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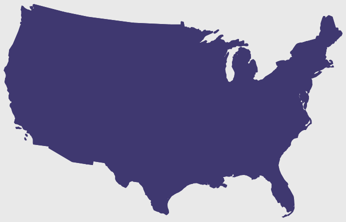
Technical Report
Executive Summary

pathways to deep decarbonization *in the United States*



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Pathways to Deep Decarbonization in the United States

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Principal Authors:

E3: Dr. James H. Williams, Benjamin Haley, Dr. Fredrich Kahrl, Jack Moore

LBNL: Dr. Andrew D. Jones, Dr. Margaret S. Torn

PNNL: Dr. Haewon McJeon

Contributing Authors:

Dr. Sam Borgeson, Jamil Farbes, Dr. Elaine Hart, Gabe Kwok, Ryan Jones, Amber Mahone, Katie Pickrell, Dr. Rich Plevin, Snuller Price, Dr. Alexandra von Meier

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Energy and Environmental Economics, Inc.
101 Montgomery Street, Suite 1600
San Francisco, CA 94104
415-391-5100
https://ethree.com/

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Energy and Environmental Economics, Inc. (E3)
Lawrence Berkeley National Laboratory
Pacific Northwest National Laboratory

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

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Preface

Deep Decarbonization Pathways Project

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

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

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

Research Team

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

Advisory Committee

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

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

Addendum to November 2015 Revision

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

Executive Summary

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

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

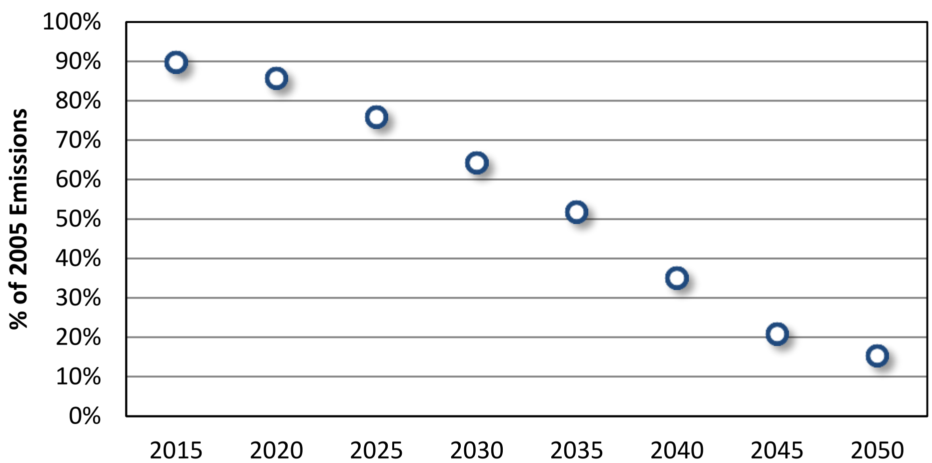
1. Is it technically feasible to reduce U.S. GHG emissions to 80% below 1990 levels by 2050, subject to realistic constraints?

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

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

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

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



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

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

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

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

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

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

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

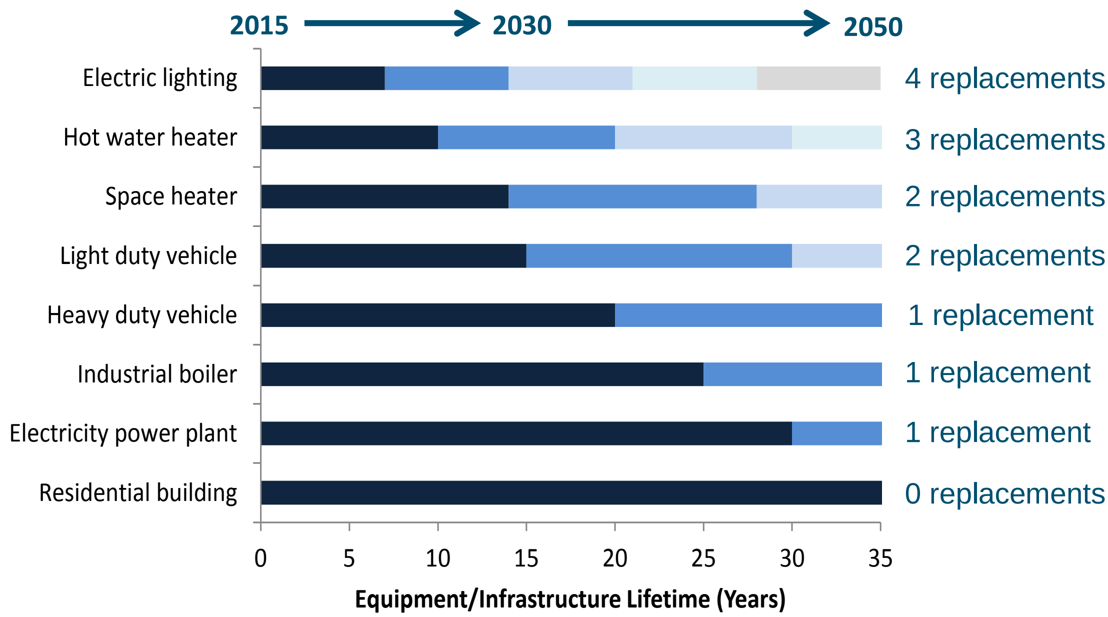
As a result, electricity generation would need to approximately double (an increase of 60-110% across scenarios) by 2050 while its carbon intensity is reduced to 3-10% of its current level. Concretely, this would require the deployment of roughly 2,500 gigawatts (GW) of wind and solar generation (30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

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

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

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

Figure ES 2. Stock Lifetimes and Replacement Opportunities



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

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

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

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

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

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