecasts/archive/aeo05/emission.html.

13 EIA, "U.S. Energy-Related Carbon Dioxide Emissions in 2015 Are 12% Below Their 2005 Levels," May 6, 2016, https://www.eia.gov/todayinenergy/detail.php?id=26152.

14 Ibid. U.S. Bureau of Economic Analysis, "National Data," Section 1, "Domestic Product and Income," Table 1.1.6, www.bea.gov/iTable/index_nipa.cfm (accessed May 1, 2017). Figures adjusted for inflation.

15 EIA, "U.S. Energy-Related Carbon Dioxide Emissions, 2015," March 16, 2017, http://www.eia.gov/environment/emissions/carbon/.

16 EIA, *Annual Energy Outlook 2017*, January 5, 2017, https://www.eia.gov/forecasts/aeo/tables_ref.cfm. The Reference Case accounts for the complete implementation of the Clean Power Plan by 2030.

17 The EIA tends to over-forecast energy use and thus emissions, because its methodology considers only existing, established energy regulations and standards, even for laws that require regular administrative review and revision of standards at fixed dates.

18 J.H. Williams et al., *Pathways to Deep Decarbonization in the United States*, revision with technical supplement, Energy and Environmental Economics, Inc. (hereinafter E3), November 16, 2015. The DDPP is led by the Sustainable Development Solutions Network (SDSN) and the Institute for Sustainable Development and International Relations (IDDRI). The DDPP includes 16 research teams from countries representing 75 percent of global GHG emissions. 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 relationships between the United Nations, DDPP and the United States were largely unofficial, although each drew from the other. For more detail on the U.S. DDPP analysis, see the Deep Decarbonization Pathways Project's "Countries" page, http://deepdecarbonization.org/countries/#united-states.

19 J.H. Williams, et al., *Pathways to Deep Decarbonization in the United States*, E3, November 2014, http://unsdsn.org/wp-content/uploads/2014/09/US-Deep-Decarbonization-Report.pdf.

20 Deep Decarbonization Pathways Project (hereinafter DDPP), home page, http://deepdecarbonization.org/. The California report is available at E3, "Summary of the California State Agencies' PATHWAYS Project: Long-Term GHG Reduction Scenarios, 2015, 2016, https://ethree.com/public_projects/energy_principals_study.php. The California PATHWAYS model is being used by the California Air Resources Board as part of their proposed strategy for achieving California's 2030 GHG target as part of the Scoping Plan Update, https://www.arb.ca.gov/cc/scopingplan/scopingplan.htm.

21 EIA, *Electric Power Monthly with Data for December 2016*, February 2017, https://www.eia.gov/electricity/monthly/current_year/february2017.pdf.

22 EIA, "Power-to-Gas Brings a New Focus to the Issue of Energy Storage from Renewable Sources," July 24, 2015.

23 Ottmar Edenhofer, et al., *Special Report on Renewable Energy Sources and Climate Change Mitigation*, prepared by Working Group III of the IPCC (Cambridge, U.K.: Cambridge University Press, 2011), https://www.ipcc.ch/pdf/special-reports/srren/SRREN_FD_SPM_final.pdf. Martin Hoffert, et al., "Advanced Technology Paths to Global Climate Stability: Energy for a Greenhouse Planet," *Science* 298.5595 (2002): 981-987. David McCollum and Christopher Yang, "Achieving Deep Reductions in US Transport Greenhouse Gas Emissions: Scenario Analysis and Policy Implications," *Energy Policy* 37, no. 12 (2009): 5580-5596. David McCollum, et al., "Deep Greenhouse Gas Reduction Scenarios for California—Strategic Implications from the CA-TIMES Energy-Economic Systems Model," *Energy Strategy Reviews* 1, no. 1 (2012): 19-32. Jesse Jenkins and Samuel Thernstrom, "Deep Decarbonization of the Electric Power Sector: Insights from Recent Literature," Energy Innovation Reform Project, March 2017, http://innovationreform.org/wp-content/uploads/2017/03/EIRP-Deep-Decarb-Lit-Review-Jenkins-Thernstrom-March-2017.pdf.

24 Christopher Clack, et al., "Evaluation of a Proposal for Reliable Low-cost Grid Power with 100% Wind, Water, and Solar," *Proceedings of the National Academy of Sciences* 114, no. 26 (June 27, 2017):6722-6727, http://www.pnas.org/content/114/26/6722.full. Mark Z. Jacobson, et al. "100% clean and renewable wind, water, and sunlight (WWS) all-sector energy roadmaps for the 50 United States," Energy & Environmental Science 8, no. 7 (2015): 2093-2117, https://web.stanford.edu/group/efmh/jacobson/Articles/I/USStatesWWS.pdf.

25 J.H. Williams, et al., *Pathways to Deep Decarbonization*, 2015 revision.

26 The White House, *United States Mid-Century Strategy*.

27 National Research Council, *America's Energy Future: Technology and Transformation* (Washington, D.C.: The National Academies Press, 2010).

28 National Research Council, National Academy of Sciences and National Academy of Engineering, *Real Prospects for Energy Efficiency in the United States* (Washington, D.C.: The National Academies Press, 2010).

29 “Projected Decline in U.S. Buildings’ Primary Energy Consumption with Integrative Design, 2010–2050,” graph in Amory Lovins and the Rocky Mountain Institute, *Reinventing Fire* (Chelsea, Vermont: Chelsea Green Publishing, October 2011), https://www.rmi.org/wp-content/uploads/2017/06/RF_decline_US_buildings_fuel_use.jpg.

30 J.A. Laitner et al., *The Long-Term Energy Efficiency Potential: What the Evidence Suggests*, American Council for an Energy-Efficient Economy (hereinafter ACEEE), January 11, 2012, http://aceee.org/research-report/e121.

31 NRDC calculations based on Anthony Fryer, “Why Recent Progress in Television Efficiency Should Make You Feel Better About Binge Watching Your Favorite Shows,” Appliance Standards Awareness Project, 2017, https://appliance-standards.org/blog/why-recent-progress-television-efficiency-should-make-you-feel-better-about-binge-watching.

32 NRDC calculations based on Joanna Mauer et al., *Better Appliances: An Analysis of Performance, Features, and Price as Efficiency Has Improved,* ACEEE, May 2013, https://appliance-standards.org/sites/default/files/Better_Appliances_Report.pdf.

33 Pierre Delforge, “Simulation of Heat Pump Water Heater Real-World Performance,” NRDC, November 2016. https://www.nrdc.org/resources/nrdc-ecotope-heat-pump-water-heater-performance-data.

34 Steven Nadel, “Comparative Energy Use of Residential Furnaces and Heat Pumps,” ACEEE, May 2016, http://aceee.org/comparative-energy-use-residential-furnaces-and.

35 Center for Climate and Energy Solutions, “Federal Vehicle Standards,” http://www.c2es.org/federal/executive/vehicle-standards (accessed October 27, 2016).

36 National Research Council, *Transitions to Alternative Vehicles and Fuels* (Washington, D.C.: The National Academies Press, 2013).

37 EIA, *Annual Energy Outlook 2014 with Projections to 2040*, April 2014, http://www.eia.gov/outlooks/aeo/pdf/0383(2014).pdf. See page IF-26 for particular details.

38 U.S. Department of Energy (hereinafter DOE), “All-Electric Vehicles,” https://www.fueleconomy.gov/feg/evtech.shtml (accessed June 28, 2017).

39 National Research Council, *Transitions to Alternative Transportation Technologies* (Washington, D.C.: The National Academies Press, 2010), https://www.nap.edu/catalog/12222/transitions-to-alternative-transportation-technologies-a-focus-on-hydrogen.

40 Dan Meszler, Nic Lutsey, and Oscar Delgado, *Cost Effectiveness of Advanced Efficiency Technologies for Long-Haul Tractor-Trailers in the 2020–2030 Timeframe,*” International Council on Clean Transportation, April 21, 2015, http://theicct.org/us-tractor-trailer-tech-cost-effectiveness. Jerry Hirsch, “Tesla’s Road to Electric Trucking May Be Easier than Many Assume,” *Trucks*, May 10, 2017, https://www.trucks.com/2017/05/10/tesla-electric-truck-easy/. Liane Yvkoff, “In the Race to Full Electrification, Buses May Take First Place,” *Forbes,* September 12, 2016, http://www.forbes.com/sites/lianeyvkoff/2016/09/12/in-the-race-to-full-electrification-buses-may-take-first-place/#441bd1d85693.

41 DOE, “Adoption of New Fuel-Efficient Technologies from SuperTruck: Report to Congress,” June 2016, https://energy.gov/eere/vehicles/downloads/report-adoption-new-fuel-efficient-technologies-supertruck.

42 Shell Oil, *A Better Life with a Healthy Planet: Pathways to Net-Zero Emissions,* May 2016, http://www.shell.com/energy-and-innovation/the-energy-future/scenarios/a-better-life-with-a-healthy-planet.html.

43 Hannah Granade et al., *Unlocking Energy Efficiency in the U.S. Economy,*” p. 79 et. seq., McKinsey Global Energy and Materials, July 2009, http://www.mckinsey.com/client_service/electric_power_and_natural_gas/latest_thinking/~/media/204463a4d27a419ba8d05a6c280a97dc.ashx.

44 National Research Council, National Academy of Sciences and National Academy of Engineering, *Real Prospects for Energy Efficiency in the United States*.

45 Rocky Mountain Institute, “U.S. Industry Energy Saving Potential, 2010–2050,” https://www.rmi.org/wp-content/uploads/2017/06/RF_US_industry_energy_saving_potential.jpg. RMI analysis estimates potential industrial sector energy use in 2050 to be 21.2 quadrillion BTUs. NRDC’s Core Scenario puts the figure at just under 20 quadrillion BTUs.

46 NRDC, “Comments on EPA’s Proposed Carbon Pollution Emission Guidelines for Existing Stationary Sources: Electric Utility Generating Units,” December 1, 2014, https://www.nrdc.org/sites/default/files/air_14120101b.pdf. See Section 7 for multiple references and details.

47 See “Better Buildings Progress Reports” for Spring 2015, Fall 2015, and Winter 2016 for the latest savings figures. Available at DOE, “Learn About Better Buildings,” http://energy.gov/eere/better-buildings (accessed July 19, 2017).

48 Hannah Granade et al., *Unlocking Energy Efficiency in the U.S. Economy.*

49 National Research Council, National Academy of Sciences and National Academy of Engineering, *Real Prospects for Energy Efficiency in the United States*.

50 David Goldstein, “A Jobs and Infrastructure Program to Arrest Climate Change,” NRDC, February 2017, https://www.nrdc.org/experts/david-b-goldstein/jobs-and-infrastructure-program-arrest-climate-change. Hannah Granade et al., *Unlocking Energy Efficiency in the U.S. Economy*.

51 Hannah Granade et al., *Unlocking Energy Efficiency in the U.S. Economy.*

52 David Goldstein, “A Jobs and Infrastructure Program to Arrest Climate Change.”

53 Federal Energy Regulatory Commission, *The Potential Benefits of Distributed Generation and Rate-Related Issues that May Impede Their Expansion*, February 2007, https://www.ferc.gov/legal/fed-sta/exp-study.pdf.

54 EIA, *Electric Power Monthly with Data for December 2016*. Non-hydro renewable energy generation in 2016 was approximately 300 terawatt-hours (TWh). The total in 2050 in NRDC’s scenario is approximately 4,000 TWh. However, only 3,250 TWh are consumed as electricity; the rest is converted into synthetic fuels.

55 DOE, *2015 Renewable Energy Data Book*, p. 25 graph: “U.S. Annual Installed Renewable Electricity Capacity Growth,” November 2016, https://www.nrel.gov/docs/fy17osti/66591.pdf.

56 Austin Perea et al., *Solar Market Insight Report 2016 Year in Review*, Solar Energy Industries Association, June 2017.

57 EIA, “Annual Capacity by State,” last revised November 2016, https://www.eia.gov/electricity/data.php#gencapacity.

58 EIA, *Wind and Solar Data and Projections from the U.S. Energy Information Administration: Past Performance and Ongoing Enhancements,* March 2016, https://www.eia.gov/outlooks/aeo/supplement/renewable/pdf/projections.pdf.

59 Bloomberg New Energy Finance, *2017 Sustainable Energy in America Factbook*, January 2017, https://data.bloomberglp.com/bnef/sites/14/2017/02/BCSE-BNEF-2017-Sustainable-Energy-in-America-Factbook.pdf.

60 Ibid. Bloomberg New Energy Finance, *New Energy Outlook 2017*, June 2017, https://about.bnef.com/new-energy-outlook/. DOE, 2016 Wind Technologies Market Report, August 2017, https://energy.gov/eere/wind/downloads/2016-wind-technologies-market-report.

61 Ryan H. Wiser and Mark Bolinger, *2015 Wind Technologies Market Report*, Lawrence Berkeley National Laboratory, Electricity Markets Policy Group, August 2016.

62 EIA, *Electric Power Monthly with Data for March 2017*, May 2017. https://www.eia.gov/electricity/monthly/current_year/may2017.pdf.

63 Bloomberg New Energy Finance, *New Energy Outlook 2017*.

64 Ibid.

65 Ibid.

66 Projections do not include the Clean Power Plan but do reflect the Investment Tax Credit and Production Tax Credit extensions for solar and wind, respectively. See Bloomberg New Energy Finance, *New Energy Outlook 2017* and *New Energy Outlook 2016*, June 2016. https://about.bnef.com/new-energy-outlook/

67 Pieter Gagnon and Ben Sigrin, “Distributed PV Adoption—Sensitivity to Market Factors,” National Renewable Energy Laboratory (hereinafter NREL), February 2016, http://www.nrel.gov/docs/fy16osti/65984.pdf.

68 Deepwater Wind, “America’s First Offshore Wind Farm Powers Up,” December 12, 2016, http://dwwind.com/press/americas-first-offshore-wind-farm-powers/.

69 Bureau of Ocean Energy Management, “Lease and Grant Information,” https://www.boem.gov/Lease-and-Grant-Information/ (accessed July 4, 2017). Jacques Beaudry-Losique, et al., *A National Offshore Wind Strategy: Creating an Offshore Wind Energy Industry in the United States,* DOE, February 2011, https://energy.gov/sites/prod/files/2013/12/f5/national_offshore_wind_strategy.pdf.

70 Bloomberg New Energy Finance, *New Energy Outlook 2017*.

71 Average vehicle life spans are assumed to be 15–20 years. See J.H. Williams et al., *Pathways to Deep Decarbonization*, November 2014.

72 Ellie Stutts, “Annual Plug-in Electric Vehicle Sales in North America Are Expected to Exceed 1.1 Million by 2024,” Navigant Research, 2015, https://www.navigantresearch.com/newsroom/annual-plug-in-electric-vehicle-sales-in-north-america-are-expected-to-exceed-1-1-million-by-2024. Steve Hanley, “Electric Car Revolution Will Accelerate Soon, Predicts Morgan Stanley Report,” CleanTechnica, November 22, 2016, https://cleantechnica.com/2016/11/22/electric-car-revolution-will-accelerate-soon-predicts-morgan-stanley-report/.

73 Bloomberg New Energy Finance, *2017 Sustainable Energy in America Factbook*. Bloomberg New Energy Finance, “EV Data Hub”, accessed August 14, 2017 (data updated quarterly), subscription service access only.

74 Ewing, Jack, “Volvo, Betting on Electric, Moves to Phase Out Conventional Engines”, *New York Times*, July 5, 2017, https://www.nytimes.com/2017/07/05/business/energy-environment/volvo-hybrid-electric-car.html?_r=0

75 Bloomberg New Energy Finance, *2017 Sustainable Energy in America Factbook*.

76 Bertel Schmitt, “Ultrafast-Charging Solid-State EV Batteries Around The Corner, Toyota Confirms”, *Forbes*, July 25, 2017, https://www.forbes.com/sites/bertelschmitt/2017/07/25/ultrafast-charging-solid-state-ev-batteries-around-the-corner-toyota-confirms/#2ed95bd244bb .

77 IRU, “Commercial Vehicle of the Future,” February 2017, https://www.iru.org/resources/newsroom/iru-commercial-vehicle-future-report-maps-out-action-plan-reduce-co2-emissions.

78 F. Teng et al., *Pathways to Deep Decarbonization in China*, DDPP, SDSN-IDDRI, 2015, http://deepdecarbonization.org/wp-content/uploads/2015/09/DDPP_CHN.pdf. J. Tovilla et al., *Pathways to deep decarbonization in Mexico*, DDPP, SDSN-IDDRI, 2015, http://deepdecarbonization.org/wp-content/uploads/2015/09/DDPP_MEX.pdf.

79 EIA, “Residential Energy Consumption Survey,” Table HC1.1, “Fuels used and end uses in U.S. homes by housing unit type, 2015,” February 2017, https://www.eia.gov/consumption/residential/data/2015/hc/php/hc1.1.php.

80 Union of Concerned Scientists, “The Promise of Biomass: Clean Power and Fuel—If Handled Right,” September 2012, http://www.ucsusa.org/sites/default/files/legacy/assets/documents/clean_vehicles/Biomass-Resource-Assessment.pdf.

81 Union of Concerned Scientists, “The Hidden Costs of Fossil Fuels,” last revised August 2016, http://www.ucsusa.org/clean-energy/coal-and-other-fossil-fuels/hidden-cost-of-fossils#.WO-_-WnysdU.

82 Examples Include: Yousif Kharaka & Nancy Dorsey, *Environmental Issues of Petroleum Exploration and Production: Introduction*, *Environmental Geosciences*, June 2005, https://toxics.usgs.gov/pubs/KharakaIntro.PDF; EPA, *An Assessment of the Environmental Implications of Oil and Gas Production: A Regional Case Study*, *EPA*, September 2008, https://archive.epa.gov/sectors/web/pdf/oil-gas-report.pdf; Richard Liroff, *Extracting the Facts: An Investor Guide to Disclosing Risks From Hydraulic Fracturing Operations*, *Investor Environmental Health Network*, 2011, http://iehn.org/documents/frackguidance.pdf; Secretary of Energy Advisory Board Natural Gas Subcommittee, *Shale Gas Production Subcommittee 90-Day Report*, *DOE*, August 18, 2011, https://energy.gov/sites/prod/files/Final_90_day_Report.pdf; George King, *Hydraulic Fracturing 101: What Every Representative, Environmentalist, Regulator, Reporter, Investor, University Researcher, Neighbor and Engineer Should Know About Estimating Frac Risk and Improving Frac Performance in Unconventional Gas and Oil Wells*, p. 80, *Society of Petroleum Engineers*, http://www.kgs.ku.edu/PRS/Fracturing/Frac_Paper_SPE_152596.pdf; Robert Jackson, et al., *The Environmental Costs and Benefits of Fracking*, Annual Review of Environmental Resources, 2014, http://www.annualreviews.org/doi/pdf/10.1146/annurev-environ-031113-144051.

83 Examples Include: Ramón Alvarez et al., *Greater Focus Needed on Methane Leakage from Natural Gas Infrastructure*, *National Academy of Science*, December 21, 2011, http://www.pnas.org/content/109/17/6435.full.pdf; Scot Miller et al., *Anthropogenic Emissions of Methane in the United States*, *National Academy of Science*, October 18, 2013, http://www.pnas.org/content/110/50/20018.abstract; A.R. Brandt et al., *Methane Leaks from North American Natural Gas Systems*, Science, February 14, 2014, https://nature.berkeley.edu/er100/readings/Brandt_2014.pdf.

84 Examples Include: Hedeff Essaid et al., *Crude Oil at the Bemidji Site: 25 Years of Monitoring, Modeling, and Understanding*, *National Ground Water Association*, 2011, https://pdfs.semanticscholar.org/56f1/bbb0c6de81ea58634b1f126bd0412d060e20.pdf. Stephen Osborn et al., *Methane Contamination of Drinking Water Accompanying Gas-Well Drilling and Hydraulic Fracturing*, *National Academy of Sciences*, April 14, 2011, http://www.pnas.org/content/108/20/8172.full.pdf; EPA, *Hydraulic Fracturing for Oil and Gas: Impacts from the Hydraulic Fracturing Water Cycle on Drinking Water Resources in the United States*, *EPA*, December 2016, https://www.epa.gov/sites/production/files/2016-12/documents/hfdwa_executive_summary.pdf.

85 Examples Include: Kate Konschnik et al., *Legal Fractures in Chemical Disclosure Laws: Why the Voluntary Chemical Disclosure Registry FracFocus Fails as a Regulatory Compliance Tool*, *Harvard Law School*, April 23, 2013, https://blogs.harvard.edu/environmentallawprogram/files/2013/04/4-23-2013-LEGAL-FRACTURES.pdf; Jane Long et al., *An Independent Scientific Assessment of Well Stimulation in California: Potential Environmental Impacts of Hydraulic Fracturing and Acid Stimulations*, *California Council on Science & Technology*, July 2015, https://ccst.us/publications/2015/2015SB4-v2.pdf; EPA, *Analysis of Hydraulic Fracturing Fluid Data from the FracFocus Chemical Disclosure Registry 1.0*, *EPA*, March 2015, https://www.epa.gov/sites/production/files/2015-03/documents/fracfocus_analysis_report_and_appendices_final_032015_508_0.pdf.

86 Examples include: John Adgate et al., *Potential Public Health Impacts of Natural Gas Development and Production in the Marcellus Shale in Western Maryland*, *Maryland Institute for Applied Environmental Health School of Public Health*, July 2014, http://www.marcellushealth.org/uploads/2/4/0/8/24086586/final_report_08.15.2014.pdf; Tanja Srebotnjak & Miriam Rotkin-Ellman, *Fracking Fumes: Air Pollution from Hydraulic Fracturing Threatens Public Health and Communities*, *NRDC*, December 2014, https://www.nrdc.org/sites/default/files/fracking-air-pollution-IB.pdf.

87 Examples include: Bethany Alley et al., *Chemical and Physical Characterization of Produced Waters from Conventional and Unconventional Fossil Fuel Resources*, *Chemosphere*, September 2011, http://www.sciencedirect.com/science/article/pii/S0045653511005960; EPA, *Review of State and Industry Spill Data: Characterization of Hydraulic Fracturing-Related Spills*, *EPA*, May 2015, https://www.epa.gov/sites/production/files/2015-05/documents/hf_spills_report_final_5-12-15_508_km_sb.pdf; EPA, "Tenorm: Oil and Gas Production Wastes," *EPA*, https://www.epa.gov/radiation/tenorm-oil-and-gas-production-wastes (last updated December 19, 2016).

88 Examples include: Drohan PJ et al., *Early Trends in Landcover Change and Forest Fragmentation Due to Shale-Gas Development in Pennsylvania: A Potential Outcome for the Northcentral Appalachians*, *Environmental Management*, 2012, https://www.ncbi.nlm.nih.gov/pubmed/22447181; Brittingham MC et al., *Ecological Risks of Shale Oil and Gas Development to Wildlife, Aquatic Resources and their Habitats*, *Environmental Science & Technology,* 2014, https://www.ncbi.nlm.nih.gov/pubmed/25188826.

89 National Research Council. *Induced Seismicity Potential in Energy Technologies*, *National Academies Press*, 2014, https://www.nap.edu/read/13355/chapter/1.

90 Russell Gold & Tom McGinty, "Energy Boom Puts Wells in America's Backyards: Hydraulic Fracturing Largely Driving Transformation of the Nation's Landscape," *The Wall Street Journal*, October 25, 2013, https://www.wsj.com/articles/energy-boom-puts-wells-in-america8217s-backyards-1382756256.

91 U.S. Government Accountability Office (GAO), *Unconventional Oil and Gas Development: Key Environmental and Public Health Requirements*, *GAO*, September 2012, http://www.gao.gov/assets/650/647782.pdf.

92 NRDC, "Reduce Fossil Fuels," https://www.nrdc.org/issues/reduce-fossil-fuels (last visited August 1, 2017).

93 Robert Mullin, "Study Touts Benefits of CAISO Expansion," *RTO Insider*, July 13, 2016, https://www.rtoinsider.com/study-benefits-caiso-expansion-28718/

94 Michael Goggin, "The Records Keep Falling: More New Highs in Wind Energy Output," Into the Wind, American Wind Energy Association, February 23, 2016, http://www.aweablog.org/the-records-keep-falling-more-new-highs-in-wind-energy-output/.

95 Tom Kleckner, "ERCOT Approaches 50% Wind Penetration Mark," RTO Insider, April 4, 2016, https://www.rtoinsider.com/ercot-wind-penetration-24384/. Southwest Power Pool, "SPP Sets North American Record for Wind Power," February 13, 2017, https://www.spp.org/about-us/newsroom/spp-sets-north-american-record-for-wind-power/. ERCOT stands for Electric Reliability Council of Texas, and SPP stands for Southwest Power Pool.

96 Ian Clover, "California ISO Hits New Solar Record," *PV Magazine,* July 15, 2016, http://www.pv-magazine.com/news/details/beitrag/california-iso-hits-new-solar-record_100025426/#axzz4MQ8JqaLK.

97 Trieu Mai et al., *Renewable Electricity Futures Study*, NREL, 2012.

98 President's Council of Economic Advisers, "Economic Benefits of Increasing Electric Grid Resilience to Weather Outages," August 2013*,* http://energy.gov/sites/prod/files/2013/08/f2/Grid%20Resiliency%20Report_FINAL.pdf.

99 Ibid.

100 Ibid.

101 Lazard, "Lazard's Levelized Cost of Energy Analysis – Version 10.0," December 2016, https://www.lazard.com/media/438038/levelized-cost-of-energy-v100.pdf. An example of CCS can be seen at the Petra Nova - W.A. Parish Project. DOE, "Petra Nova - W.A. Parish Project," https://energy.gov/fe/petra-nova-wa-parish-project (accessed August 17, 2017).

102 NRDC, *Forests Not Fuel: Burning Trees for Energy Increases Carbon Pollution and Destroys Out Forests*, NRDC, August 2011, https://www.nrdc.org/sites/default/files/forests-not-fuel.pdf. NRDC, *Money To Burn?: The U.K. Needs to Dump Biomass and Replace Its Coal Plants With Truly Clean Energy*, NRDC, October 2016, https://www.nrdc.org/sites/default/files/uk-biomass-replace-coal-clean-energy-ib.pdf.

103 National Institutes of Health, "Looking Inside: Get the Facts About Radiation," October 2012, https://newsinhealth.nih.gov/issue/Oct2012/Feature1. Cathy Vakil and Linda Harvey, Human Health Implications of the Nuclear Energy Industry, Canadian Association of Physicians for the Environment, May 2009, https://cape.ca/human-health-implications-of-the-nuclear-energy-industry-2009/. National Research Council, *Technical Bases for Yucca Mountain Standards* (Washington, D.C.: National Academy Press, 1955), https://www.nap.edu/read/4943/chapter/1. Geoffrey H. Fettus and Matthew G. McKinzie, *Nuclear Fuel's Dirty Beginnings: Environmental Damage and Public Health Risks From Uranium Mining in the American West*, NRDC, March 2012.

104 Peter Bradford, "How to Close the US Nuclear Industry: Do Nothing," *Bulletin of the Atomic Scientists*, March 1, 2013, http://thebulletin.org/2013/march/how-close-us-nuclear-industry-do-nothing. Joe Romm, "Nuclear Industry Prices Itself Out of Power Market, Demands Taxpayers Keep It Afloat," *ThinkProgress*, May 25, 2017, https://thinkprogress.org/nuclear-demands-subsidies-b8bfa9bdd8fa.

105 U.S. Nuclear Regulatory Commission, "List of Power Reactor Units," last updated June 12, 2017, https://www.nrc.gov/reactors/operating/list-power-reactor-units.html. We note that the Fort Calhoun nuclear power plant listed here is actually shut down. EIA, "Fort Calhoun becomes fifth U.S. nuclear plant to retire in past five years", *Today in Energy*, October 23, 2016, https://www.eia.gov/todayinenergy/detail.php?id=28572.

106 Geoffrey Haratyk, "Early Nuclear Retirements in Deregulated U.S. Markets: Causes, Implications and Policy Options," MIT Center for Energy and Environment Policy Research, Working Paper Series, March 2017, https://assets.documentcloud.org/documents/3723775/MIT-Early-Nuclear-Retirement-3-2017.pdf.

107 Darrell Proctor, "Cost Overruns at Vogtle Expected to Soar," *Power,* June 19, 2017, http://www.powermag.com/cost-overruns-at-vogtle-expected-to-soar/.

108 Extension of nuclear power reactor operating licenses to 80 years is termed "subsequent license extension" by the NRC. In December 1991, the commission issued regulations that allowed it to renew nuclear power reactor licenses in 20-year increments beyond an initial 40-year license as defined in the 1954 Atomic Energy Act. The NRC began subsequent license review guidance development in 2014 and is scheduled to complete the final guidance documents in 2017. Letters of intent have been submitted to the NRC for future subsequent license renewal applications for four reactors at two nuclear plants (Peach Bottom in Pennsylvania and Surrey in Virginia). The license renewal process will evaluate whether reactors can continue to meet the NRC's safety and environmental regulations. U.S. Nuclear Regulatory Commission, "Reactor License Renewal," accessed August 24, 2017, https://www.nrc.gov/reactors/operating/licensing/renewal.html.

109 According to the Nuclear Energy Institute, the decision to apply for a subsequent license renewal is an economic one, "driven by the costs of continued operations, major component replacements, operations and maintenance costs, and local electricity markets." While the cost of preparing and submitting the regulatory documents for license renewal will likely be in the same range as for first license renewal—$15 million to $25 million—much greater costs are estimated for evaluating and preparing a nuclear reactor for license renewal. For example, subsequent license renewal for the two reactors at Surrey will involve "a year-long process of testing and inspections that Dominion expects will cost $1.5–2.5bn." Under-construction nuclear power plants in the Southeast was assumed to come online by the end of 2019. Nuclear retirements were assumed to all occur between 2030 and 2050. This assumption diverges from current expectations, with a portion of the nuclear fleet already announced to retire early or considered at risk for early retirement by the early 2020s. Nuclear Energy Institute, "Second License Renewal Roadmap," May 2015, https://www.nei.org/CorporateSite/media/filefolder/Federal-State-Local-Policy/Regulatory-Information/Second-License-Renewal-Roadmap-small.pdf?ext=.pdf.

110 Environmental impacts reflect the annual social cost of carbon values associated with each year between 2015 and 2050, starting at $33.63 per metric ton in 2010 and rising to $74.86 per metric ton in 2050 ($2011). We note that the energy system costs discussed are cumulative costs that are not discounted. The environmental costs, however, include an implicit discounting associated with the social cost of carbon. For more information see the Interagency Working Group, "Technical Update on the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866," May 2013, revised July 2015, https://obamawhitehouse.archives.gov/sites/default/files/omb/inforeg/scc-tsd-final-july-2015.pdf.

111 According to a National Research Council study, the forecast non-climate costs of coal and gas generation (not including upstream impacts) are 1.7 cents and 0.11 cents per kilowatt-hour by 2030. Using this figure as the average health externality for 2015–2050, there would be a public health benefit of $557 billion, with a benefit of $26.9 billion in 2050 alone. National Research Council, *Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use* (Washington, D.C.: The National Academies Press, 2010), http://www.ourenergypolicy.org/wp-content/uploads/2012/06/hidden.pdf. A recent journal article in Nature Energy estimated $88 billion in historical health and environmental benefits of wind and solar energy. Dev Millstein, et al., "The climate and air-quality benefits of wind andsolar power in the United States", Nature Energy 6, 17134 (August 14, 2017), https://www.nature.com/articles/nenergy2017134.

112 Gail Parson et al., "Clean Jobs America: A Comprehensive Analysis of Clean Energy Jobs in America," Environmental Entrepreneurs, March 2016. https://www.e2.org/wp-content/uploads/2016/03/CleanJobsAmerica_FINAL.pdf.

113 Luke Tonachel, "Supplying Ingenuity II: U.S. Suppliers of Key Clean, Fuel-Efficient Vehicle Technologies," NRDC, May 23, 2017, https://www.nrdc.org/resources/supplying-ingenuity-ii-us-suppliers-key-clean-fuel-efficient-vehicle-technologies.

114 Bureau of Labor Statistics, "Quarterly Census of Employment and Wages," 2015 Second Quarter, http://data.bls.gov/cew/apps/table_maker/v4/table_maker.htm#type=8&year=2015&qtr=2&own=5&area=US000&supp=0.

115 Edison Electric Institute, *Delivering America's Energy Future: Electric Power Industry Outlook*, Wall Street briefing, February 8, 2017, http://www.eei.org/resourcesandmedia/industrydataanalysis/industryfinancialanalysis/Documents/Wall_Street_Briefing.pdf

116 James Hamilton, "Powering the Nation: Smart Grid Careers," Bureau of Labor Statistics Career Outlook, Fall 2013, https://www.bls.gov/careeroutlook/2013/fall/art03.pdf.

117 Ibid.

118 Tyler Comings, Kenji Takahashi, and Geoff Keith, "Employment Effects of Investing in Select Electricity Resources in Washington State," Synapse Economics for Sierra Club, October 21, 2013, http://content.sierraclub.org/coal/sites/content.sierraclub.org.coal/files/docs/Employment%20Effects%20of%20Elec%20Resources%20in%20WA%20-%20FINAL_0.pdf.

119 Environmental Entrepreneurs, "Opportunity Lost: How Rolling Back the Clean Power Plan Hurts America's Economy," June 2017, https://www.e2.org/wp-content/uploads/2017/06/FINAL-CPP-jobs-report-6.21.17.pdf

120 Maggie Molina, Patrick Kiker, and Seth Nowak, "The Greatest Energy Story You Haven't Heard: How Investing in Energy Efficiency Changed the US Power Sector and Gave Us a Tool to Tackle Climate Change," ACEEE, August 2016, updated October 2016, http://aceee.org/sites/default/files/publications/researchreports/u1604.pdf.

121 ACEEE, "How Does Energy Efficiency Create Jobs?" 2012, http://aceee.org/files/pdf/fact-sheet/ee-job-creation.pdf.

122 Jason Brown et al., "Ex Post Analysis of Economic Impacts from Wind Power Development in US Counties," Energy Economics 34, no. 6 (2012): 1743-1754, http://www.sciencedirect.com/science/article/pii/S0140988312001466.

123 U.S. Census Bureau, "Growth in Urban Population Outpaces Rest of Nation," March 26, 2012, https://www.census.gov/newsroom/releases/archives/2010_census/cb12-50.html.

124 CleanEdge, "Getting to 100: A Status Report on Rising Commitments Among Corporations and Governments to Reach 100% Renewables," November 2015, https://cleanedge.com/reports/Getting-to-100.

125 Cristina Gimenez, Vicenta Sierra, and Juan Rodon, "Sustainable Operations: Their Impact on the Triple Bottom Line," *International Journal of Production Economics* 140, no. 1 (2012): 149-159, http://www.sciencedirect.com/science/article/pii/S0925527312000503. Kathy Babiak and Sylvia Trendafilova, "CSR and Environmental Responsibility: Motives and Pressures to Adopt Green Management Practices," *Corporate Social Responsibility and Environmental Management* 18, no. 1 (2011): 11-24, http://onlinelibrary.wiley.com/doi/10.1002/csr.229/abstract.

126 Clean Air Task Force, NRDC, and Sierra Club, "Waste Not: Common Sense Ways to Reduce Methane Pollution from the Oil and Natural Gas Industry," Report Summary, November 2014, https://www.nrdc.org/sites/default/files/ene_14111901a.pdf.

127 EPA, "EPA's Actions to Reduce Methane Emissions from the Oil and Natural Gas Industry: Final Rules and Draft Information Collection Request," September 2016, https://www.epa.gov/sites/production/files/2016-09/documents/nsps-overview-fs.pdf.

128 UN Environment Programme (UNEP), "The Kigali Amendment to the Montreal Protocol: Another Global Commitment to Stop Climate Change," December 2016, http://www.unep.org/africa/news/kigali-amendment-montreal-protocol-another-global-commitment-stop-climate-change.

129 California Energy Commission, "Clean Energy & Pollution Reduction Act SB 350 Overview," http://www.energy.ca.gov/sb350/.

130 New York State Energy Plan, "The Energy to Lead: 2015 New York State Energy Plan," https://energyplan.ny.gov/ (accessed July 18, 2017).

131 Massachusetts Executive Office of Energy and Environmental Affairs, "Massachusetts' Progress Towards Reducing Greenhouse Gas (GHG) Emissions by 2020," http://www.mass.gov/eea/air-water-climate-change/climate-change/massachusetts-global-warming-solutions-act/ (accessed July 18, 2017).

132 Regional Greenhouse Gas Initiative, "Welcome," https://www.rggi.org/ (accessed June 21, 2017). Regional Greenhouse Gas Initiative, "Frequently Asked Questions," http://www.rggi.org/docs/mou_faqs_12_20_05.pdf (accessed June 21, 2017).

133 Paul Hibbard et al., *The Economic Impacts of the Regional Greenhouse Gas Initiative on Nine Northeast and Mid-Atlantic States: Review of RGGI's Second Three-Year Compliance Period (2012–2014)*, Analysis Group, July 14, 2015, https://www.c2es.org/docUploads/rggi-mou.pdf.

134 LSU Law Center, "U.S. Environmental Protection Agency Fact Sheet: Overview of the Clean Power Plan," August 2015, http://biotech.law.lsu.edu/blog/fs-cpp-overview.pdf.

135 Resources regarding the American Clean Energy and Security Act of 2009 (H.R. 2454 of the 111th Congress) are available at: Center for Climate and Energy Solutions, "The American Clean Energy and Security Act (Waxman—Markey Bill)," https://www.c2es.org/federal/congress/111/acesa (accessed June 28, 2017).

136 Center for Climate and Energy Solutions, "Kerry–Lieberman American Power Act," https://www.c2es.org/federal/congress/111/kerry-lieberman-american-power-act (accessed June 28, 2017).

137 NRDC, "The Road from Paris: Galvanizing a Global Climate Action Agenda," November 2016, https://www.nrdc.org/sites/default/files/paris-climate-conference-action-IB.pdf.

138 Office of Washington Governor Jay Inslee, "United States Climate Alliance Adds 10 New Members to Coalition Committed to Upholding the Paris Accord," June 5, 2017, http://governor.wa.gov/news-media/united-states-climate-alliance-adds-10-new-members-coalition-committed-upholding-paris.

139 American Wind Energy Association, "U.S. Wind Energy State Facts," http://www.awea.org/state-fact-sheets (accessed July 18, 2017).

140 Solar Energy Industries Association, "Top 10 Solar States," http://www.seia.org/research-resources/top-10-solar-states (accessed July 18, 2017).

141 ACEEE, "Energy Efficiency Resource Standard (EERS)," http://aceee.org/topics/energy-efficiency-resource-standard-eers (accessed June 25, 2017).

142 Climate Mayors, “359 US Climate Mayors Commit to Adopt, Honor and Uphold Paris Climate Agreement Goals,” *Medium* blog, June 1, 2017, https://medium.com/@ClimateMayors/climate-mayors-commit-to-adopt-honor-and-uphold-paris-climate-agreement-goals-ba566e260097.

143 Douglass Sims, Catherine Cox Blair, and Sarah Dougherty, “Taking the High Road to More and Better Infrastructure in the United States,” NRDC, July 20, 2016, https://www.nrdc.org/resources/taking-high-road-more-and-better-infrastructure-united-states.

144 City Energy Project, web home page, http://www.cityenergyproject.org/ (accessed July 18, 2017).

145 For example, see Sierra Club’s Ready for 100 campaign, which works with cities to transition electricity supply to 100% clean, zero-carbon resources. Sierra Club, “Campaigns and Programs: Ready for 100,” http://www.sierraclub.org/ready-for-100 (accessed July 18, 2017).

146 CleanEdge, “Getting to 100: A Status Report,” https://cleanedge.com/reports/Getting-to-100 (accessed August 15, 2017).

147 We Mean Business, web home page, https://www.wemeanbusinesscoalition.org/ (accessed July 18, 2017).

148 Global Climate Action, “About Global Climate Action,” http://climateaction.unfccc.int/ (accessed July 18, 2017).

149 DOE, “Revolution . . . Now: The Future Arrives for Five Clean Energy Technologies—2015 Update,” November 2015, http://energy.gov/sites/prod/files/2015/11/f27/Revolution-Now-11132015.pdf.

150 IPCC, “Climate Change 2014, Synthesis Report Summary for Policymakers,” 2014, https://www.ipcc.ch/pdf/assessment-report/ar5/syr/AR5_SYR_FINAL_SPM.pdf.

151 Andrew deLaski and Joanna Mauer, “Energy-Saving States of America: How Every State Benefits from National Appliance Standards,” February 2017, Appliance Standards Awareness Project and ACEEE, https://appliance-standards.org/sites/default/files/Appliances%20standards%20white%20paper%202%202-14-17.pdf.

152 Ibid.

153 EPA, “ENERGY STAR Celebrating 20 Years,” March 2012, https://www.energystar.gov/ia/about/20_years/ES_20th_Anniv_brochure_spreads.pdf?3965-f653.

154 Bloomberg New Energy Finance, *2017 Sustainable Energy in America Factbook*.

155 California Energy Commission, “Title 20 Appliance Efficiency Program,” http://www.energy.ca.gov/appliances/ (accessed July 18, 2017).

156 NRDC, *NRDC and Energy Efficiency: Building the Clean Energy Future*, https://www.nrdc.org/sites/default/files/nrdc-building-clean-energy-future-brochure.pdf (accessed July 18, 2017).

157 U.S. Green Building Council, “LEED: Better Buildings Are Our Legacy,” January 26, 2015, https://www.usgbc.org/leed.

158 ACEEE, “Energy Efficiency Resource Standard (EERS)”.

159 Ibid.

160 Massachusetts Energy Efficiency Advisory Council, “2016 Electric Statewide Summary,” http://ma-eeac.org/results-reporting/ (accessed June 28, 2017).

161 Database of State Incentives for Renewables & Efficiency (hereinafter DSIRE), “Find Policies & Incentives by State,” http://www.dsireusa.org/ (accessed July 18, 2017).

162 Dylan Sullivan and Donna DeCostanzo, “Gas and Electric Decoupling,” NRDC, August 30, 2014, https://www.nrdc.org/resources/gas-and-electric-decoupling.

163 District heating and cooling refers to energy systems that produce steam, hot water, or chilled water at a central plant and then pipe it underground to individual buildings for space heating, domestic hot water heating, and air-conditioning. Thus, individual buildings served by a district energy system don’t need their own boilers or furnaces, chillers, or air conditioners. See International District Energy Association, “What Is District Energy?” https://web.archive.org/web/20160409123128/http://www.districtenergy.org/what-is-district-energy (accessed July 19, 2017).

164 Sara Conzemius, *Northwest Ductless Heat Pump Initiative: Market Progress Evaluation Report #5*, prepared by Illume Advising for Northwest Energy Efficiency Alliance, June 28, 2016.

165 Robin Roy, “Advanced Electric Water Heaters Could Save Money and Cut Pollution,” NRDC, February 10, 2016, https://www.nrdc.org/experts/robin-roy/advanced-electric-water-heaters-could-save-money-and-cut-pollution.

166 For example, see DOE, “TVA Partner Utilities–Energy Right Heat Pump Program,” http://energy.gov/savings/tva-partner-utilities-energy-right-heat-pump-program (accessed July 18, 2017).

167 DSIRE, “Renewable Portfolio Standards,” http://programs.dsireusa.org/system/program?type=38& (accessed July 6, 2017).

168 DSIRE, “Hawaii Renewable Portfolio Standard Program Overview,” http://programs.dsireusa.org/system/program/detail/606 (accessed July 6, 2017).

169 DSIRE, “Vermont Renewable Portfolio Standard Program Overview,” http://programs.dsireusa.org/system/program/detail/5786 (accessed July 6, 2017).

170 DSIRE, “Oregon Renewable Portfolio Standard Program Overview,” http://programs.dsireusa.org/system/program/detail/2594 (accessed July 6, 2017).

171 EIA, “Hawaii and Vermont Set High Renewable Portfolio Standard Targets,” Today in Energy, June 29, 2015, https://www.eia.gov/todayinenergy/detail.php?id=21852. Oregon Department of Energy, “Renewable Portfolio Standard,” http://www.oregon.gov/energy/energy-oregon/Pages/Renewable-Portfolio-Standard.aspx (accessed June 21, 2017).

172 California Energy Commission, “Clean Energy & Pollution Reduction Act SB 350 Overview” (accessed July 18, 2017). Governor New York State, Office of Governor Andrew M. Cuomo, “Governor Cuomo Announces Establishment of Clean Energy Standard that Mandates 50 Percent Renewables by 2030,” August 1, 2016, https://www.governor.ny.gov/news/governor-cuomo-announces-establishment-clean-energy-standard-mandates-50-percent-renewables.

173 NRDC, “NRDC’s Fourth Annual Energy Report: Accelerating into a Clean Energy Future,” December 2016, https://www.nrdc.org/sites/default/files/energy-environment-report-2016.pdf.

174 This could include something similar to Xcel’s Renewable*Connect, which offers long- and short-term power purchase agreements to commercial and municipal governments, as well as other utility or third-party offerings such as community solar, solar leasing, green pricing, net metering or value of solar tariffs, and community choice aggregation. Xcel Energy, “Xcel Energy Proposes Option that Allows Customers to Get Energy Exclusively from Wind and Solar Energy,” November 12, 2015, https://www.xcelenergy.com/company/media_room/news_releases/xcel_energy_proposes_option_that_allows_customers_to_get_energy_exclusively_from_wind_and_solar_energy.

175 For instance, the Sierra Club’s Ready for 100 campaign has signed on 28 cities as of May 2017. Sierra Club, “Campaigns and Programs: Ready for 100,” http://www.sierraclub.org/ready-for-100 (accessed August 15, 2017).

176 Helen O’Shea, “A Landmark Plan for Conservation and Renewable Energy,” NRDC, September 24, 2014, https://www.nrdc.org/experts/helen-oshea/landmark-plan-conservation-and-renewable-energy.

177 Stephen Lacey, “Congress Passes Tax Credits for Solar and Wind: ‘Sausage-Making at Its Most Intense,’” Greentech Media, Markets & Policy, December 18, 2015, https://www.greentechmedia.com/articles/read/breaking-house-passes-1.1-trillion-spending-bill-with-renewable-energy-tax.

178 NREL, “Western Wind and Solar Integration Study,” 2010, http://www.nrel.gov/grid/wwsis.html.

179 California Independent System Operator, “Exploring a Regional Independent System Operator (ISO),” https://www.caiso.com/informed/Pages/RegionalEnergyMarket.aspx (accessed June 5, 2017).

180 John Moore, “As Clean Energy Grows, Electricity Markets Must Evolve,” January 5, 2017, http://sustainableferc.org/as-clean-energy-grows-electricity-markets-must-evolve/.

181 Doug Hurley, Paul Peterson, and Melissa Whited, *Demand Response as a Power System Resource*: *Program Designs, Performance, and Lessons Learned in the United States*, Synapse Energy Economics, May 2013, http://www.raponline.org/wp-content/uploads/2016/05/synapse-hurley-demandresponseasapowersystemresource-2013-may-31.pdf.

182 Abbas Akhil et al., *DOE/EPRI Electricity Storage Handbook in Collaboration with NRECA*, Sandia National Laboratories, 2015, http://prod.sandia.gov/techlib/access-control.cgi/2015/151002.pdf.

183 David Goldstein and Amanda Levin, “The Strategic Value of SEM in Limiting Climate Pollution,” in *ACEEE Summer Study on Energy Efficiency in Industry*, August 2017.

184 Guidance from the International Organization for Standardization (ISO) on strategic energy management. International Organization for Standardization, “ISO 50001—Energy management,” https://www.iso.org/iso-50001-energy-management.html (accessed June 27, 2017).

185 Federal Register, “2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards: Final Rule,” October 15, 2012, https://www.gpo.gov/fdsys/pkg/FR-2012-10-15/pdf/2012-21972.pdf.

186 California Air Resources Board, *California’s Advanced Clean Cars Midterm Review*, January 2017, https://www.arb.ca.gov/msprog/acc/acc-mtr.htm.

187 California Air Resources Board, “Analysis of Zero Emission Vehicle Regulation Compliance Scenarios,” Appendix A in *California’s Advanced Clean Cars Midterm Review*, January 2017, https://www.arb.ca.gov/msprog/acc/mtr/appendix_a.pdf.

188 Ying Wang et al., “Study on International Practices for Low Emission Zone and Congestion Charging,” *World* Resources Institute, March 2017,http://www.wri.org/publication/study-international-practices-low-emission-zone-and-congestion-charging.

189 EIA, *Annual Energy Outlook 2014*.

190 “Summary of U.S. VMT Reduction Strategies,” in Amory Lovins and the Rocky Mountain Institute, *Reinventing Fire* (Chelsea, Vermont: Chelsea Green Publishing, October 2011), https://www.rmi.org/wp-content/uploads/2017/06/RF_Summary_of_US_VMT_reduction_strategies.jpg (accessed July 18, 2017).

191 Lindsey Hilde et al., “Demographic Trends and the Future of Mobility,” Fehr & Peers, February 2014, http://www.fehrandpeers.com/wp-content/uploads/2015/07/FP_Think_Demo_Trends_and_Mobility_FINAL.pdf.

192 California Air Resources Board, “Sustainable Communities,” last updated July 10, 2017, https://www.arb.ca.gov/cc/sb375/sb375.htm.

193 Pacific Gas and Electric, “Joint Proposal Application,” August 11, 2016, https://www.pge.com/en_US/safety/how-the-system-works/diablo-canyon-power-plant/joint-proposal-application.page.

194 Ralph Cavanagh, “The Story Behind Today’s Diablo Canyon Announcement,” NRDC, June 21, 2016, https://www.nrdc.org/experts/ralph-cavanagh/story-behind-todays-diablo-canyon-announcement. Ralph Cavanagh, “Diablo Retirement: Pennies Now to Save Billions Later,” NRDC, October 27, 2016, https://www.nrdc.org/experts/ralph-cavanagh/diablo-retirement-pennies-now-save-billions-later.

195 NRDC, “Affordable Multifamily Housing Integrated Retrofit Demonstration Project,” April 25, 2016, https://www.nrdc.org/resources/affordable-multifamily-housing-integrated-retrofit-demonstration-project.

196 For example, see BlueGreen Alliance’s “Proposal for Financing the Clean Energy Transition.” This proposal looks at “clean energy transition funds” that would provide training and unemployment benefits for displaced workers, expand economic development programs to fossil fuel–dependent communities, and support climate resiliency projects. BlueGreen Alliance, “Proposal for Financing the Clean Energy Transition,” https://www.bluegreenalliance.org/resources/a-proposal-for-financing-the-clean-energy-transition/ (accessed July 18, 2017).

197 The latest performance reports on the Workforce Investment Act are available from the U.S. Department of Labor’s ETA Library, https://www.doleta.gov/reports/ (accessed June 28, 2017).

198 U.S. Department of Labor, “Community Based Job Training Grant Fact Sheet,” p. 11, https://www.doleta.gov/BRG/Grants/pdf/CBJT_FACT_SHEET.pdf (accessed June 28, 2017). The Colorado program was funded through a Community Based Job Training Grant to Northeastern Junior College .

199 U.S. Department of Labor, “Community Based Job Training Grant Fact Sheet,” p. 34, https://www.doleta.gov/BRG/Grants/pdf/CBJT_FACT_SHEET.pdf (accessed June 28, 2017). The Tennessee program was funded through a Community Based Job Training Grant to Roane State Community College.

Appendix A: Modeling Methodology

OUTLINE OF MODELING APPROACH

As schematically depicted in Exhibit A-1 below, NRDC and E3 engaged in a three-stage process to undertake the entire modeling effort. Stage 1 was the pre-modeling stage, during which assumptions and other inputs were developed collaboratively by E3 and NRDC to feed into the model. Stage 2 represented the actual modeling conducted by E3, with extensive feedback and discussion with NRDC; particularly in the early period, results from preliminary model runs iteratively helped to refine and finalize the assumptions from Stage 1. The output from Stage 2 consisted of many charts and data in the form of spreadsheets. Stage 3 represented post-modeling analysis conducted independently and separately by NRDC, mainly to extract useful information that was not readily available from the model data output from Stage 2.

EXHIBIT A-1. SCHEMATIC DEPICTING MODELING PROCESS, KEY OUTPUTS, AND INDEX TO APPENDIXES

STAGE 2: E3'S PATHWAYS MODEL

According to E3, its PATHWAYS model is built on a bottom-up representation of the U.S. energy system and how each component changes over time (i.e., stock rollover). Full documentation is available elsewhere.[1] PATHWAYS shares a common architecture with the U.S. Energy Information Administration's (EIA) National Energy Modeling System (NEMS), which is used to generate the EIA's annual projections of energy production, demand, imports, and prices. It also uses many of the same inputs as NEMS.[2] However, the PATHWAYS model possesses additional capabilities, such as incorporating a more detailed representation of the electricity sector, which allows for a more granular and accurate representation of the energy resource portfolio. For example, PATHWAYS uses an hourly dispatch of regional electricity markets, ensuring that grid reliability is maintained and that supply (including from variable sources) and demand are balanced in all hours under all scenarios.

PATHWAYS is a scenario-based model. Portfolios of measures, such as the electricity supply mix and the makeup of transportation fuels, are chosen by the user as inputs. Unlike energy-economy optimization models, which minimize the overall cost of energy supply or maximize social utility subject to imposed constraints, the PATHWAYS model does not optimize measures based on such characteristics but identifies pathways based on selected portfolios that achieve the deep decarbonization goals for the U.S. energy system.[3,4] In this context, NRDC has excluded impractical technologies (subjectively defined, such as those based on exorbitant cost) from our scenario to the extent possible. The selected solutions are technically proven, and many are commercially deployed at scale today.

Given the modeling architecture—based on NEMS, but with greater electricity sector detail—the modeled solutions ensured that the chosen technologies can be accommodated into the power grid (and the broader energy system) without insurmountable technical or reliability challenges. However, the scenarios do call for clean energy solutions to be deployed at a faster pace and with broader reach than has occurred thus far. Such levels of deployment (and associated enabling policies and mechanisms) are untested by the model from the standpoints of labor and capital availability and political tractability. That said, recent trends and demonstrated successes offer many reasons to be optimistic on this front.

In any scenario, the main design choices and drivers fell into the six categories listed below. The model solved for the emissions reduction goal on the basis of all of these in totality, so if some of these were specified by user inputs, it may have been necessary for others to be left unconstrained in order to meet the final goals. (For instance, if the amount of renewables is limited, more fossil-fired generation with CCS [carbon capture and sequestration] will be needed).

The six categories we worked with were:

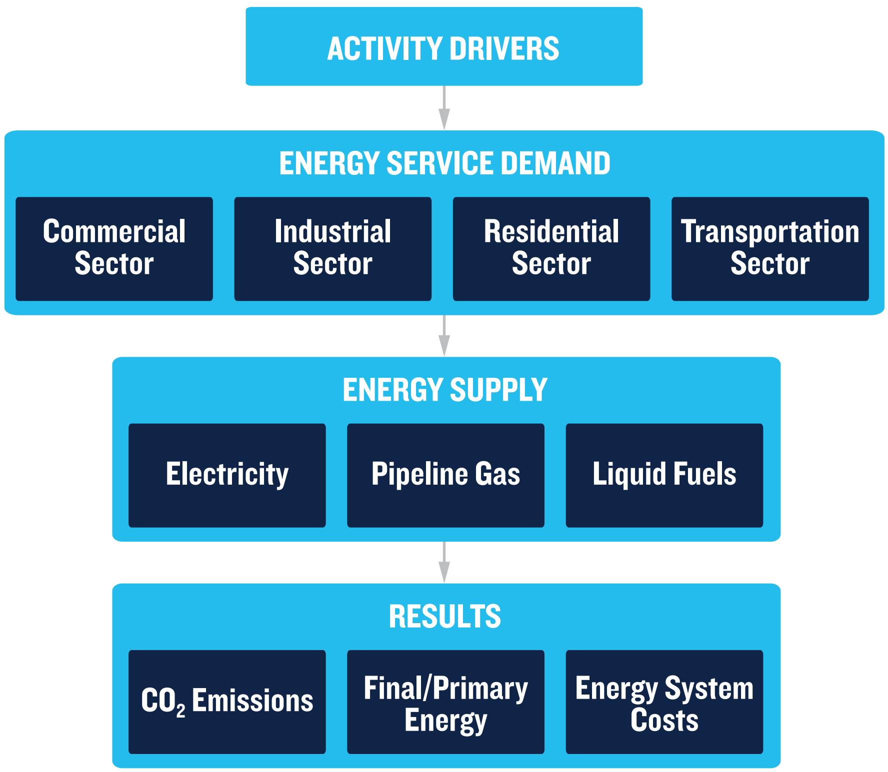
- **Total energy demand** (energy efficiency, consumer behavior)
- **End use and fuel choice** (fuel-switching and electrification of appliances, processes, and vehicles; choices applied to buildings, transportation and industry)
- **Low-carbon electricity** (energy resource mix, including distributed and centralized renewables; CCS; nuclear)
- **Biomass supply and use** (limits on land-use impacts; imports versus in-state-only; technology breakthroughs; fuel sources such as biodiesel, ethanol, biogas, electricity)
- **Electricity balancing** (resource type and location; flexible loads and end uses for EV charging, hydrogen and/or power-to-gas production; storage through batteries, pumped hydro, etc.)
- **CCS** (use in power generation; industrial CCS applications; biomass energy with CCS potentially resulting in negative emissions)

Furthermore, PATHWAYS has an extensive list of end uses whose energy trends, costs, and performance can be specified. For a complete list of all specific end uses incorporated into the PATHWAYS model, see Exhibit A-2.

EXHIBIT A-2: ALL END USES INCLUDED IN MODEL, BY SECTOR	
COMMERCIAL	**TRANSPORTATION**
Commercial Air-Conditioning	Aviation
Commercial Cooking	Buses
Commercial Lighting	Domestic Shipping
Commercial Refrigeration	Freight Rail
Commercial Space Heating	Heavy-Duty Trucking
Commercial Ventilation	Light-Duty Vehicles
Commercial Water Heating	Medium-Duty Trucking
Miscellaneous	Passenger Rail
Office Equipment (Non-P.C.)	Transportation Other
Office Equipment (P.C.)	
RESIDENTIAL	**INDUSTRIAL**
Ceiling Fans	Agriculture—Crops
Coffee Machines	Agriculture—Other
Dehumidifiers	Aluminum Industry
DVD Players	Balance of Manufacturing—Other
Electric Other	Bulk Chemicals
External Power Supplies	Cement
Furnace Fans	Coal Mining
Home Audio Equipment	Computer and Electronic Products
Liquefied Petroleum Gas (LPG) Other	Construction
Microwaves	Fabricated Metal Products
Personal Computers	Food and Kindred Products
Rechargeable Devices	Glass and Glass Products
Residential Central Air-Conditioning	Iron and Steel Industry
Residential Clothes Drying	Machinery
Residential Clothes Washing	Metal and Other (Nonmetallic) Mining
Residential Cooking	Oil and Gas Mining
Residential Dishwashing	Paper and Allied Products
Residential Freezers	Plastic and Rubber Products
Residential Lighting	Refining
Residential Refrigerators	Transportation Equipment
Residential Room Air-Conditioning	Wood Products
Residential Space Heating	
Residential Water Heating	
Security Systems	
Set-top Boxes	
Spas	
Televisions	
Video Game Consoles	

As schematically described in Exhibit A-3, the end uses have a direct bearing on the energy services demanded in each PATHWAYS end-use sector module. Some of these can be driven by exogenously specified activities. Macroeconomic drivers—such as GDP, population, estimated commercial and household building stock, and jobs—are the same across all reference and policy cases. These macroeconomic metrics are based on the EIA 2013 Annual Energy Outlook (AEO) Reference Case, which is effectively a linear extrapolation of the U.S. economy from that time. All cases share the same cost and performance assumptions for both conventional and alternative energy technologies, which are based on AEO 2013 projections. The Reference Case in PATHWAYS follows an emissions trajectory very similar to that in the AEO 2013 Reference Case. AEO 2013 was also used for the United States' Pathways to Deep Decarbonization report submitted to the United Nations.

EXHIBIT A-3: CONCEPTUAL ARCHITECTURE OF THE PATHWAYS MODEL



Source: Williams, J.H., et al. *Pathways to Deep Decarbonization in the United States*. 2014.

As for energy supply, the main sources are electricity, gas, and liquid fuels. Again, the Reference Case values are drawn from AEO 2013, while the policy scenarios diverge from AEO 2013 based on NRDC's assumptions (e.g., renewables build-out). Typically, not all clean energy supply drivers are specified, to allow the model to analyze what the full complement of clean energy supply would need to be to meet emissions goals, given a smaller set of specified assumptions. The underlying energy technology cost and performance assumptions, which are used for both the Reference Case and policy cases, is shown in Exhibit A-4 at the end of Appendix A. These assumptions are the same as those used by E3 in *Pathways to Deep Decarbonization in the United States*.

On this basis, energy measures, on both the demand and supply sides, are incorporated in PATHWAYS through a stock rollover process. At the end of each year, some amount of energy generation and distribution equipment, buildings, and end use equipment and appliances ("energy infrastructure") is retired. New infrastructure is needed to replace this and meet growth in energy service demand. User input dictates the composition of new energy infrastructure (as discussed above). Although infrastructure can be retired early, before the end of its useful life, this imposes a cost in the model. Unless specified by the user, infrastructure retires at the end of its useful life. Both DDPP and NRDC policy scenarios did not assume early retirement of end-use stock. NRDC did assume that nuclear units would shut down after 60 years, as per current licenses (please see Section 2.6 for detailed discussion).

PATHWAYS' main outputs are final (delivered) and primary energy use (in exajoules, or EJ), CO_2 emissions (in million metric tons of carbon dioxide equivalent, or MMT CO_2e), and energy system costs (nominal $) across four end-use sector modules: commercial, industrial, residential, and transportation (see Exhibit A-3). Non-CO_2 emissions are considered in a separate model and accounted for in PATHWAYS' emissions targets.[5]

Primary energy includes all fuel and energy produced and consumed, including all energy that is lost (i.e., wasted heat) in the generation, transmission, and distribution of energy. Final (or delivered or end-use) energy is only the energy that reaches the final consumer (excluding, for instance, transmission line losses and uncaptured waste heat).

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. As an aside, the final outputs may not exactly match the inputs since the model may need to rely less or more on a given resource as it balances energy needs economy-wide.

(To illustrate how these different pieces interact, energy efficiency can provide a helpful example. In a scenario with high energy efficiency (e.g., NRDC Core Scenario), the model applies to the residential and commercial sectors annual improvements to appliance energy use resulting in a 50 percent reduction by 2050, a 5 percent annual improvement in new building shell heating and cooling needs up to a maximum of 70 percent improvement, a 30 percent reduction in heating and cooling demand in existing buildings, complete saturation of LEDs, and improvements via lighting controls and behavior changes that result in energy demand reductions. These efficiency assumptions interact with and reduce the necessary energy and fuel demand in each case. The lower demand impacts emissions reductions necessary from energy supply improvements and electrification. Taken together, these factors result in emissions reductions of hundreds of millions of tons of carbon dioxide annually by 2050 in each of the two sectors (residential and commercial).

The pathways are not cost-optimized, but the model does provide both total costs and per-unit prices of energy as outputs for any given scenario, based on available cost data from AEO 2013. This enables a rough comparison between scenarios of the cost impacts at a national level, as well as between individual sectors and census regions. Capital and operational and maintenance costs of energy technologies throughout the forecast period are derived from AEO 2013. As cost information is available for all scenarios modeled in PATHWAYS, each scenario can be compared with others in terms of cost; this provides a relative sense of cost-effectiveness and feasibility. An important caveat is that between the release of AEO 2013 and the publication of this report, costs and projections of energy resources have changed markedly. Specifically, renewables have become much cheaper and natural gas has become cheaper, although price volatility remains. On balance, however, as the data used are consistent between NRDC and DDPP scenarios, comparisons are still meaningful, if imperfect.

PATHWAYS makes no assumptions about the mechanisms, be they mandate- or market-driven, through which the needed technologies are deployed. Consequently, PATHWAYS does not specify necessary policies to achieve the modeled decarbonization. However, the results can reveal important implications and provide insights for policy development. E3 released a follow-up report to its initial analysis as part of DDPP, titled *Policy Implications of Deep Decarbonization in the U.S.*[6] In it, they expand upon the initial analysis and develop the "physical and economic requirements of the transitional steps along the way. This provides unique insight . . . and concrete guidance for what policy must accomplish in all these areas."

NRDC designed two scenarios and six sensitivities.[7] The **Core Scenario** is designed to be ambitious yet achievable and represents a view of the future that is aligned with NRDC's principles and advocacy, which emphasizes the benefits of energy efficiency, renewables, electrification across all sectors (residential, commercial, industrial, and transportation), decarbonization of end uses, and limited use of biofuels. Thus, it assumes aggressive levels of these preferred clean energy resources. As modeling assumptions, nuclear capacity gradually declines by 2050 and sustainability constraints are imposed on the availability of biomass.

The **Delay/Secondary Scenario** aimed to simulate the effects of roughly 10 years' worth of delays on the main clean energy pillars in the Core Scenario. Accordingly, constraints were imposed on energy/fuel efficiency in all sectors, vehicle-miles-traveled (VMT) reductions, and electrification and fuel-switching in industrial and transportation sectors.[8] Without any further changes, the 2050 emissions target was missed by about 25 percent, or 1 billion tons of CO_2. For the gap to be closed, significantly more biomass, CCS, and nuclear energy than assumed in the Core Scenario would have to be deployed to meet the necessary emissions reductions.

The **six sensitivities** imposed an equivalent 10-year delay compared with the Core Scenario on particular measures or (sub)sectors, one at a time, as follows: reduced energy efficiency gains in buildings and industry, reduced CCS, use of biomass with CCS for power instead of fuel production, reduced electrification in buildings and industry, reduced vehicle-miles-traveled improvements and electric vehicle penetration, and reduced renewables build rates. The sensitivities were useful for internal understanding but are not discussed in detail in this report.

The set of modeling assumptions for the **Core** and **Secondary Scenarios** are described in more detail in Appendix C.

EXHIBIT A-4: DATA SOURCES FOR PATHWAYS TECHNOLOGY COST AND PERFORMANCE ASSUMPTIONS

Sector	Subdivisons	Categories	Data Types	Data sources
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 2012 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 Tuna 2014 Swanson 2010
Others	Fuels Produced from Electricity	Hydrogen Synthetic Natural Gas	Efficiencies Capital cost Operating cost Other	SGC 2013 NREL 2009

Source: Williams, J.H., et al. *Pathways to Deep Decarbonization in the United States*. 2014.

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

FHA 2010 = Federal Highway Administration (2010), Highways Statistics 2010

FHA 2011 = Federal Highway Administration (2011), Highways Statistics 2011

Kuramochi 2012 = Kuramochi, T., Ramírez, A., Turkenburg, W., & Faaij, A. (2012). Comparative assessment of CO_2 capture technologies for carbon-intensive industrial processes

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

Swanson 2010 = Swanson, R. M., Platon, A., Satrio, J. A., & Brown, R. C. (2010). Techno-economic analysis of biomass-to-liquids production based on gasification

Tuna 2014 = Tuna, P., & Hulteberg, C. (2014). Woody biomass-based transportation fuels–A comparative techno-economic study

Appendix B: Stage 3, Post-Modeling Analysis Methodology—NRDC's Analysis of E3's Deep Decarbonization Modeling Outputs

E3 MODEL OUTPUTS

The output data provided by E3 included:

- emissions (in million metric tons of carbon dioxide equivalent, or MMT CO_2e)
- delivered energy use (in exajoules, or EJ) for all end uses by census region;
- primary energy use (in EJ) at a national level;
- installed electricity capacity (in megawatts, or MW) and the generation mix at a national level;
- delivered renewable energy (in megawatt-hours, or MWh) at an interconnect level;
- vehicle miles traveled by type and fuel source, by census region;
- vehicle stock by type and fuel source at a national level;
- and average emissions intensity (in kilograms of carbon dioxide per gigajoule, or kg CO_2/GJ) and cost of each energy source (in dollars per gigajoule, or $/GJ).

Output data were for all years between 2010 and 2050. Four modeling runs were included: NRDC/DDPP Reference Case, DDPP Mixed Case, NRDC Core Scenario, and NRDC Delay/Secondary Scenario. E3 subdivided the output into separate data files by indicator (e.g., emissions, final energy, primary energy) and sector (residential, commercial, industrial, and transportation).

NRDC POST-MODELING RATIONALE AND METHODOLOGY

While the E3 model outputs included final emissions by sector and end use, they did not provide information on the emissions reductions attributable to each main emissions-reduction driver (e.g., energy efficiency, electrification, decarbonization). However, it is important to understand the relative magnitude of each driver to determine the structure of the decarbonized energy system and policy needs. NRDC independently undertook a post-modeling analysis to attribute emissions reductions to specific reduction measures for each end use and sector. This approach was inherently approximate, but we believe a substantiated and well-reasoned approximation, as the methodology below describes. The alternative would have been to run innumerable sensitivities, a lengthy and extremely resource-intensive undertaking.

This post-modeling analysis was completed for only a few select years of interest (e.g., 2030 and 2050), though the same may be completed for other years as needed, using the same approach.

STEP 1: DETERMINING ENERGY AND GHG REDUCTIONS DUE TO NRDC ENERGY EFFICIENCY (PART 1)

As a preparatory step, outputs for both the NRDC Core Scenario and for the NRDC/DDPP Reference Case for the select year were compiled for all sectors, by end use and fuel source.

The first step of the deconstruction was to determine the reduction in energy use by source due to NRDC's energy efficiency assumptions. Because of additional assumptions concerning electrification and fuel switching (which can also result in *energy* savings), it was inappropriate to attribute the entire difference in energy use between the Core Scenario and Reference Case solely to energy efficiency and conservation measures. We needed to instead develop another baseline to capture just the impact of energy efficiency and conservation.

For heating and cooling end uses, both shell and appliance efficiency improvements had to be calculated; for other appliances, such as personal electronics, only appliance efficiency needed to be accounted for. Using the underlying population and housing stock rollover data, NRDC could determine the makeup of building stock vintages in 2050. The associated shell efficiency of the stock was calculated using NRDC's new and existing building shell efficiency assumptions (as detailed in Appendix C). In the NRDC Core Scenario, the entire stock achieves a shell efficiency improvement of approximately one-third compared with the Reference Case by 2050. Appliance efficiency was then layered on, with consideration for stock rollover and HVAC appliance life. In 2050, shell and appliance efficiency combined result in a reduction of approximately 40 percent in heating energy needs compared with the Reference Case. These reductions in energy use associated with efficiency were used to calculate the energy use (and GHG emissions) that would have occurred if only energy efficiency, but no other measures, such as electrification or fuel switching, had been implemented. This NRDC-derived baseline scenario with *only* NRDC energy efficiency will be referred to as "Energy-Efficiency-Only Reference Case" throughout this remaining section.

STEPS 2 AND 3: DETERMINING ENERGY AND GHG SAVINGS DUE TO ELECTRIFICATION AND FUEL SWITCHING

For end uses in all sectors (except industry) where a portion of the stock switches from liquid fuels to electricity, NRDC determined the additional electricity use in the Core Scenario due to electrification. The electricity use calculated in the Energy-Efficiency-Only Reference Case was used as the baseline for electricity use without electrification. Any difference (always excess) between actual electricity use in the Core Scenario and the revised Reference Case was attributed to electrification. To determine electrification-driven avoided energy and emissions, NRDC first applied an approximate but end-use-specific "efficiency gain" factor, which reflected the thermodynamic advantage of switching to electricity from certain kinds of direct fuel use (e.g., switching from natural gas heat to ground-source heat pumps, or switching from internal combustion to electric drive trains in vehicles).[9] Taking the additional electricity in the Core Scenario and multiplying it by the efficiency gain allowed us to determine the equivalent energy use that would have been required had the end use remained powered by a fossil fuel. The emissions reductions from switching to electricity from a less thermodynamically efficient source was determined by subtracting emissions associated with the additional electricity usage from the avoided emissions associated with not burning the equivalent energy required if powered with fossil fuels.

Then, the difference between Core Scenario emissions and the calculated emissions of the Energy-Efficiency-Only Reference Case for all fuel sources besides electricity was computed, capturing the additional emissions reductions from switching away from and between other fuel sources. The sum of these emissions is the total emissions reductions from both electrification and fuel switching.

STEP 4: DETERMINING EMISSIONS REDUCTIONS FROM DECARBONIZATION OF ENERGY SUPPLY

To determine the contributions from a cleaner grid, NRDC multiplied the counterfactual expected electricity use in the Energy-Efficiency-Only Reference Case by the difference in emissions intensity for electricity between the Core Scenario and Reference Case. We used the expected electricity use from the Energy-Efficiency-Only Reference Case to avoid double-counting the emissions reduction impact of electrification.

E3 provided NRDC separately with the emissions reductions associated with CCS on electricity generation for the NRDC Core Scenario; NRDC also separately calculated the emissions increases associated with the retirement of 80 GW of nuclear in the NRDC Core Scenario. The shutdown of these nuclear plants is equivalent to an increase of 372 MMT CO_2, if lost output is replaced by the Reference Case mix of nonnuclear generation in 2050. These components were applied to each end use based on its pro-rata share of electricity consumption in the Energy-Efficiency-Only Reference Case. The CCS component was subtracted from the cleaner grid and treated as a separate reduction measure; the nuclear component was added to the cleaner grid calculation. Essentially, renewables in the Core Scenario reduce emissions more than would appear through a straight comparison of emissions intensity, as 80 GW of zero-emitting nuclear capacity is lost between the Reference Case and Core Scenario in 2050. In other words, increased renewables deployment is required to not only lower the emissions intensity but also back-fill the lost zero-emitting energy from nuclear.

To calculate the contribution of lower carbon fuels (e.g., bio-derived fuels and synthetic fuels from excess renewable electricity), NRDC followed a process like the first step of the cleaner grid calculation. However, to account for reduced fuel use beyond what would be expected in the Energy-Efficiency-Only Reference Case due to electrification and fuel switching, the energy use from the Core Scenario (not from the Energy-Efficiency-Only Reference Case) was used. The Core Scenario energy use (for diesel and natural gas, separately) was multiplied by the difference in emissions intensity for individual fuels between the Core Scenario and Reference Case.

STEP 5: DETERMINING ENERGY AND GHG REDUCTIONS DUE TO NRDC ENERGY EFFICIENCY (PART 2)

The Energy-Efficiency-Only Reference Case scenario provided a baseline for energy based only on NRDC efficiency assumptions. Using this counterfactual baseline, the contributions from electrification, fuel switching, and decarbonization of energy sources were calculated. The emissions reduction contribution from energy efficiency was finally calculated by subtracting from the Reference Case the emissions reduction contributions from electrification, fuel switching, and decarbonization of energy sources (results from steps 2 through 4) and the remaining emissions in the Core Scenario.

We adopted this "leftover" approach to attribute emissions reductions from energy efficiency, instead of using a direct estimate as may have been suggested by Step 1, because there were minor discrepancies between estimates suggested by Step 1 and actual model results. This was because the efficiency assumptions that we used to construct the Energy-Efficiency-Only Reference Case in Step 1 were set at a sector level, but the PATHWAYS model endogenously determined varying levels of electrification and efficiency by end use to achieve the assumed average electrification and efficiency by sector. These endogenous determinations at the end-use level were based on the installed cost of new equipment, discounted operating costs of new equipment, and the cost of switching technologies for each end use, which are already included in the model's architecture.[10] Due to data output limitations, our post-modeling analysis methodology was unable to precisely re-create the actual electrification and efficiency levels by end use, and instead relied on the average assumed levels at the sector level. Other assumptions, such as the efficiency-gain factors, were also averages. With these limitations, NRDC believes the "leftover" approach properly accounts for all emissions reductions and provides a reasonable and defensible approximation of the magnitude of each emissions reduction driver.

MODIFICATIONS TO METHODOLOGY FOR INDUSTRIAL SECTOR

Determining appropriate thermodynamics-based efficiency-gain factors for individual industrial subsectors proved infeasible. Given this, NRDC instead estimated potential energy reductions from electrification through a two-step approach that used an approximate corrective adjustment to account for electrification-related energy savings.

Unlike the residential and commercial sectors, it was not possible to break out the energy reductions from energy efficiency versus electrification or fuel switching. Accordingly, the Energy-Efficiency-Only Reference Case for industry was developed by applying the specific sub-industry percentage energy reductions (from efficiency, electrification, and/or fuel switching measures) between the Reference Case and Core Scenario, instead of just energy savings from efficiency, as was used for the Energy-Efficiency-Only Reference Case for the other sectors.

The emissions difference between the Energy-Efficiency-Only Reference Case GHG emissions and Core Scenario GHG emissions by energy source was attributed to fuel switching and electrification. Apportioning the contributions between fuel switching and electrification were done toward the end; this is discussed below. Cleaner grid and lower-carbon fuel contributions were calculated the same way as for residential and commercial sectors.

A few select industries have CCS implemented on their processes. These include chemicals, cement, iron and steel, and refining. CCS reduced the emissions intensity of coal, coke, and gas used (as well as petrochemical feedstocks in the chemicals subsector). The reductions from installed CCS was calculated by taking the Core Scenario energy use for the specific source and multiplying it by the difference between the average emissions intensity of that fuel in the Core Scenario and the emissions intensity of that fuel for the specific subindustry in the Core Scenario. These CCS contributions were subtracted from the sub-industry's electrification/fuel switching contribution, to avoid double counting.

After these calculations, energy efficiency was assigned the remaining emissions reductions. Given that energy savings from both energy efficiency and electrification/fuel switching had been factored into the Energy-Efficiency-Only Reference Case, after determining the initial split between all the measures, NRDC added a corrective adjustment factor. Rolling in the savings from electrification/fuel switching into the Energy-Efficiency-Only Reference Case resulted in the decomposition process overestimating the impact of efficiency (and underestimating the impact from electrification/fuel switching). Thus, NRDC reapportioned 30 percent of the initial reductions attributed to energy efficiency to electrification as a rough counterbalance.

To calculate the split between electrification and fuel switching, a counterfactual NRDC case was developed for energy consumption by fuel and subsector based on subsector energy efficiency assumptions. NRDC then calculated actual deviations in the NRDC scenario from this counterfactual case, of consumption by fuel for each subsector, which were attributed to electrification or fuel switching depending on the fuel/energy source in question. Then, for each subsector, the additional energy use (positive deviation) was totaled for both electrification and fuel switching, separately. This represented extra energy due to either electrification or fuel switching, respectively, that were observed after only efficiency was accounted for. The ratio of total extra energy use due to electrification versus fuel switching was then applied to overall GHG reductions, to distribute in the same proportion GHG savings due to electrification or fuel switching.

MODIFICATIONS TO METHODOLOGY FOR TRANSPORTATION SECTOR

For LDVs, NRDC assumed VMT reductions, in addition to engine efficiency, electrification, and decarbonization of energy, as an emissions reduction strategy. To calculate the emissions reductions from VMT measures, NRDC took the total reduction in VMT between the Reference Case and Core Scenario and multiplied it by a weighted emissions intensity per mile. The emissions intensity per mile was calculated by determining the emissions intensity per mile in both the Reference Case and the Core Scenario. Gasoline VMT sees a larger percentage reduction than total VMT under the Core Scenario, compared to the Reference Case.[11] Therefore, we took a weighted average of the two cases—giving the Reference Case (which is more emissions-intensive) a larger weight than the Core Scenario (which is less emissions-intensive). For the rest of the transportation sector post-modeling emissions deconstruction, we followed the same steps as we did for the residential and commercial sectors. In the end, the emissions reductions attributable to VMT were subtracted out of the energy efficiency contribution for LDVs.

Appendix C: Assumptions (and Model Outputs) in NRDC Core and Secondary Scenarios

In this table, assumptions are in regular type, while model outputs that deviated from assumptions are italicized. Supporting resources for assumptions are provided in the endnotes.

EXHIBIT C-1: ASSUMPTIONS AND MODEL OUTPUTS FOR THE NRDC CORE AND SECONDARY SCENARIOS

			Assumptions (regular type) & **Model Outputs** (*italicized*)	
Sector		**End Use(s)**	**NRDC Core Scenario** (in comparison with Reference Case)	**NRDC Delay/Secondary Scenario** (in comparison with Reference Case, unless otherwise specified)
ENERGY EFFICIENCY AND CONSERVATION	**Residential and Commercial**	All	2% annual improvement in appliances[12]	"Best available" existing technology saturation, no early replacement
			50% total reduction in appliance energy use by 2050 (compared with 2014)[13]	Additional 10% reduction in water heater demand in commercial sector by 2050
		Air-Conditioning, Space Heating	5% annual improvement in new building shell heating and cooling needs. Maximum of 70% total improvement in building shell by 2050 (achieved in 2037)[14]	New commercial buildings: 20% reduction in heating and 30% reduction in cooling need by 2050 New residential: Introduces new codes over time based on EIA modeling of four code variants; also reduces heating and cooling demand by 10% due to control improvements by 2050
			30% reduction in heating and cooling demand in existing buildings by 2050[15]	Existing commercial buildings: 20% reduction in heating and 30% reduction in cooling need by 2050 Existing residential: reduced heating and cooling demand by 10% due to control improvements by 2050
		Lighting	Complete saturation of LEDs[16]	Same
	Res.	Behavioral	10% behavioral reduction in demand[17]	None modeled
	Commercial	Lighting	Additional 20% reduction in lighting demand from controls[18]	Additional 10% reduction in lighting demand from controls
			Additional 10% reduction in lighting demand from daylighting[19] (e.g. window and skylight systems)	Additional 5% reduction in lighting demand from daylighting
		Behavioral	15% behavioral reduction in demand[20]	None modeled
	Industrial	All Sectors	3% annual improvement in energy intensity (first decade), decreasing to 1% annual improvement by 2050. Equivalent to 55% total improvement in energy intensity by 2050[21]	1.1% energy intensity improvement per year
			200 GW of new CHP (285 GW in total) by 2050[22]	Same
	Transportation	Light-Duty Vehicles (LDVs)[a]	VMT matches AEO 2014 low VMT side case.[23] This is equivalent to a ~24% reduction from the Reference Case	VMT reductions are halved. Represent ~12% reduction from the Reference Case
			Mainly electric vehicles (EVs) and plug in hybrids (PHEVs) (together nearly 85 percent sales in 2050). *Fuel efficiency of entire fossil fuel–based fleet is ~80 mpg*[24]	Fuel efficiency of the LDV fleet is halved compared with Core Scenario
		Heavy-Duty Vehicles (HDVs)[b]	For tractor trailers, 55% reduction in fuel consumption by 2050 (compared to 2010)	Fuel efficiency gains in the HDV sector are halved compared with Core Scenario
		Medium-Duty Vehicles (MDVs), HDVs	Vocational, MD, and HD pickups and vans have 100% hybrid adoption. Equal to 50% fuel consumption reduction by 2050	Hybrid adoption rates are halved compared with Core Scenario

a Further discussion in support of these assumptions is provided in Section 2.1.

b This reflects SuperTruck technologies as discussed in Section 2.1

EXHIBIT C-1: ASSUMPTIONS AND MODEL OUTPUTS FOR THE NRDC CORE AND SECONDARY SCENARIOS

Sector		End Use(s)	Assumptions (regular type) & Model Outputs (*italicized*)	
			NRDC Core Scenario (in comparison with Reference Case)	**NRDC Delay/Secondary Scenario** (in comparison with Reference Case, unless otherwise specified)
CLEANER GRID	All	Renewables	75% non-hydro renewables generation in 2050, as measured by electricity usage (capacity of 1,500 GW)[25] *71% of electricity (1,547 GW of capacity), from non-hydro renewables*	*61% of electricity (1,714 GW of capacity), from non-hydro renewables*
CLEANER GRID	All	Nuclear	20 GW of nuclear in 2050 (~20% of Reference Case)[c]	*55.3 GW of nuclear in 2050*
CLEANER GRID	All	CCS	*32 MMT of CO_2 captured by CCS from industry processes*	*10 MMT of CO_2 captured by CCS from industry processes*
CLEANER GRID	All	CCS	*8.4 GW of coal with CCS by 2050*	*Same*
CLEANER GRID	All	CCS	*77.7 GW of gas with CCS by 2050*	*165.4 GW of gas with CCS by 2050*
CLEANER GRID	All	Electricity Balancing	750 gigawatt-hour (GWh) of battery storage on grid[26]	Same
DECARBONIZATION OF END USES	Residential	All	95% electrification of demand[27] *Model outputs for electrification by 2050:* *Water heating: 99.99%* *Space Heating: 85.3%* *Cooking: 96.7%* *Clothes Drying: 99.97%*	Same
DECARBONIZATION OF END USES	Commercial	All	89% electrification of demand.[28] *Model outputs for electrification by 2050:* *Water Heating: 73.8%* *Space Heating: 83.1%* *Air-Conditioning: 99.89%* *Cooking: 54%* *Miscellaneous: 77.8%*	Same
DECARBONIZATION OF END USES	Ind.	All Sectors	44% electrification of boilers[29]	21% electrification of boilers
DECARBONIZATION OF END USES	Ind.	All Sectors	44% electrification of industrial processes[30]	10% electrification of industrial process
DECARBONIZATION OF END USES	Ind.	All Sectors	Some fuel switching[31]	Same
DECARBONIZATION OF END USES	Ind.	Iron and Steel Sector	60% of production of steel from DRI (direct reduced iron) in an EAF (electric arc furnace)[32]	Same
DECARBONIZATION OF END USES	Trans.	All	*1.72 EJ of biomass-diesel used in 2050*	*5.35 EJ of biodiesel used in 2050* *(a higher level than in Core Scenario is required to meet emissions targets, as discussed in body of the report)*
DECARBONIZATION OF END USES	Trans.	HDVs	*1.4 million liquefied natural gas (LNG) HDVs in 2050*	*0.8 million LNG HDVs in 2050*
DECARBONIZATION OF END USES	Trans.	LDVs	*225 million EV or PHEV LDVs in 2050*	*120 million EV or PHEV LDVS in 2050*
DECARBONIZATION OF FUEL	All	Biomass	*430 million (dry) tons of biomass used*[33]	Approximately 1 billion (dry) tons of biomass used[34]
DECARBONIZATION OF FUEL	All	Biomass	*0.24 EJ of biomass-pipeline gas in 2050*	*0.60 EJ of biomass-pipeline gas in 2050*
DECARBONIZATION OF FUEL	All	Biomass	*1.72 EJ of biodiesel in 2050 (all used for transportation)*	*5.35 EJ of biomass-diesel in 2050 (all used for transportation)*
DECARBONIZATION OF FUEL	All	Biomass	*196 MMT of CO_2 captured by CCS on biomass production*	*652 MMT of CO_2 captured by CCS on biomass production*
DECARBONIZATION OF FUEL	All	Electricity Balancing	*Electricity provides 10–15% of natural gas supply via power-to-gas*	Same
DECARBONIZATION OF FUEL	All	Electricity Balancing	*Electricity provides 7% of natural gas supply via pipeline hydrogen*	Same

c Please refer to Section 2.6 for more detailed discussion.

Appendix D: Key Results and Charts

Underlying raw data is available to external parties upon request. Please contact the authors of the paper to obtain data output files.

Energy use: In the NRDC Core Scenario, in 2050 the primary energy use is 55.6 exajoules (EJ) and final (or delivered or end-use) energy is 42.2 EJ. This compares with 2015 values of 102.8 EJ for primary energy and 78.1 EJ for delivered energy.[d] The contrast is much larger when comparing with the Reference Case, which has 107 EJ for primary energy and about 82 EJ for end-use energy. The annual end-use energy demand in the Core Scenario is about half that in the Reference Case in 2050, primarily due to both energy efficiency and electrification-related energy savings. Other scenarios can be contemplated that meet the 80 percent emissions reduction goal, such as "High Renewables" or "High Nuclear" or "High CCS," but these will have distinctly higher energy demand. See Exhibit D-1.

EXHIBIT D-1: TOTAL PRIMARY AND DELIVERED ENERGY IN DIFFERENT SCENARIOS AND YEARS

	2015 Values[35]	NRDC/DDPP Reference Case	DDPP Mixed Case	NRDC Core Scenario	NRDC Secondary Scenario
Primary Energy (EJ)	102.8	107.6	74.0	55.6	88.5
Final Energy (EJ)	78.1	81.7	54.5	42.2	60.0

GHG emissions: The Reference Case in 2050 has CO_2 emissions of roughly 5,800 million tons and non-CO_2 emissions of roughly 1,800 million tons CO_2e, compared with approximately 5,300 and 1,200 in 2015, respectively.[36] In the NRDC Core Scenario, the annual CO_2 emissions in 2050 are 1,000 million tons and non-CO_2 GHG emissions are just over 800 million tons CO_2e. Overall, after subtracting terrestrial (carbon) sink contributions of about 800 million tons CO_2e, total 2050 GHG emissions in the NRDC Core Scenario are just over 1,000 million tons of CO_2e. (Terrestrial sinks reflect the estimated amount of carbon emissions that plant matter can absorb from the atmosphere and temporarily sequester in soils and other geological formations.[37]) The DDPP Mixed Case achieves around 800 million tons of CO_2, but it does not achieve as much non-CO_2 emissions reduction, resulting in overall 2050 GHG emissions of also around 1,000 million tons CO_2e. The NRDC Secondary Scenario achieves 1,045 million tons of CO_2e emissions.

Non-CO_2 GHG emissions: While E3's PATHWAYS model focuses on energy-related CO_2 emissions, non-CO_2 GHGs and possible mitigation measures are included and accounted for in E3's final analysis. Please refer to Section 2.7 for some details on non-CO_2 GHG assumptions.

Under the Reference Case, non-CO_2 emissions are expected to increase by 50 percent from 1990 levels. In the Core Scenario, non-CO_2 emissions are 27 percent below 1990 levels and around 55 percent below the Reference Case 2050 levels. While these reductions are greater than those in the DDPP Mixed Case, we nonetheless believe, based on NRDC expert opinion, that the NRDC estimates are still conservative. In fact, our experts concluded that more sizeable reductions of non-CO_2 gases can be achieved by 2050 than our modeling assumed, based on new studies and policy developments. For example, the Obama administration had a goal of cutting methane emissions from the oil and gas sector by 40 to 45 percent from 2012 levels by 2025. NRDC's modeling assumes around a 40 percent reduction from 2012 levels by 2050 (25 years later than the Obama administration assume feasible).[38] Likewise, the recent HFC amendment (Kigali Amendment) to the Montreal Protocol would have the United States freeze the production and consumption of HFCs by 2018 and then reduce HFC emissions by 85 percent compared to 2012 levels by 2036. NRDC's modeling only reduced HFCs by around 70 percent compared to 2012 levels by 2050.[39] Finally, while not directly and solely related to non-CO_2 emissions, E3 and NRDC assumed that carbon sinks are held constant at 1990 levels. There is good reason to think that the amount of carbon sinks in the United States could grow above 1990 levels.[40] If this is the case, more carbon than we assumed will be stored in the natural environment, further reducing the amount of carbon emitted annually that ends up accumulating in the atmosphere and contributing to climate change. The total gross and net emissions, including both CO_2 and non-CO_2 gases, are shown in Exhibit D-2.

d As a reminder, primary energy includes all fuel and energy produced and consumed, including all energy that is lost (i.e., wasted heat) in the generation, transmission, and distribution of energy. Final or delivered energy or end-use energy captures only the energy that reaches the final consumer (excluding, for example, transmission line losses, uncaptured waste heat).

EXHIBIT D-2: TOTAL GROSS AND NET EMISSIONS, INCLUDING BOTH CO_2 AND NON-CO_2 GASES, IN DIFFERENT SCENARIOS AND YEARS						
Emissions Category	1990 Emissions (MMT CO_2e)	2050 Remaining Emissions (MMT CO_2e)			Percent Reduction from 1990 Levels	
		NRDC/DDPP Reference Case	DDPP Mixed Case	NRDC Core Scenario	DDPP Mixed Case	NRDC Core Scenario
A. Fossil fuel and industrial CO_2 emissions	5,108	5,798	~750	~1,000	84%	79%
B. Non-CO_2 emissions (all)	1,125	~1,790[41]	992	820	12%	27%
C. [A+B] Gross CO_2e emissions	6,233	~7,588	~1,742	~1,820	71%	70%
D. Terrestrial CO_2 sink	831	831	831	831	0%	0%
E. [C-D] Net CO_2e (including sink)	5,402	~6,757	~911	~989	82%	81%

Energy demand reduction by sector: Energy demand must be reduced in all sectors in all scenarios to achieve the 2050 emissions targets. However, the scenarios differ in the extent and types of reduction by sector as well as how sector demand is served. (For instance, compared with the NRDC Core Scenario, in the NRDC Secondary Scenario synthetic diesel plays a larger role in the transportation sector, and both synthetic and extracted natural gas play larger roles in the industrial sector.)

In the residential sector, the Core Scenario results in decarbonized energy supply and nearly a 70 percent reduction in total energy use from the Reference Case (and about 60 percent from 2015), mainly from major energy savings in space heating and cooling and in water heating.

In the commercial sector, the Core Scenario results in decarbonized energy supply and more than a 50 percent reduction in total energy use from the Reference Case (and about a 30 percent reduction from 2015), mainly from large energy savings in space heating and cooling as well as lighting.

In the industrial sector, the Core Scenario results in a 33 percent reduction in total energy use from the Reference Case, mainly from cuts in energy intensity and boiler improvements. Annual sector-wide energy intensity improvements are highest in the first decade, at 3 percent annual efficiency improvement per year, decreasing to 1 percent annual improvement by 2050.[e] These intensity improvements are in line with historical corporate achievements as well as with the DOE's Better Buildings, Better Plants initiative.[42] For example, the average Better Buildings participant is on track to achieve 2 percent annual savings over 10 years, and DOE Superior Energy Performance participants have achieved up to 30 percent energy savings in less than 5 years, posting annual savings of between 5 and 10 percent.[43] State-level commercial and industrial programs, such as Energy Trust of Oregon's Strategic Energy Management (SEM) program, have reported average cohort electricity savings as high as 8.5 percent for a single year and gas savings of up to 14 percent in a single year. These participants were able to continue to achieve further savings, albeit at slightly lower levels, achieving average annual energy savings of 11 to 15 percent compared to baseline by the third year.[44]

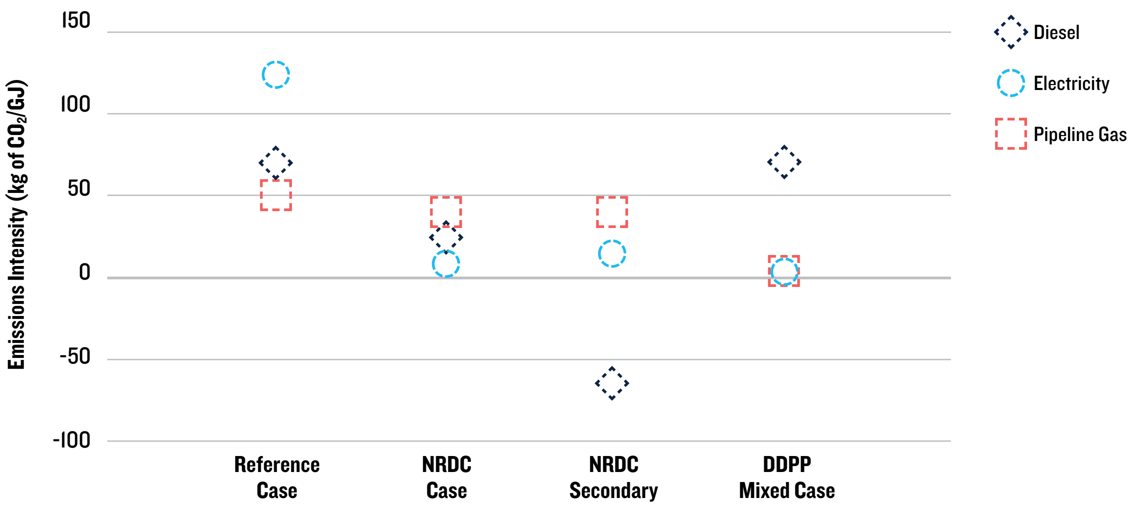
In the transportation sector, the Core Scenario achieves LDV emissions reductions mainly via vehicle electrification and use of hybrids (near-total sales penetration in 2050 of battery electric vehicles, plug-in hybrids, and hybrid vehicles), as well as VMT (adapted from AEO 2014's Low VMT Case) corresponding to a 25 percent VMT reduction from the Reference Case. When using gasoline, average fuel economy of the entire fleet is around 80 mpg. Emissions reductions in heavy-duty and medium-duty vehicles occur mainly via LNG operating on gas produced from renewable electricity, and diesel hybrid vehicles operating on renewable-based diesel, and other fuel efficiency measures like the full implementation of "SuperTruck" technologies, which seeks to improve heavy-duty vehicle engine efficiency by 55 percent by 2050.[45] As noted earlier, the modeling for heavy-duty trucks at the time did not include electric-drive options operating on renewable electricity or hydrogen, so results should be treated as generally pointing to the need for ultra-efficient trucks operating on ultra-low carbon fuels.

Supply-side drivers of decarbonization: In the Core Scenario, the decarbonization of electricity supply is the primary driver of emissions reductions. This is supplemented by reducing the carbon content of pipeline gas via synthetic gas (i.e., power-to-gas) and reducing the carbon in diesel by using biodiesel. In contrast, while electricity decarbonization and gas

e By 2050, the industrial sector will have cut its energy intensity by about 55 percent from current levels. Energy intensity refers to the amount of energy it takes to produce one unit of a good. While these reductions make industry more efficient, lower intensity does not always reduce total energy demand—at least not by the same amount. This is because total units produced may increase, resulting in increased energy demand or smaller reductions in energy demand (but still reduced demand per unit and, thus, reduced energy intensity).

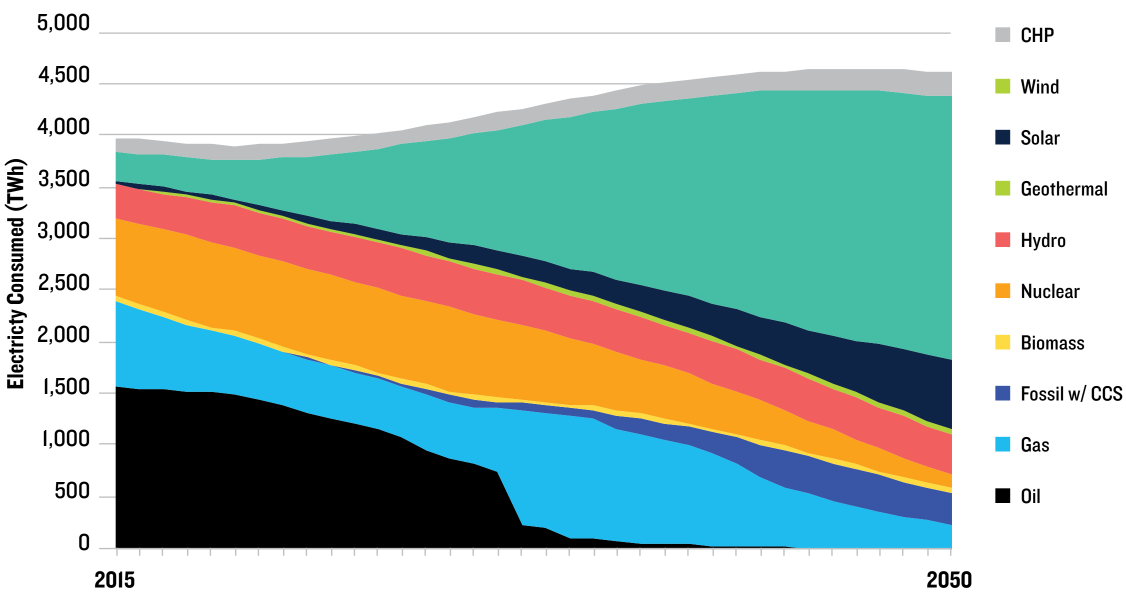
decarbonization still play a role in the NRDC Delay/Secondary Scenario, the delay in this scenario necessitates much deeper decarbonization of synthetic diesel. The extent of decarbonization of the different fuels in the different scenarios is depicted in Exhibit D-3, in terms of their emissions intensity.

EXHIBIT D-3: EMISSIONS INTENSITY BY MAJOR ENERGY SOURCE IN KG CO_2 PER GIGAJOULE, IN THE REFERENCE CASE, TWO NRDC SCENARIOS, AND DDPP MIXED CASE



Electricity supply: 2050 electricity use increases by only about 20 percent from modeled 2015 levels (but about 25 percent from actual 2015 levels). This is despite a significant move toward electrification of end uses in the Core Scenario. Electricity also fills about 45 percent of all end-use demand in 2050 (approximately 18 EJ of 42 EJ), up from about 20 percent in 2015), which constitutes a major paradigm shift. 70 percent of electricity comes from wind and solar energy by 2050, up from 7 to 8 percent in 2015. Fossil fuel–fired electric plants with CCS provide about 7 percent of the electricity mix. The rest is supplied by hydropower (9 percent, distributed fairly equally between small-scale and conventional), nuclear (3 percent), natural gas without CCS (4 percent), industrial CHP (5 percent), and geothermal (1 percent). See Exhibit D-4.

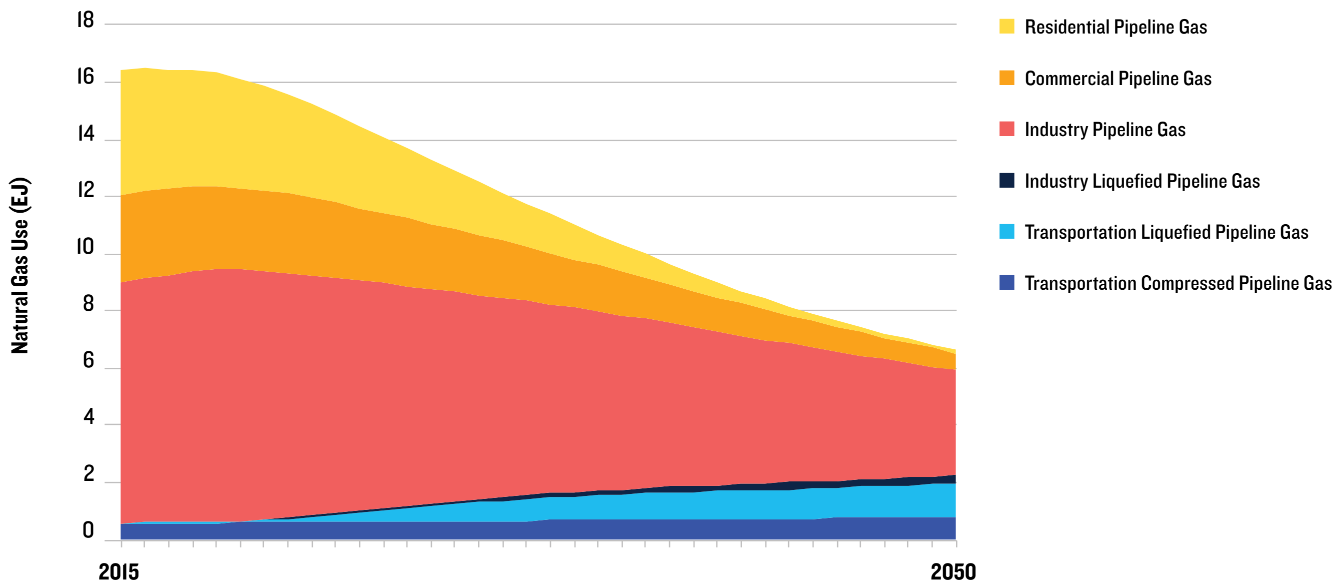
EXHIBIT D-4: THE TREND AND CHANGING SOURCE MIX OF ELECTRICITY FROM 2015 TO 2050, IN THE NRDC CORE SCENARIO



Electricity is shown in terawatt-hours (TWh). 1 TWh is equivalent to the electricity produced from burning around 125,000 pounds of coal, or enough to meet the annual electricity needs of 96,000 households (2014 data). 1 exajoule (EJ) = 277.8 TWh.

Natural gas supply: In terms of energy supply, most of the natural gas used in 2050 would be extracted gas (gas that is drawn out of the earth). Power-to-gas (not explicitly shown in the graphic below), where synthetic gas is produced using renewable electricity, supplies about 10 to 15 percent of the pipeline gas demand. Use of extracted gas could be reduced by two-thirds from current levels under certain conditions. See Exhibit D-5.

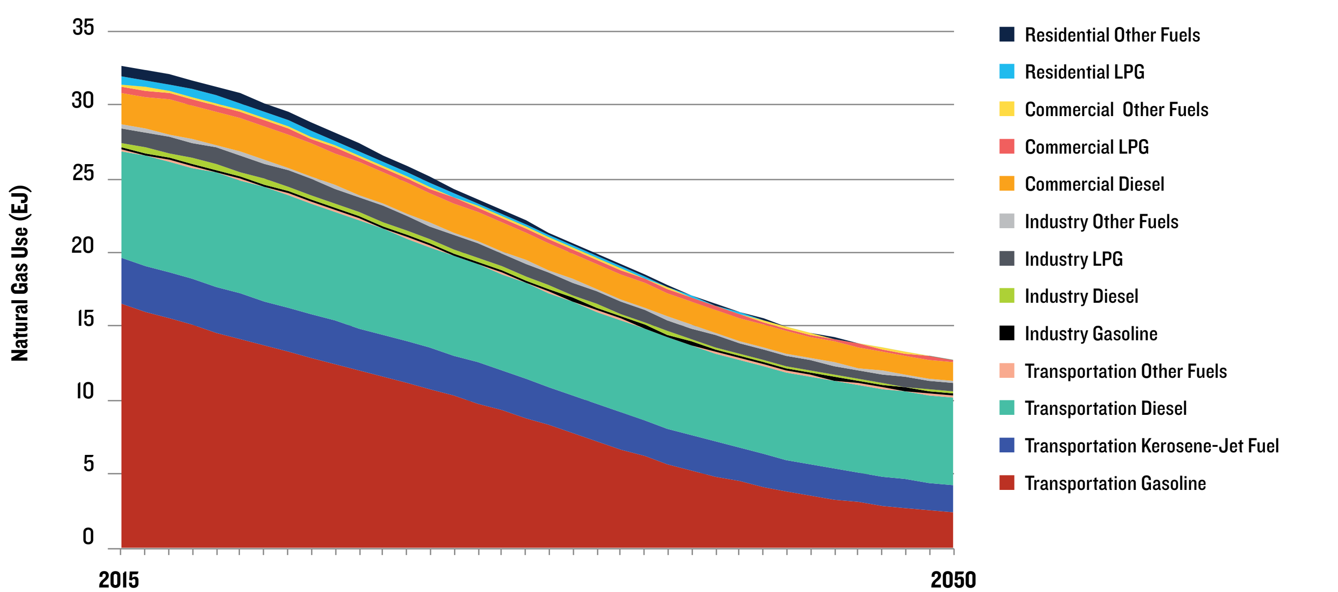
EXHIBIT D-5: THE TREND AND CHANGING SOURCE MIX OF NATURAL GAS FROM 2015 TO 2050, IN THE NRDC CORE SCENARIO



Natural gas use is show in exajoules (EJ). 1 EJ is equivalent to approximately 950 million MMBtu, or around 925 billion cubic feet of gas (2015 data).

Other liquid fuel supply: Liquid fuel use drops by nearly 60 percent and the supply composition changes, as can be seen in Exhibit D-6. Of this drop, VMT reduction contributes up to one-sixth, while fuel efficiency improvements (along with fuel switching) contribute about one-half and the electrification of LDVs contributes about one-third. Among the liquid fuels used, gasoline use drops most sharply, while other fuels see a more gradual decline in demand due to either increased utilization from fuel switching (e.g., diesel) or projected growth in sectoral energy use (e.g., aviation jet fuel).

EXHIBIT D-6: THE TREND AND CHANGING SOURCE MIX OF LIQUID FUELS FROM 2015 TO 2050 IN THE NRDC CORE SCENARIO



Energy cost: As shown in Exhibit D-7, the average annual U.S. energy-related cost over the 2015–2050 period in the Core Scenario is $1.755 trillion (2011$). This is about $22 billion higher—or just over 1 percent higher—than the average annual nominal cost of $1.733 trillion in the Reference Case. Both scenarios are substantially cheaper than the NRDC Delay/ Secondary Scenario and the DDPP Mixed Case.

In 2050, the total annual cost of energy (in 2011$) in the NRDC/DDPP Reference Case is approximately $2.4 trillion. The system-wide cost of energy in the Core Scenario is roughly $30 billion less (see Exhibit D-8). The Reference Case has higher fuel and variable costs, in sharp contrast to the NRDC Core Scenario, which has much lower overall fuel costs, stemming largely from much lower demand and higher reliance on renewable-powered electricity. In the NRDC Core Scenario (and to a lesser extent in the Delay Scenario), a significant portion of energy costs are driven by "efficient, electric, and fuel switched end-use stock costs." This category reflects the increased up-front costs of purchasing more efficient and/or electric appliances and vehicles (which yield energy and cost savings in later years). The NRDC Delay/ Secondary Scenario (as well as the DDPP Mixed Case) would cost about 10 to 15 percent more than the Reference Case in 2050 (about $300 billion more). Efficiency is a key driver of low overall costs in the 2050 and later time frame: even as the cost per unit of energy supply in the Core Scenario exceeds that in the Reference Case, lower overall demand results in net cost savings. On the other hand, our scenarios are quite sensitive to long-term gas prices, which are dependent on the cost of synthetic gas. In fact, just in the industrial sector, annual costs could swing by as much as $30 billion depending on the cost of gas. Research and development can play a big role in reducing the cost of advanced energy technologies. Cumulative energy costs from 2015 to 2050 are in Exhibit D-9.

Between 2027 and 2047, the Core Scenario has slightly higher costs (~$43 billion annually, on average, in incremental costs (2011$), or around 2.3 percent of average annual Reference Case energy spending for 2027–2047). This is due to increasing investments to modernize the nation's energy system and the deployment of clean energy resources and electric vehicles across the economy. Costs prior to 2027 in the Core Scenario are slightly lower than in the Reference Case, made possible by the availability of lower-cost efficiency measures with very short payback periods in the earliest years. Costs after 2047 are also lower than in the Reference Case, and the magnitude of this cost differential (i.e., relative cost reduction) can be expected to consistently increase post-2050, driven by markedly lower variable costs (e.g., fuel costs) and lower load growth in the NRDC Core Scenario. The lower costs in the earlier and later years reduce the average, incremental nominal cost of the NRDC Core Scenario between 2015 and 2050.

Again, it should be noted that the model does not optimize energy solutions based on costs, but rather calculates the cost of solutions required to meet the specified emissions reductions goals. In addition, the costs below are based on AEO estimates that likely overstate the cost of renewables and natural gas. It is reasonable to expect that the annual costs of each scenario would be lower.

EXHIBIT D-7: AVERAGE ANNUAL COSTS OF THE U.S. ENERGY SYSTEM, BY CATEGORY AND SCENARIO, IN 2011$ BILLIONS

	Average Annual Costs (2015–2050)			
Total Costs by Source (in 2011$ billions)	**NRDC/DDPP Reference Case**	**NRDC Core Scenario**	**NRDC Delay/ Secondary Scenario**	**DDPP Mixed Case**
Efficient, Electric, and Fuel-Switched End-Use Stock Costs	$ –	$301.26	$170.22	$228.80
Waste Heat	$0.59	$0.56	$0.56	$0.56
Hydrogen	$0.02	$2.34	$2.28	$104.68
Electricity	$708.23	$731.58	$832.73	$866.21
Natural Gas	$196.86	$177.28	$222.75	$235.09
Petroleum & Oil	$821.86	$537.98	$640.33	$472.70
Coal and Coke	$6.36	$4.51	$3.48	$3.43
Total Annual Average Costs (2015–2050)	**$1,733.92**	**$1,755.51**	**$1,872.35**	**$1,911.47**

EXHIBIT D-8: COST OF THE U.S. ENERGY SYSTEM IN 2050, BY CATEGORY AND SCENARIO, IN 2011$ BILLIONS				
	Costs in 2050			
Total Costs by Source (in 2011$ billions)	**NRDC/DDPP Reference Case**	**NRDC Core Scenario**	**NRDC Delay/ Secondary Scenario**	**DDPP Mixed Case**
Efficient, Electric, and Fuel-Switched End-Use Stock Costs	$ –	$680.68	$367.48	$470.50
Waste Heat	$1.22	$1.15	$1.15	$1.15
Hydrogen	$0.03	$4.55	$4.35	$251.25
Electricity	$928.93	$999.23	$1,265.84	$1,331.46
Natural Gas	$293.09	$261.13	$428.86	$384.91
Petroleum & Oil	$1,169.77	$420.54	$629.41	$255.73
Coal and Coke	$7.26	$2.47	$0.74	$0.65
Total Costs in 2050	**$2,400.30**	**$2,369.75**	**$2,697.83**	**$2,695.65**

EXHIBIT D-9: TOTAL CUMULATIVE COSTS OF THE U.S. ENERGY SYSTEM FROM 2015 TO 2050, BY CATEGORY AND SCENARIO, IN 2011$ BILLIONS				
	Cumulative Costs (2015–2050)			
Total Costs by Source (in 2011$ billions)	**NRDC/DDPP Reference Case**	**NRDC Core Scenario**	**NRDC Delay/ Secondary Scenario**	**DDPP Mixed Case**
Efficient, Electric, and Fuel-Switched End-Use Stock Costs	$ –	$10,845.35	$6,127.79	$8,236.91
Waste Heat	$21.31	$20.13	$20.13	$20.13
Hydrogen	$0.54	$84.07	$82.03	$3,768.53
Electricity	$25,496.20	$26,336.95	$29,978.44	$31,183.68
Natural Gas	$7,086.80	$6,382.14	$8,019.09	$8,463.11
Petroleum & Oil	$29,587.01	$19,367.41	$23,051.74	$17,017.34
Coal and Coke	$229.08	$162.51	$125.28	$123.56
Total Cumulative Costs (2015–2050)	**$62,420.94**	**$63,198.56**	**$67,404.50**	**$68,813.26**

Electricity cost: A direct and simplistic comparison of electricity rates and costs between the Reference Case and the Core Scenario has its limits, as the role that electricity plays in these two scenarios is vastly different, emblematic of the paradigm shift discussed earlier. Nonetheless, a comparison is helpful. Electric rates are governed largely by fuel costs and necessary capital investments. Their mix is very different between the two scenarios: in the Reference Case, both fixed and variable conventional generation costs are higher; the Core Scenario has lower fuel and distribution costs but higher fixed and transmission costs (see Exhibit D-10). Core Scenario transmission costs are around $925 billion higher compared with the Reference Case between 2015 and 2050 (annual incremental cost of $25 billion), due to increased spending to connect and integrate renewables, though this is offset by distribution cost savings of $660 billion (annual incremental savings of $18 billion). Distribution costs are lower in the NRDC Core Scenario due to assumptions of wide-scale changes and programs that better moderate and/or lower load across the day at the local, substation level. This includes measures that shift electricity consumption and expand the utilization of distributed storage, such as time-of-use pricing, electric vehicle batteries providing ancillary services, daylighting, and load control programs.

These factors result in the NRDC Core Scenario having electricity rates that are about 15–20 percent higher than in the NRDC/DDPP Reference Case. For a breakdown of electric rates by category (e.g., variable, fixed fossil and fixed renewable generation, transmission, and distribution) see Exhibits D-11 and D-12. However, while electricity rates do increase, lower demand results in lower overall cost and consumer spending of about 6 percent off a base of roughly $900 billion in the residential, commercial, and industrial sectors. The electricity costs in the transportation sector are notably higher due to widespread electrification of vehicles, but the overall energy cost is lower due to avoided petroleum use.

EXHIBIT D-10: TOTAL ELECTRICITY SPENDING, BROKEN DOWN BY CATEGORY, FROM A CUMULATIVE AND AVERAGE ANNUAL PERSPECTIVE				
	Cumulative Costs (2015–2050)		**Annual Average Costs (2015–2050)**	
Total Electricity-Related Costs by Source (in 2011$ billions)	**NRDC/DDPP Reference Case**	**NRDC Core Scenario**	**NRDC/DDPP Reference Case**	**NRDC Core Scenario**
Transmission Costs	$2,329.30	$3,255.44	$64.70	$90.43
Distribution Costs	$5,456.31	$4,796.27	$151.56	$133.23
Fossil Generator Costs (Fixed and Variable)	$13,696.91	$7,904.93	$380.47	$219.58
Renewable Generator Costs	$2,476.31	$7,976.78	$68.79	$221.58
Other Costs	$1,537.37	$2,403.53	$42.71	$66.76
Total Costs	**$25,496.20**	**$26,336.95**	**$708.23**	**$731.58**

EXHIBIT D-11: BREAKDOWN OF ELECTRICITY RATES BY COMPONENT, IN 2050				
	In 2050			
Breakdown of Electric Rates ($/kWh)	**NRDC/DDPP Reference Case**	**NRDC Core Scenario**	**NRDC Delay/ Secondary Scenario**	**DDPP Mixed Case**
CHP	$0.0018	$0.0017	$0.0012	$0.0011
Conventional Generator Fixed	$0.0444	$0.0242	$0.0290	$0.0525
Distribution	$0.0388	$0.0347	$0.0306	$0.0289
Energy Storage	$0.0008	$0.0064	$0.0045	$0.0020
Generator Variable and Fuel	$0.0415	$0.0130	$0.0276	$0.0184
Other	$0.0023	$0.0022	$0.0017	$0.0016
Renewable Generator Fixed	$0.0259	$0.0969	$0.0743	$0.0668
Transmission	$0.0158	$0.0222	$0.0203	$0.0180
Total	**$0.1713**	**$0.2013**	**$0.1892**	**$0.1893**

EXHIBIT D-12: BREAKDOWN OF ELECTRICITY RATES BY COMPONENT, AVERAGE ACROSS MODELING PERIOD				
	Average for 2015–2050			
Breakdown of Electric Rates ($/kWh)	**NRDC/DDPP Reference Case**	**NRDC Core Scenario**	**NRDC Delay/ Secondary Scenario**	**DDPP Mixed Case**
CHP	$0.0010	$0.0009	$0.0008	$0.0007
Conventional Generator Fixed	$0.0511	$0.0366	$0.0382	$0.0481
Distribution	$0.0359	$0.0340	$0.0328	$0.0314
Energy Storage	$0.0009	$0.0036	$0.0029	$0.0025
Generator Variable and Fuel	$0.0318	$0.0187	$0.0247	$0.0215
Other	$0.0015	$0.0014	$0.0013	$0.0012
Renewable Generator Fixed	$0.0161	$0.0517	$0.0433	$0.0387
Transmission	$0.0158	$0.0222	$0.0203	$0.0180
Total	**$0.1541**	**$0.1691**	**$0.1643**	**$0.1621**

Appendix E: 2030 Emissions Reduction Breakdown by Driver and Sector

EXHIBIT E-1: SUMMARY OF CO_2E EMISSIONS REDUCTIONS IN 2030 BY CLEAN ENERGY DRIVER AND SECTOR

DRIVER OF EMISSIONS REDUCTIONS		SECTOR: Residential	Commercial	Industrial	Transportation	Total MMT CO_2e reduced by driver (compared w. Reference Case)
1. Energy efficiency (technologies and system-wide efficiency)	More-efficient appliances and lighting, building shells, factories, and vehicles, including behavioral changes	283	200	92	157	732 (36.9%)
	Reduced vehicle miles traveled (light-duty vehicle fleet only)	–	–	–	85	85 (4.3%)
2. Cleaner grid	Widespread renewables	219	253	244	12	728 (36.7%)
	CCS with natural gas–fired and coal-fired generation	20	24	22	3	69 (3.5%)
3. Electrification of end uses	Electrification of buildings, transport (light-duty vehicles, rail, and some medium-duty vehicles), and industry	68	30	12	91	201 (10.1%)
4. Decarbonization of some remaining fuel use	Production of biodiesel and biogas	-	-	17	116	133 (6.7%)
	Fuel switching in industry and transport (freight and some medium-duty vehicles)	-	-	3	13	16 (0.8%)
	Production of synthetic gas (power-to-gas) and hydrogen	~0	~0	~0	3	3 (0.2%)
	CCS on industrial processes	–	–	19	–	19 (1.0%)
Total MMT CO_2e reduced by sector (compared with Reference Case)		**590 (29.7%)**	**507 (25.5%)**	**409 (20.6%)**	**480 (24.1%)**	**1,986**

The emissions reductions are in millions of metric tons of CO_2 equivalent, as compared with the Reference Case. The post-modeling analysis was undertaken separately by NRDC on the basis of E3 model outputs.

Appendix F: Comparison with Other Scenarios

The finding that substantial emissions reduction is possible has been made by a number of other analyses and reports. However, the approaches do differ. In this section, we compare two of these analyses with ours to illustrate the similarities and the main differences.[46]

COMPARISON WITH THE DDPP MIXED CASE SCENARIO

The work by researchers of the Deep Decarbonization Pathways Project (DDPP) to determine credible pathways to an 80 percent emission reduction by 2050 in the United States also used the E3 model.[47] The main policy scenario that we refer to in the DDPP report is the DDPP Mixed Case. NRDC relied on the same modeling and baseline assumptions as the DDPP Mixed Case to allow comparison between the two scenarios. While the Reference Case is the same for the two, the policy cases offer two distinct pathways to achieve the emissions reductions required.

A comprehensive set of the assumptions and outputs present in the NRDC Core Scenario and the DDPP Mixed Case is presented in Exhibit F-1, along with a tabulation of the similarities and differences.

Both scenarios achieve 80 percent GHG emissions reductions by 2050, with the four main strategies for achieving these emissions reductions represented by energy efficiency, renewables, decarbonization of end uses, and decarbonization of other energy supply. For instance, both the DDPP and NRDC scenarios are similar in areas like renewable build-out (though they use different penetration levels of renewable generation), deployment of commercial and residential building electrification, near-universal LED lighting by 2050, and similar fuel efficiency for the passenger vehicle fleet in 2050. However, there are notable differences as well in the importance and role of the clean energy resources.

Simply put, the DDPP Mixed Case relies more heavily on a mix of supply-side energy resources and more expensive and risky technologies, or ones currently deployed at a smaller scale, including nuclear, bioenergy and fuels, synthetic fuels, and CCS. NRDC's Core Scenario, on the other hand, relies much more on energy efficiency, and there are other differences as well. Consequently, while efficiency is the greatest contributor to emissions reductions in the Core Scenario, it is a much smaller contributor in the DDPP Mixed Case. Instead, a significant majority of emissions reductions in the DDPP Mixed Case come from renewable electricity and bio-derived and synthetically derived fuels. Due to the reduced role of energy efficiency, the DDPP Mixed Case sees substantially larger total electricity generation and electricity use than does the Core Scenario, requiring substantial investments in CCS and nuclear on top of renewable capacity (which is comparable to that in the Core Scenario). The reliance on decarbonization strategies, rather than strategies centered on efficiency, also results in the DDPP Mixed Case coming in at a higher cost than either the Core Scenario or the Reference Case.

NRDC is confident that the Core Scenario's higher assumed levels of energy efficiency are technically feasible. However, achieving these required levels will take substantial effort and a more proactive, purposeful, and steadfast policy environment than what we have seen historically.

Given the importance of energy efficiency in our pathway, a focused discussion of the underpinning rationale is warranted (see also Section 2.1). When crafting building shell assumptions, NRDC relied primarily on the ACEEE report *The Long-Term Energy Efficiency Potential: What the Evidence Suggests*.[48] This report modeled various scenarios, including an Advanced scenario and a Phoenix scenario. These scenarios found that a 70 percent or 90 percent savings in heating and cooling needs could be achieved in new building shells by 2050. For our Core Scenario we selected 70 percent savings, assuming that each year, new building shells would reduce heating and cooling needs by 5 percent compared with shells available the previous year, achieving a 70 percent efficiency improvement via shells in 2037 and holding those savings constant through 2050. For existing buildings, the ACEEE study estimated that they could realize a 40–60 percent improvement in building shells by 2050 through retrofits and other measures. NRDC more conservatively assumed that the existing building stock would see a 30 percent reduction in heating and cooling needs by 2050 via shell improvements.

While both the NRDC Core Scenario and the DDPP Mixed Case assume near-universal adoption of LED lighting by 2050 (with no early lighting replacement), NRDC assumes reductions from lighting controls and daylighting double those of DDPP. In aggregate, this assumption does not have a substantial impact on emissions or energy in 2050 due to universal LED lighting in both cases; lighting represents 5 percent of building energy demand in the Core Scenario compared with 6 percent in the DDPP Mixed Case.

In addition, NRDC assumes much more aggressive industrial energy efficiency than does the DDPP Mixed Case. The latter assumes a 1.1 percent annual reduction in industrial energy intensity from 2015 to 2050. NRDC's scenario adopts a more nuanced trajectory based on observed successes and other estimates. In the Core Scenario, the industrial sector achieves a 3 percent annual reduction in energy intensity in the first decade, falling to a 2.5 percent annual reduction in the second decade, and then falling to 2 percent, 1.5 percent, and 1 percent annual reductions in the subsequent three remaining half-decades. Examples of significant progress in line with these assumptions by companies around the country are described in Section 2.1 of the main paper.

It may also be noted that non-CO_2 emissions reductions are higher in the Core Scenario than in the DDPP Mixed Case.

EXHIBIT F-1: COMPARISON OF ASSUMPTIONS AND RESULTS FOR THE NRDC CORE SCENARIO AND DDPP MIXED CASE

NRDC Core Scenario	DDPP Mixed Case
Similarities	
3 main drivers: energy efficiency, decarbonizing fuels, switching to low-carbon energy sources (e.g., clean electricity)	Similar in principle, but lesser reliance on efficiency and more on other drivers
Achieves 80 percent GHG reduction by 2050	Achieves 80 percent GHG reduction by 2050
Renewables in 2050: solar 515 GW, wind 905 GW	Renewables in 2050: Solar 505 GW, wind 975 GW
Transportation: 2050 CO_2e emissions of ~500 MMT	Transportation: 2050 CO_2e emissions of ~500 MMT
2050 CCS (carbon capture and storage): 500 MMT CO_2e sequestered; no coal with CCS	2050 CCS: 500 MMT CO_2e sequestered; no coal with CCS
Near-universal deployment of electric HVAC & water heating in buildings; wide deployment of electric cooking	Near-universal deployment of electric HVAC & water heating in buildings; wide deployment of electric cooking
Universal adoption of LED lighting	Near-universal adoption of LED lighting
60 percent of steel production uses direct reductions in an electric arc furnace	Direct reductions in iron and steel industry
Average light-duty vehicle (LDV) fleet miles per gallon of gasoline equivalent of around 100	Average LDV fleet miles per gallon of gasoline equivalent of around 100
Differences	
Achieves 2050 CO_2 emissions of 1,000 MMT	Achieves 2050 CO_2 emissions of ~800 MMT
Achieves non-CO_2 reductions of 306 MMT CO_2e (below 1990)	Achieves non-CO_2 reductions of 133 MMT CO_2e (below 1990)
Slightly cheaper than the Reference Case in 2050 (~–$30B in 2050) and about 1 percent more expensive from 2015–2050.	More expensive than the Reference Case by ~$300B in 2050 and about 10–15 percent more expensive from 2015–2050.
Industrial: ~33 percent reduction in energy demand from the Reference Case	Industry: ~15 percent reduction in energy demand from the Reference Case
Residential + commercial sectors: 60 percent reduction in energy demand from the Reference Case	Residential + commercial Sectors: <40 percent reduction in energy demand from the Reference Case
Nuclear decreases to 20 GW in 2050	Nuclear increases to 294 GW in 2050
Overall electricity generation increases by one-quarter by 2050 from 2015 levels; end-use electricity increases by 20 percent	Overall electricity generation doubles by 2050 from 2015 levels; end-use electricity increases by 70 percent
Has 77 GW natural gas w/CCS in 2050	Has 370 GW gas w/CCS in 2050
430 million (dry) tons of sustainable biomass* (for fuels); biomass mainly used to produce biodiesel	1 billion (dry) tons of sustainable biomass* (for fuels); biomass mainly used to produce biogas
CCS on all biofuel production.	No CCS on biofuel production
CCS on select industrial processes (captures 32 MMT in 2050)	No CCS on industrial processes
Light-duty vehicles (LDVs): mainly electric vehicles (EVs) and plug-in hybrids (PHEVs) (together >75 percent sales in 2050).	LDVs: ~one-third each EVs, PHEVs, and hydrogen fuel-cell vehicles
Heavy-duty vehicles (HDVs): mainly biodiesel + LNG vehicles (80 percent of HDV VMT from blended (bio) diesel, 20 percent from LNG, in 2050)	HDVs: mainly biodiesel + LNG + hydrogen vehicles (40 percent HDV VMT from biodiesel, 40 percent of VMT from LNG, 20 percent of VMT from hydrogen, in 2050)
Rail and medium-duty vehicles (MDVs): primarily electrification	Rail and MDVs: primarily fuel switching to natural gas

* "Sustainable biomass" in this context refers to biomass associated with truly net-zero carbon over its entire life cycle.

COMPARISON WITH THE U.S. MID-CENTURY STRATEGY REPORT

As part of the United Nations Framework Convention on Climate Change's (UNFCCC) 22nd Conference of Parties (COP22) in Marrakesh, the White House released a new report, *United States Mid-Century Strategy for Deep Decarbonization* (hereafter referred to as MCS) in November 2016.[49] This report details multiple possible pathways to an 80 percent GHG emissions reduction by 2050, including a primary case (MCS Benchmark) and sensitivities on that case that assume various limitations on carbon dioxide removal technologies, carbon capture technologies, biomass supplies, and the availability of terrestrial carbon sinks. MCS also considers a Smart Growth case that highlights the potential of improved transportation and urban planning, as well as enhanced efficiency measures. In addition to these 80 percent scenarios, the MCS also studied one case that achieved reductions beyond 80 percent.

MODELING DIFFERENCES

Unlike the DDPP or NRDC scenarios, MCS relies on a different model, as well as updated cost, performance, and macroeconomic forecasts. The MCS analysis uses GCAM-USA (Global Change Assessment Model), which is not a stock-rollover model, like PATHWAYS, but instead is a dynamic recursive model. This means that GCAM optimizes the consumption of each energy source and the investments and retirements of energy technology (e.g., energy capacity, appliances, vehicles, etc.) based on cost and technology assumptions. However, GCAM optimizes only within a single, given period, and only after solving for each period does it proceed to the next one. Therefore, GCAM does not optimize decisions over the full duration of the scenario considered. It can make decisions that "seem like a good idea at the time," but these may not be optimal in the long run and are choices that might not have been made if the model knew what future costs or emissions limits looked like. Such an approach is nonetheless useful as it may actually mirror real-world decision-making processes.

In addition to MCS using a different model, both the target and reference cases vary from E3's. First, MCS achieves less emissions reductions (both carbon dioxide and non-carbon dioxide). MCS achieves an 80 percent reduction from 2005 levels, not from 1990 levels, by 2050. In terms of 1990 levels, MCS achieves only a 75 percent reduction in GHG emissions. MCS also assumes larger carbon sinks and use of carbon-removal technology, resulting in carbon dioxide emissions only declining to 1,530 MMT—50 percent higher than NRDC's scenarios in 2050. Total net emissions are around 35 percent higher than either the DDPP Mixed Case or NRDC Core Scenario in 2050. This is important to remember, as the differences in stringency and ambition between the two cases can make attempts to compare them hard or misleading.

MCS also reflects more recent data and forecasts from the AEO 2015 High Oil and Gas Resource Case, including revisions to reflect implementation of the EPA's Clean Power Plan, renewable tax credit extensions passed in 2015, and updated solar and wind cost and performance estimates. In the MCS scenarios, energy technology cost and performance values are revised to reflect the target costs and performance metrics of the DOE's various energy programs (e.g., including programs aimed at lowering the costs of solar, such as SunShot, and next-generation nuclear R&D). The Beyond 80 policy case assumes further cost reductions and performance improvements in line with more aggressive and additional research and development, as well as deployment investments beyond current programs (e.g., DOE's Market Innovation).

DECARBONIZATION RESULTS

Despite different modeling methods, a few key points can still be drawn from comparisons between NRDC's modeling and MCS.

Stemming primarily from lower energy efficiency levels, the MCS scenario's total energy demand is almost identical to that of the DDPP Mixed Case, which is about one-third higher than Core Scenario levels. The MCS case relies more heavily on gas and oil (with and without CCS) than either the NRDC or DDPP scenarios to meet economy-wide demand, due largely to lower gas-price expectations. MCS also assumes lower CCS costs than E3, which results in a thirtyfold increase in electricity generation from coal with CCS compared with the Core Scenario. The increase in both coal and gas utilization results in lower utilization of biomass, wind (especially offshore), and nuclear (compared with DDPP, which has the same total demand). Even so, MCS's nuclear and biomass levels are still higher than NRDC's. However, wind is about 30 percent less in the MCS case than in the Core Scenario in terms of power generation.

Due in part to modeling platform differences, as well as lower gas prices and natural gas heating technology assumptions, the MCS analysis has little electrification of buildings.[50] Due to this, buildings have both higher total energy and natural gas consumption in MCS than in the DDPP or NRDC scenarios, with one-fourth of all building energy demand met by gas or oil (versus just 8 percent in the DDPP Mixed Case and 11 percent in the NRDC Core Scenario). Transportation energy use is also higher in the MCS case, due to lower fuel economy assumptions than in either of the other cases. Both these results highlight the important contribution that electrification of buildings and vehicles, along with fuel economy, makes in rapidly constricting energy consumption and emissions in these sectors.

MCS does envision more electrification in the transportation and industrial sector than either the NRDC Core Scenario or the DDPP Mixed Case, however. In the MCS benchmark case almost 55 percent of all energy needs are met with electricity. In the NRDC Core Scenario, electricity serves only one-third of total industrial demand. NRDC made conservative assumptions about the number of industries and industrial processes that could be electrified, and thus we relied more heavily on fuel switching to reduce emissions from industrial consumption. MCS sees a greater and broader potential for electrification in industry, which indicates that there may be cleaner and more cost-effective electrification opportunities available to the industrial sector than NRDC assumed.

Likewise, in MCS, one-quarter of all transportation needs are met with either electricity or hydrogen. In the NRDC scenario, this figure is only 14 percent. The higher MCS figure is driven in part by more aggressive assumptions about both electrification and fuel-cell adoption in trucking as well as achievable VMT reductions in the medium- and heavy-duty vehicle sector.

ENDNOTES

1 Williams, J.H., B. Haley, and R. Jones. *Policy Implications of Deep Decarbonization in the United States*. E3, Deep Decarbonization Pathways Project, November 17, 2015.

2 Full National Energy Modeling System documentation can be found at EIA, "NEMS documentation," https://www.eia.gov/forecasts/aeo/nems/documentation/ (accessed June 20, 2017).

3 DeCarolis et al. define energy economy optimization models as follows: "Optimize consumption and/or energy supply over time in order to minimize the system-wide cost of energy or maximize social utility, subject to constraints representing physical limitations and public policy." DeCarolis, J.F., Hunter, K., and Sreepathi, S., "The Case for Repeatable Analysis with Energy Economy Optimization Models," *Energy Economics* 34, no. 6 (2012): 1845-1853.

4 As such, the pace and scale of deployment of clean energy measures are not based on a cost-minimization algorithm. They are guided by the need to achieve emissions reductions targets.

5 Williams, J.H., et al. *Pathways to Deep Decarbonization*. E3, Deep Decarbonization Pathways Project, November 2014.

6 Williams, Haley, and Jones. *Policy Implications of Deep Decarbonization in the United States*. November 17, 2015.

7 A scenario is a combination of inputs whose results meet the desired 80 percent emissions reduction target by 2050. A sensitivity does not necessarily meet this target, but isolates the effect of varying one key input parameter.

8 In the transportation sector, the NRDC Delay/Secondary Scenario's assumptions halved the VMT reductions, electric-vehicle penetration, and fuel efficiency for LDVs and HDVs, as compared with the Core Scenario.

9 NRDC referred to several sources that informed our efficiency factors, a few of which are provided as examples. Energy-efficient electric vehicles convert about 59–62 percent of the electrical energy from the grid to power at the wheels, while conventional gasoline vehicles convert only about 17–21 percent of the energy stored in gasoline to power at the wheels. For more references (under "View Data Sources") see DOE, "All-Electric Vehicles," http://www.fueleconomy.gov/feg/evtech.shtml (accessed June 20, 2017). For electric space heating, see Nadel, Steven. "Comparative Energy Use of Residential Furnaces and Heat Pumps." American Council for an Energy-Efficient Economy (hereinafter ACEEE). May 4, 2016. http://aceee.org/comparative-energy-use-residential-furnaces-and. Heat pump water heaters are 2.5 to 3 times more efficient than electric resistance or natural gas water heaters. Delforge, Pierre. "NRDC/Ecotope Heat Pump Water Heater Performance Data." NRDC. November 30, 2016. https://www.nrdc.org/resources/nrdc-ecotope-heat-pump-water-heater-performance-data.

10 A good, detailed methodology of similar model architecture is available in the NEMS "Technology Choice Component" section of the *Residential Demand Module of the National Energy Modeling System: Model Documentation 2014*. U.S. Energy Information Administration (hereinafter EIA). August 2014. https://www.eia.gov/forecasts/aeo/nems/documentation/residential/pdf/m067(2014).pdf. See pg. 13 for the beginning of the "Technology-specific modeling assumptions" discussion.

11 NRDC did account for differences in gasoline vehicle stock between the two cases. NRDC determined annual gasoline-fueled miles driven per gasoline vehicle for each case to calculate the VMT reduction by fuel source. This process was also done for other fuels, such as diesel and compressed natural gas.

12 Review of historic efficiency standards have found that several appliances have maintained or exceed this pace of improvement. This includes: refrigerators, clothes washers, dishwashers, residential AC and heat pumps, as well as televisions. Mauer, J., et. al. "Better Appliances: An Analysis of Performance, Features, And Price as Efficiency Has Improved." May 2013, https://appliance-standards.org/sites/default/files/Better_Appliances_Report.pdf.

13 DeLaski, A., et. al. "Next Generation Standards: How the National Energy Efficiency Standards Program Can Continue to Drive Energy, Economic, and Environmental Benefits," ACEEE, August 2016. http://www.eenews.net/assets/2016/08/04/document_pm_01.pdf.

14 Laitner, J.A., et al. *The Long-Term Energy Efficiency Potential: What the Evidence Suggests*. ACEEE Research Report E121. January 11, 2012. http://aceee.org/research-report/e121.

15 Ibid.

16 Williams, J.H., et al. *Pathways to Deep Decarbonization*. November 2014.

17 Early innovative dynamic and demand reducing residential programs have been able to successfully reduce customer peak demand by 20 to 50 percent. See Rocky Mountain Institute, "The Economics of Demand Flexibility," August 2015. https://www.rmi.org/wp-content/uploads/2017/03/RMI-TheEconomicsofDemandFlexibilityFullReport.pdf.

18 Lawrence Berkeley National Laboratory, "Integration with Daylighting Controls," https://facades.lbl.gov/integration-daylighting-controls (accessed June 20, 2017).

19 Initial research indicates that implementing the full suite of available daylight strategies have the potential to reduce energy use associated with U.S. commercial electric lighting demand by as much as 930 TBtu. or around 272.5 TWh of electricity annually. Lawrence Berkeley National Laboratory, "Building Façade Solutions: Daylighting Systems," https://facades.lbl.gov/daylighting-systems (accessed June 20, 2017).

20 Ehrhardt-Martinez, K., "Moving from the Laundry List to the Short List: Using Behavioral Approaches to Cut Electricity Consumption in Commercial Buildings", Presentation at Behavior, Energy, and Climate Change Conference, December 2014.

21 Therkelsen, Peter, et al. "Assessing the Costs and Benefits of the Superior Energy Performance Program." In *ACEEE Summer Study on Energy Efficiency in Industry,* 2013.

22 Williams, J.H., et al. *Pathways to Deep Decarbonization*. E3, Deep Decarbonization Pathways Project, November 2014.

23 The VMT Low Case assumptions are shown in Table 1.1. EIA, Annual Energy Outlook 2014. https://www.eia.gov/outlooks/aeo/assumptions/pdf/0554(2014).pdf (accessed June 20, 2017).

24 National Research Council. *Transitions to alternative vehicles and fuels.* Washington, D.C. National Academies Press, 2013.

25 NREL. *Renewable Electricity Futures Study.* 2012. http://www.nrel.gov/docs/fy13osti/52409-ES.pdf.

President's Council of Economic Advisers. *Economic Benefits of Increasing Electric Grid Resilience to Weather Outages*. 2013. http://energy.gov/sites/prod/files/2013/08/f2/Grid%20Resiliency%20Report_FINAL.pdf.

26 Bloomberg New Energy Finance, "New Energy Outlook 2017: Americas," June 2017, https://about.bnef.com/new-energy-outlook/.

27 Williams, J.H., et al. *Pathways to Deep Decarbonization*. November 2014.

28 Ibid.

29 The White House. *United States Mid-Century Strategy for Deep Decarbonization*. November 2016. http://unfccc.int/files/focus/long-term_strategies/application/pdf/us_mid_century_strategy.pdf.

30 Ibid.

31 Williams, J.H., et al. *Pathways to Deep Decarbonization*. November 2014.

32 Ibid.

33 Union of Concerned Scientists (hereinafter UCS). "The Promise of Biomass: Clean Power and Fuel—If Handled Right." 2012. http://www.ucsusa.org/sites/default/files/legacy/assets/documents/clean_vehicles/Biomass-Resource-Assessment.pdf.

34 Williams, J.H., et al. *Pathways to Deep Decarbonization*. November 2014.

35 EIA. "U.S Energy Facts Explained," http://www.eia.gov/energyexplained/index.cfm?page=us_energy_home (accessed November 15, 2016).

36 Estimated from Williams, J.H., et al. *Pathways to Deep Decarbonization*. November 2014. See Section 9.

37 See Fern, "What are Carbon Sinks?," http://www.fern.org/campaign/forests-and-climate/what-are-carbon-sinks (accessed June 20, 2017).

38 U.S. EPA, "EPA's Actions to Reduce Methane Emissions from the Oil and Natural Gas Industry: Final Rules and Draft Information Collection Request," September 2016. https://www.epa.gov/sites/production/files/2016-09/documents/nsps-overview-fs.pdf (accessed June 20, 2017).

39 Davenport, C., "Nations, Fighting Powerful Refrigerant That Warms Planet, Reach Landmark Deal", *NY Times,* October 15, 2016. https://www.nytimes.com/2016/10/15/world/africa/kigali-deal-hfc-air-conditioners.html?_r=0.

40 For example, the midcentury strategy report found that the U.S. could add 45 million acres of forested lands by 2050. See The White House. *United States Mid-Century Strategy.*

41 Williams, J.H., et al. *Pathways to Deep Decarbonization*. E3, Deep Decarbonization Pathways Project, November 2014. See Section 9.

42 DOE, "Better Buildings Progress Report 2017," https://betterbuildingsinitiative.energy.gov/sites/default/files/attachments/Better_Buildings_Progress_Report_2017.pdf (accessed June 20, 2017).

43 Ibid.

44 Energy Trust of Oregon, "Impact Evaluation of Commercial Strategic Energy Management Final Report," October 2016. https://www.energytrust.org/wp-content/uploads/2017/03/FinalReport_EnergyTrust_CommSEM_ImpactEvaluation_wStaffResponse.pdf.

45 DOE, "Adoption of New Fuel-Efficient Technologies from SuperTruck: Report to Congress," June 2016, https://energy.gov/eere/vehicles/downloads/report-adoptionnew-fuel-efficient-technologies-supertruck.

46 Edenhofer, Ottmar, et al. "IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation." Prepared By Working Group III of the Intergovernmental Panel on Climate Change. Cambridge, U.K.: Cambridge University Press, 2011. Hoffert, Martin I., et al. "Advanced Technology Paths to Global Climate Stability: Energy for a Greenhouse Planet." *Science* 298.5595 (2002): 981-987. McCollum, David, and Christopher Yang. "Achieving Deep Reductions in US Transport Greenhouse Gas Emissions: Scenario Analysis and Policy Implications." *Energy Policy* 37, no.12 2009): 5580-5596. McCollum, David, et. al. "Deep Greenhouse Gas Reduction Scenarios for California—Strategic Implications from the CA-TIMES Energy-Economic Systems Model." *Energy Strategy Reviews* 1, no. 1 (2012): 19-32. Jenkins, Jesse, and Samuel Thernstrom. "Deep Decarbonization of the Electric Power Sector: Insights from Recent Literature." Energy Innovation Reform Project, 2017.

47 Williams, J.H., et al. *Pathways to Deep Decarbonization*. Revision with technical supplement, November 16, 2015.

48 Laitner, J.A., et al. *The Long-Term Energy Efficiency Potential.* January 11, 2012. http://aceee.org/research-report/e121.

49 The White House. *United States Mid-Century Strategy for Deep Decarbonization*. November 2016. http://unfccc.int/files/focus/long-term_strategies/application/pdf/us_mid_century_strategy.pdf.

50 The MCS uses an updated gas price forecast based on the AEO 2015 High Oil and Gas Resource Case, which envisions gas prices below $4.38/mmbtu through 2040. In comparison, AEO 2013, which was used as the baseline for E3 modeling, estimated gas prices would rise to $7.83/mmbtu by 2040. In addition, in the MCS modeling all natural gas heaters achieve levels in line with the highest efficiency models, which results in all remaining natural gas furnaces achieving the same efficiency as an electric furnace. MCS assumes electric furnaces have no changes to efficiency from its reference case.