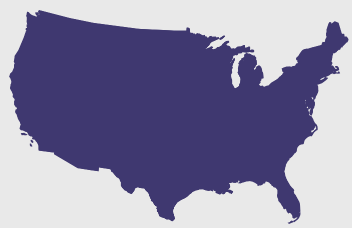
US 2050 Vol. 2
Policy Report

policy implications of **deep decarbonization** *in the United States*



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Policy Implications of Deep Decarbonization in the United States

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

November 2015

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Cite this report as:

Williams, J.H., B. Haley, R. Jones (2015). *Policy implications of deep decarbonization in the United States.* A report of the Deep Decarbonization Pathways Project of the Sustainable Development Solutions Network and the Institute for Sustainable Development and International Relations. Nov 17, 2015.

A PDF version of this report may be downloaded from these sites:

United States Deep Decarbonization Pathways Project
http://usddpp.org

or

Deep Decarbonization Pathways Project
http://deepdecarbonization.org

or

Energy and Environmental Economics, Inc.
https://ethree.com/publications/

Version: US_Policy_Report_2015Nov17

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US 2050 REPORT, VOLUME 2

Policy Implications of Deep Decarbonization in the United States

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

November 2015

Acknowledgments

The authors gratefully acknowledge Dr. Jeffrey Sachs and Guido Schmidt-Traub of the Sustainable Development Solutions Network (SDSN), and Dr. Daniel Lashof of NextGen Climate America, who provided financial support for the preparation of this report.

The authors wish to acknowledge helpful comments and suggestions from Dr. Margaret Torn, Dr. Andy Jones, Dr. Fritz Kahrl, Dr. Sam Borgeson, Dr. Ren Orans, and Amber Mahone. Thanks to Ivan Pharabod for his cover design for this document.

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

Preface

Deep Decarbonization Pathways Project

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

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

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

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

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Executive Summary

I. What is this report?

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

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

II. What is this report's intended contribution?

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

VI. What must policy accomplish to enable deep decarbonization?

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

X. What are the next steps for this research?

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

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

I. Introduction

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

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

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

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

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

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

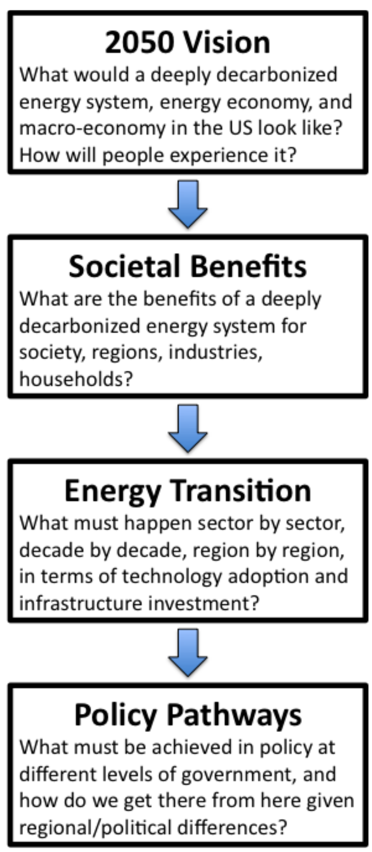
(1) **2050 vision**. This section describes key features of what deep decarbonization in the U.S. would look like from the physical energy system, energy economy, and macro-economy perspectives. It also describes how ordinary citizens might experience the changes in these areas.

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

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

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

Figure 1. Sections in This Report



II. 2050 Vision

Three Aspects of Deep Decarbonization

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

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

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

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

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

A. Deeply Decarbonized Energy System

Contrasting High and Low-Carbon Energy Systems

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

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

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

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

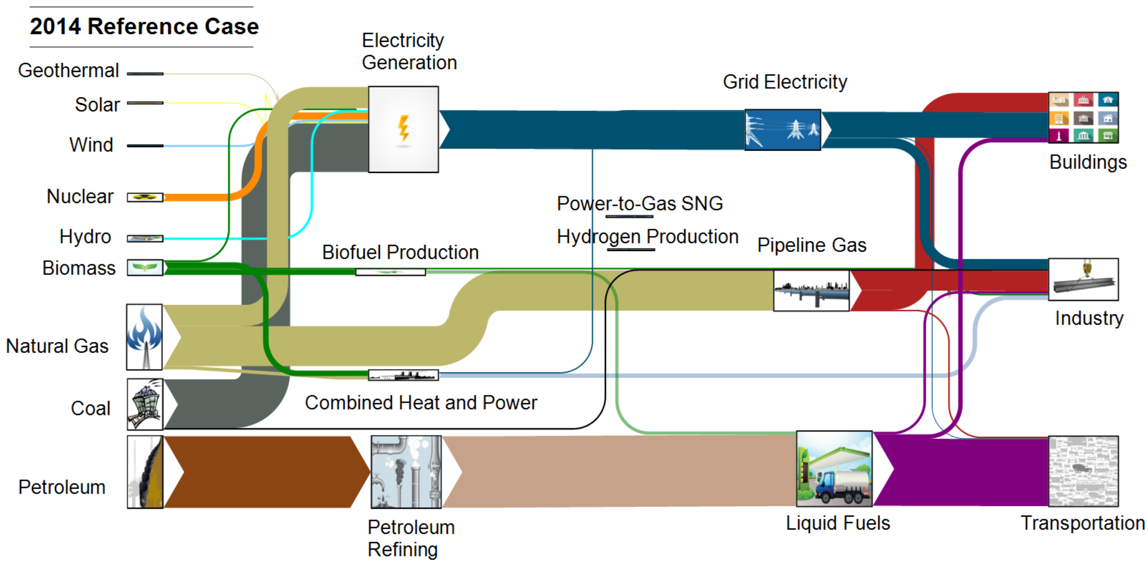
3. **Decarbonized forms of primary energy are dramatically increased,** as wind, solar, biomass, and nuclear become the dominant share of primary energy supply.

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

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

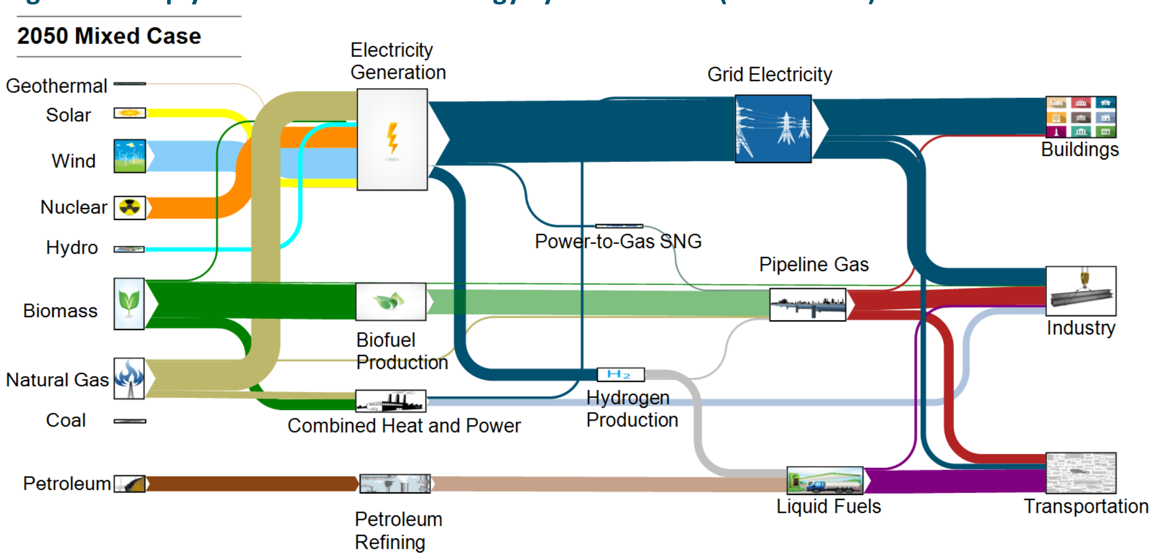
More detailed indicators of some key changes are shown in Figure 4 A-F.

Figure 2. U.S. Energy System in 2014



Source: (DOE, 2013)

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



Key Metrics of Deep Decarbonization

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

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

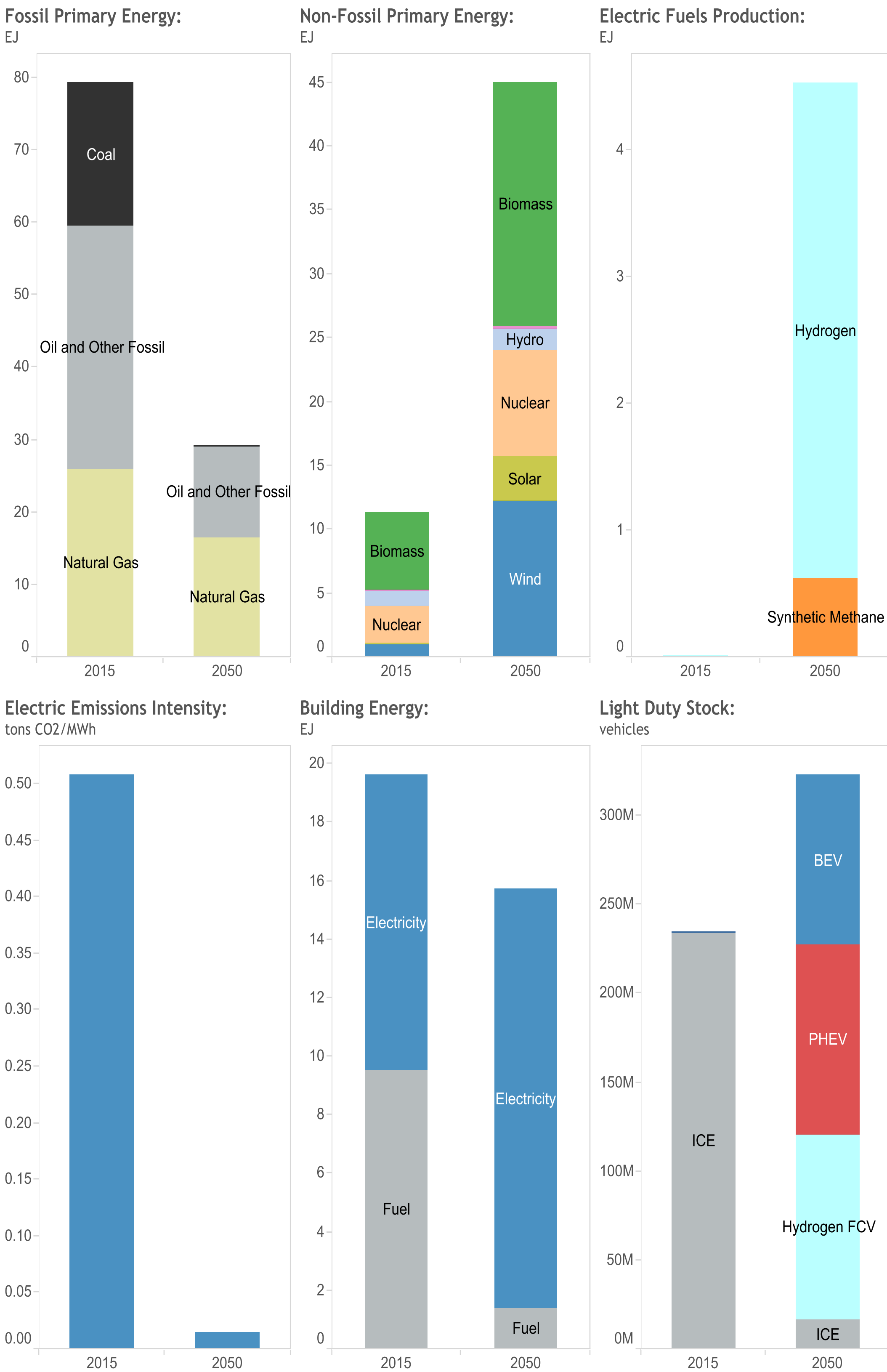
94% of light duty vehicles (LDV) are either battery electric, plug-in hybrid, or fuel cell vehicles. Overall, LDV stocks increase by a third by 2050, but LDVs with only conventional internal combustion engines and drive trains decrease to 6% of the total stock (Figure 4F).

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

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

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

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



A Decarbonized System Can Support Current Lifestyles

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

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

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

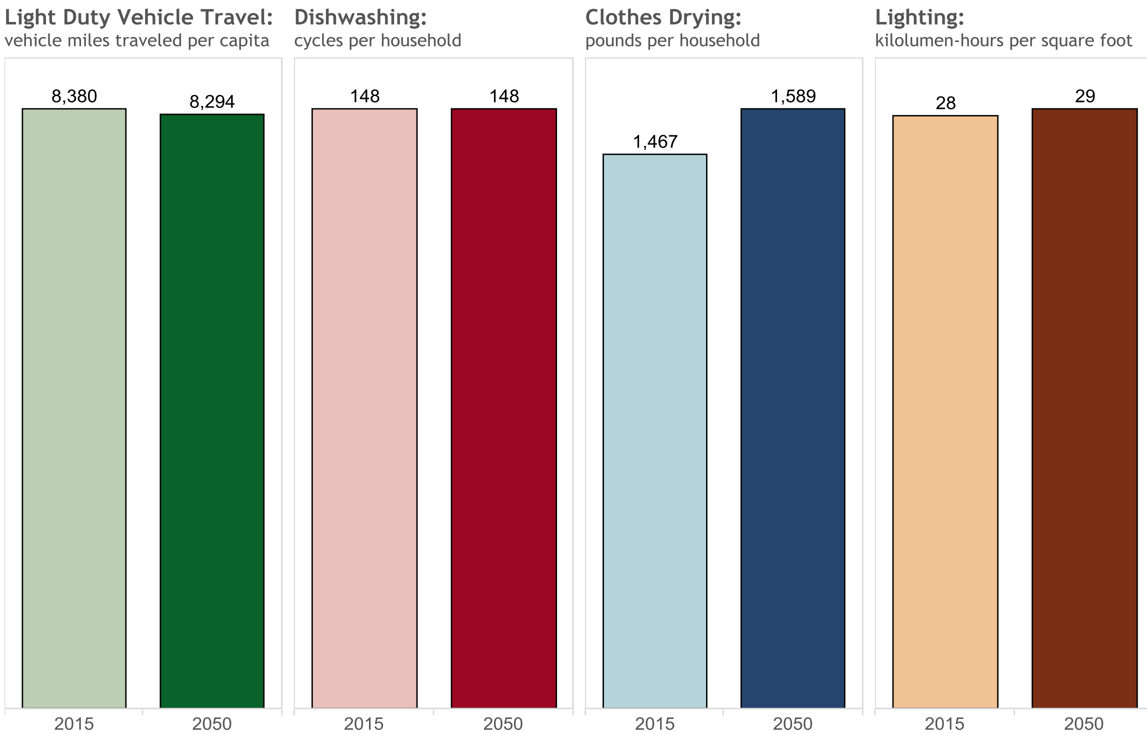
- **Residential lighting intensity increases slightly** (29 kilo-lumens per square foot of floor area). Overall lighting service demand increases, reflecting both an increase in intensity and an increase in floor area. The same is true for commercial lighting.

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

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

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

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



Source: (DOE, 2013)

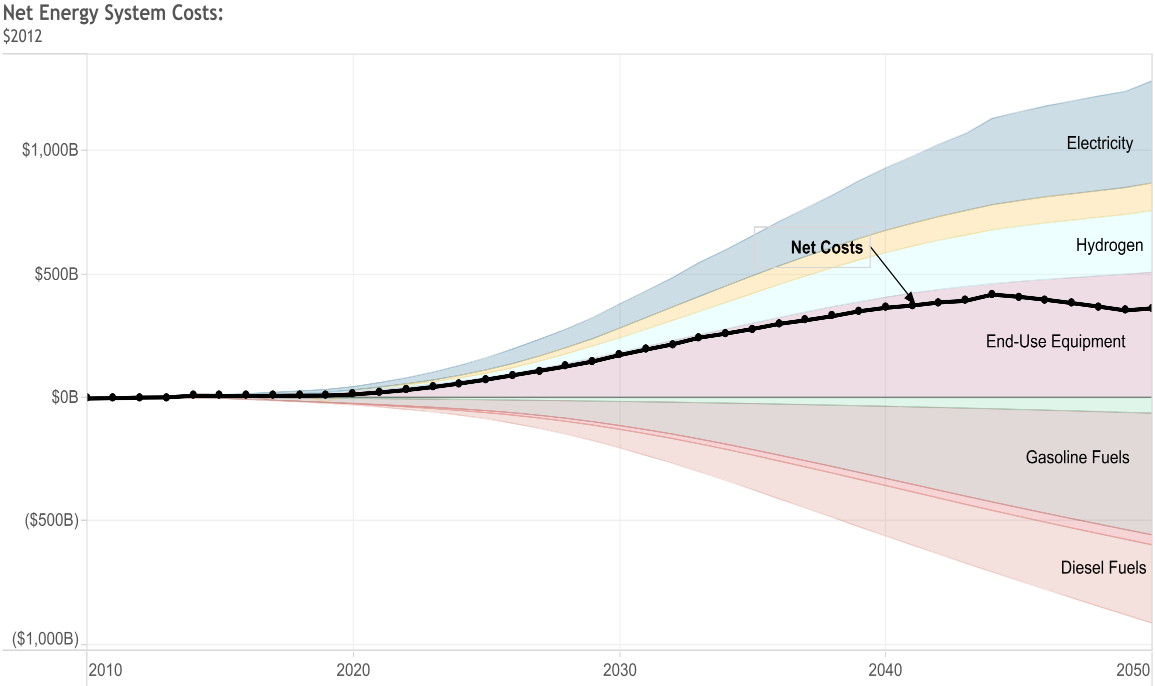
B. Deeply Decarbonized Energy Economy

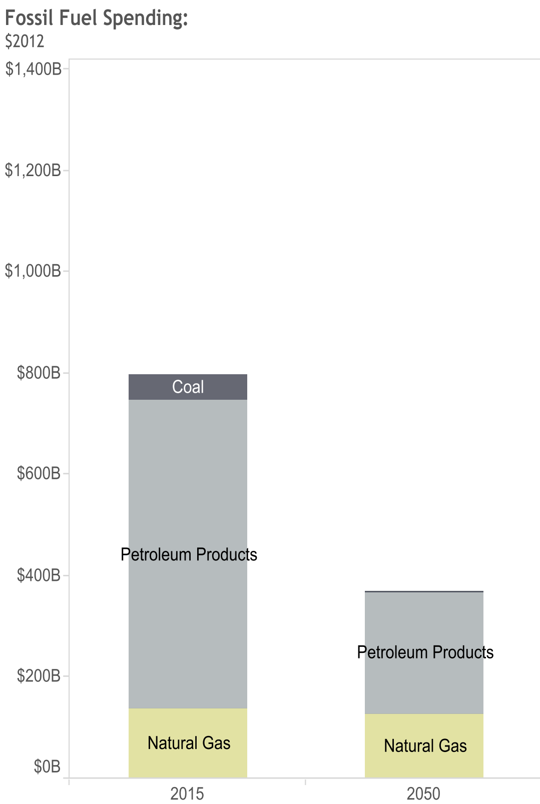
Spending More on Technology and Less on Fuel

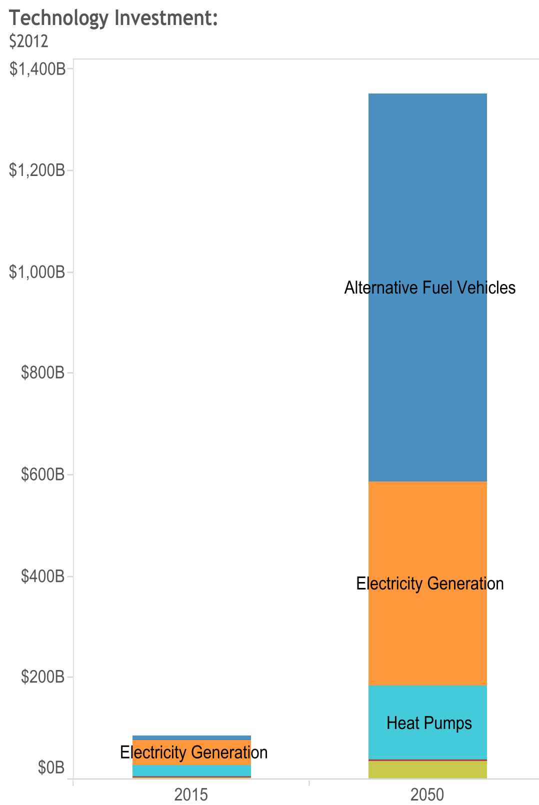
The deeply decarbonized energy economy is dominated by fixed capital costs for energy efficient and low-carbon technologies, consistent with the physical changes required. Deep decarbonization results in large increases in spending on low-carbon equipment and infrastructure, offset by large savings in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

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

Figure 6. Energy System Costs and Savings by Component





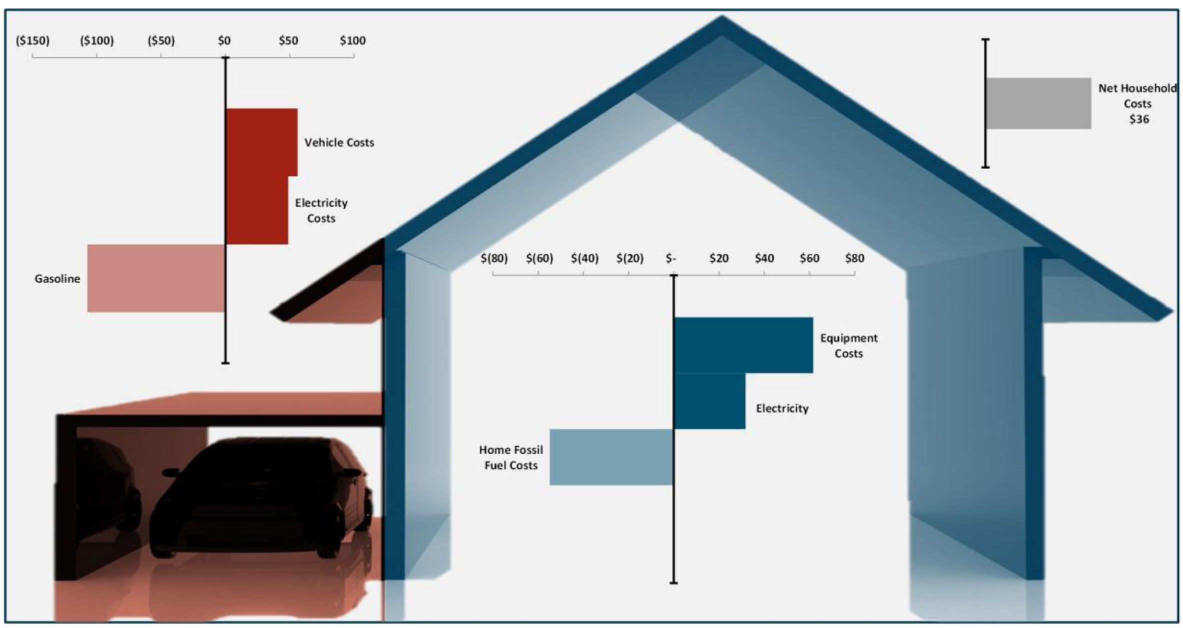


Small Change in Direct Consumer Spending for Energy

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

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

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



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

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

Average Electric Rate:
2012 cents/kWh

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

C. Deeply Decarbonized Macro-Economy

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

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

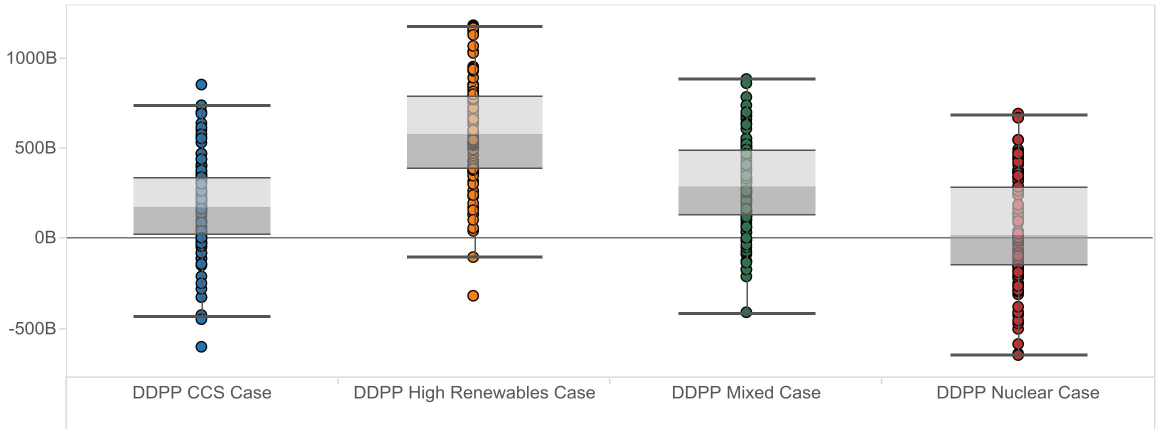
Even under unfavorable assumptions about future prices, the cost of deep decarbonization is small. Because of the long time period between the present and 2050, there is great uncertainty about future fuel prices and technologies. Using a wide range of estimates for these costs, the uncertainty analysis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

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

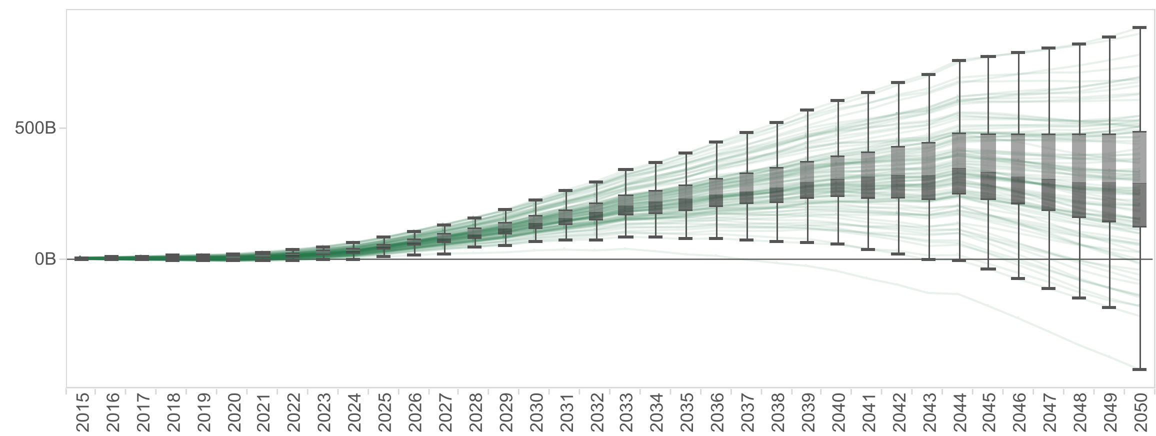
Regional costs of deep decarbonization are similar as a share of regional GDP to U.S.-wide costs, with some variation. At a regional level, mixed case net energy system costs in 2050 are shown for the nine U.S. census divisions range are shown in Figure 9C. The highest central cost estimate, and the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

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

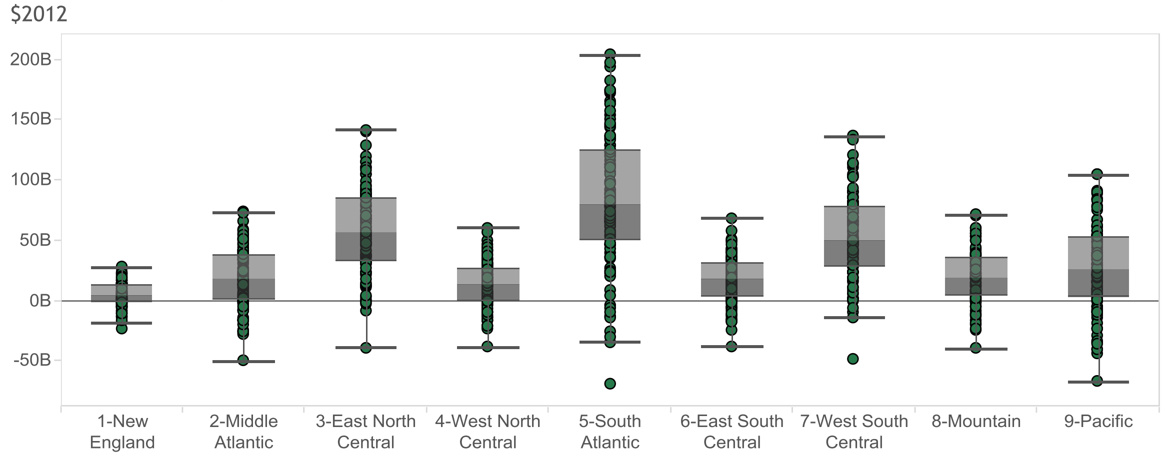
2050 Incremental Costs:
$2012



Mixed Case Incremental Costs:
$2012



2050 Mixed Case Regional Incremental Costs:
$2012

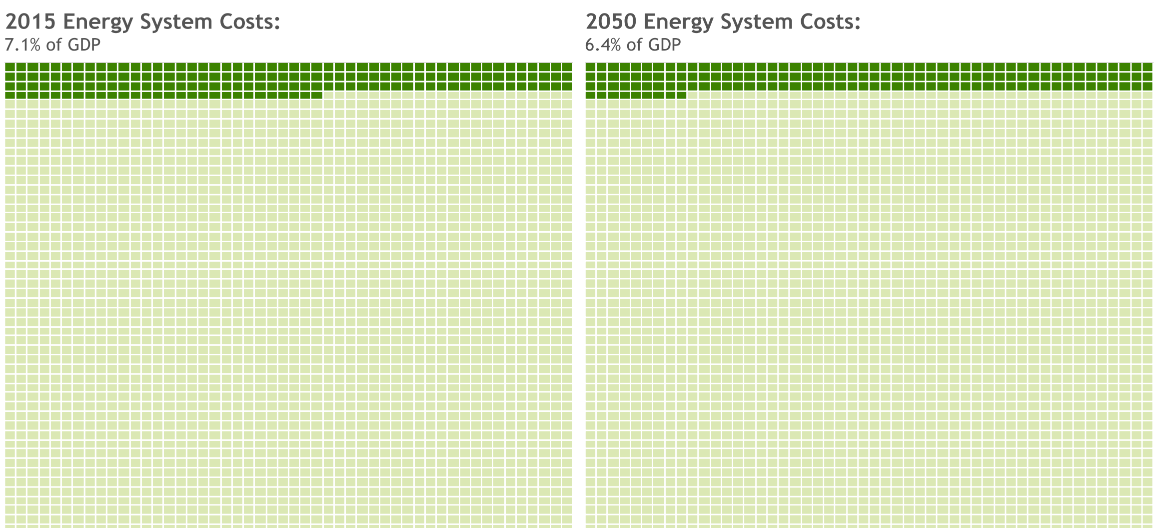


Putting Decarbonization Cost in Perspective

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

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

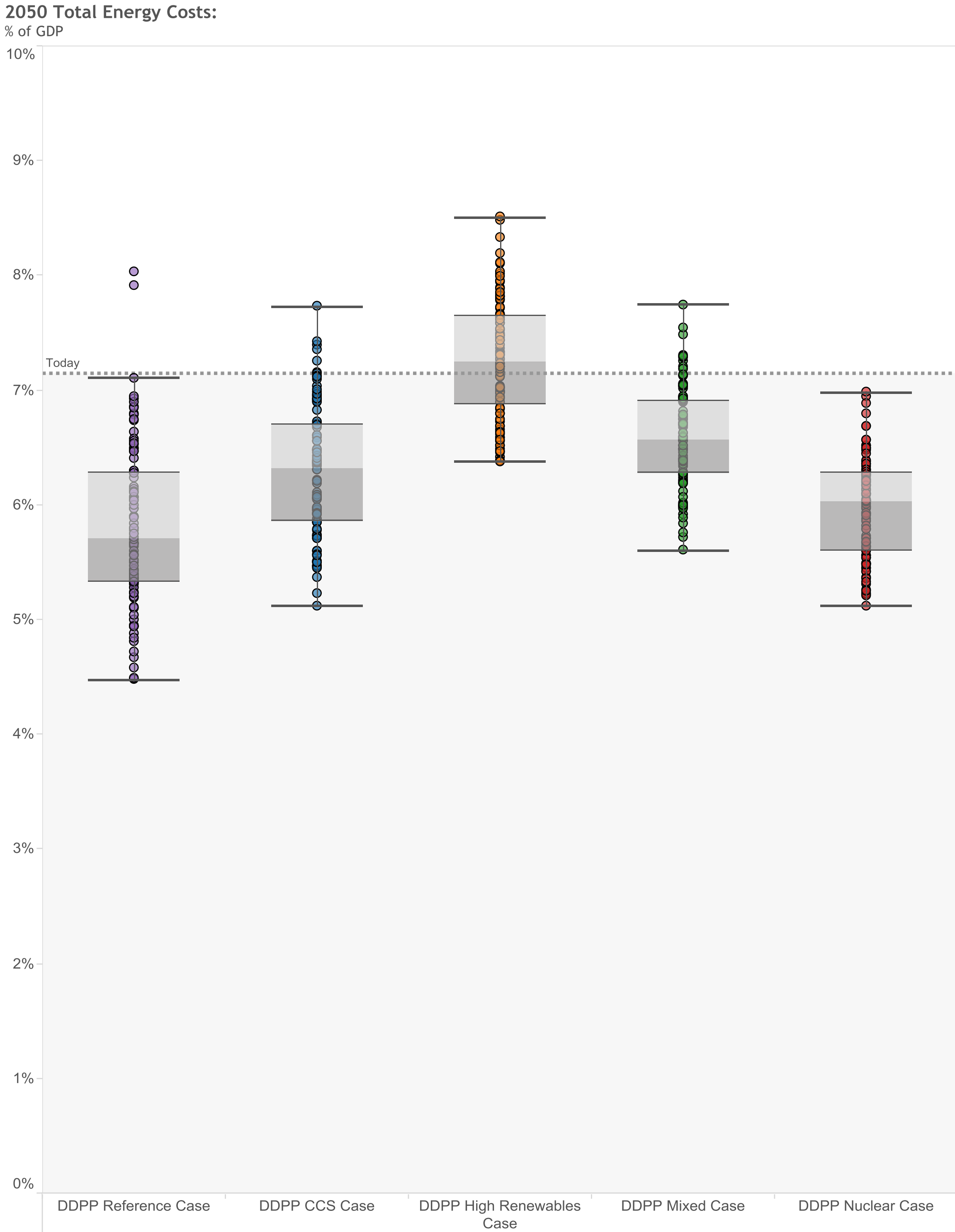
Figure 10. Energy Costs as a Share of U.S. GDP, Current and 2050 Deep Decarbonization Cases



Business as Usual Energy System Has Uncertain Costs

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

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



II. Societal Benefits

Four Essential Themes

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

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

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

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

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

A. Stable Climate and Clean Environment

The Most Important Action the U.S. Can Take

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

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

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

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

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

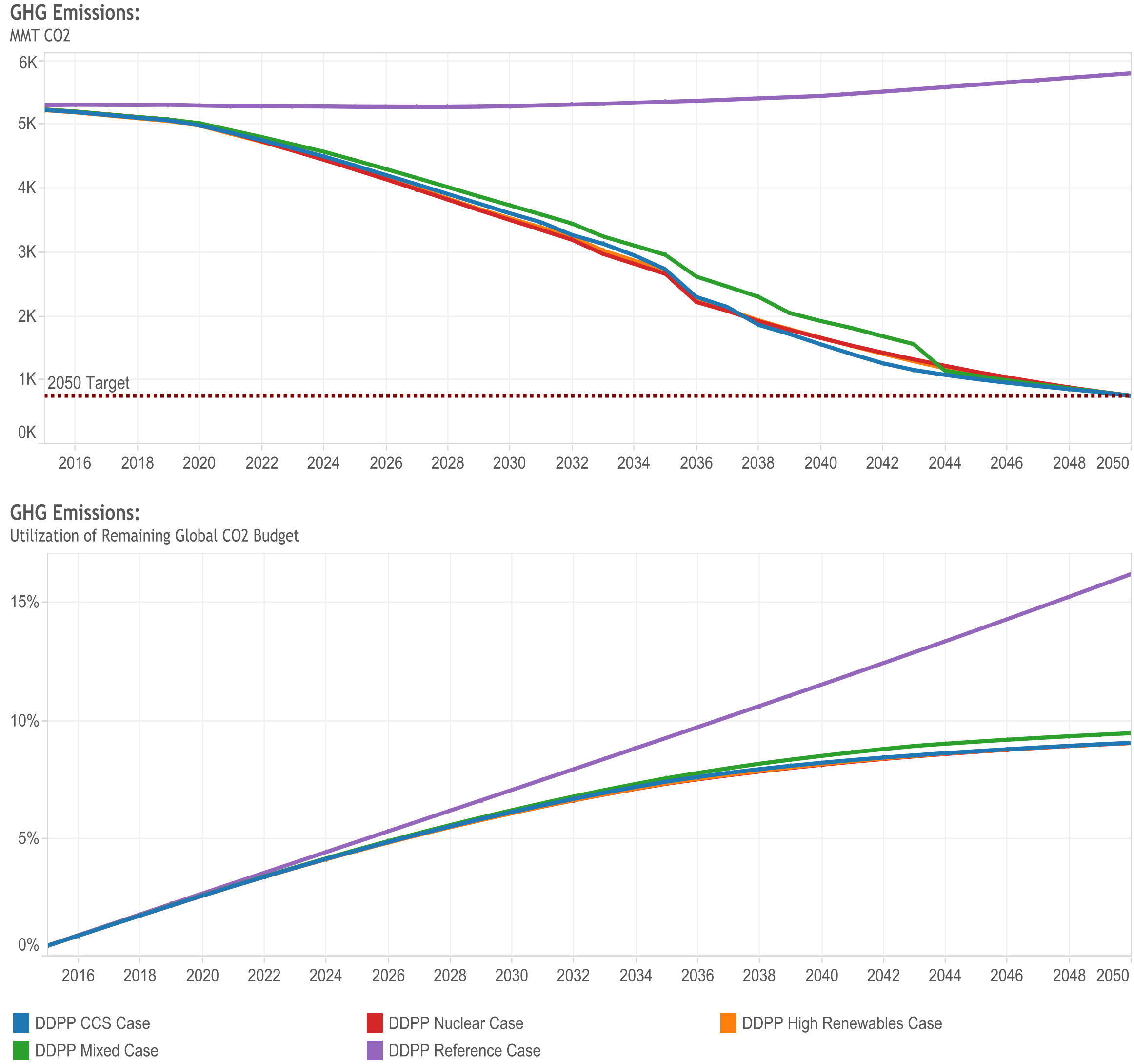
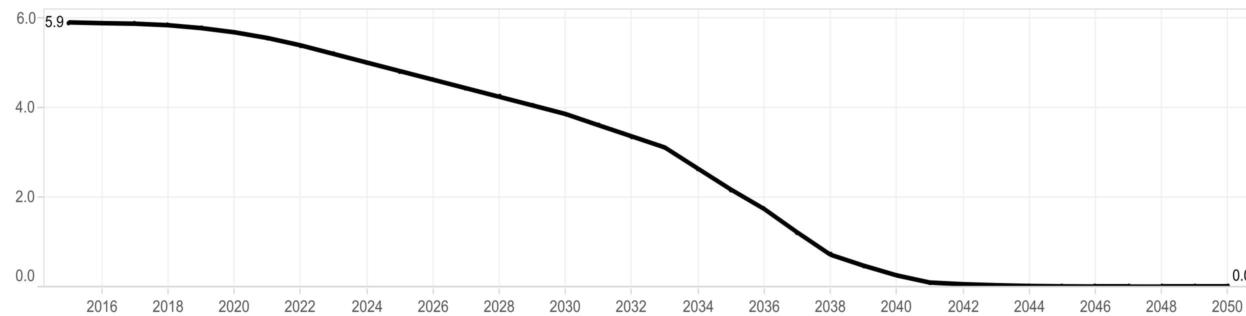


Figure 13. Reduction in Key Sources of Air Pollution as a Result of Deep Decarbonization

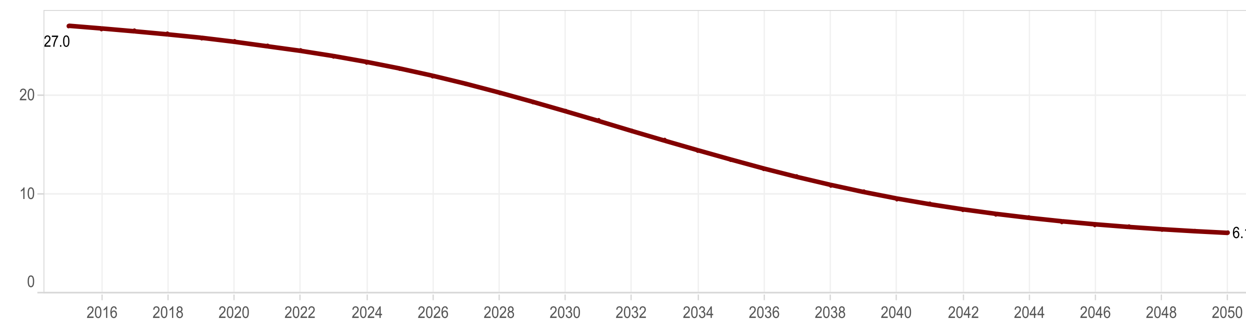
Coal Electricity Generation:

EJ



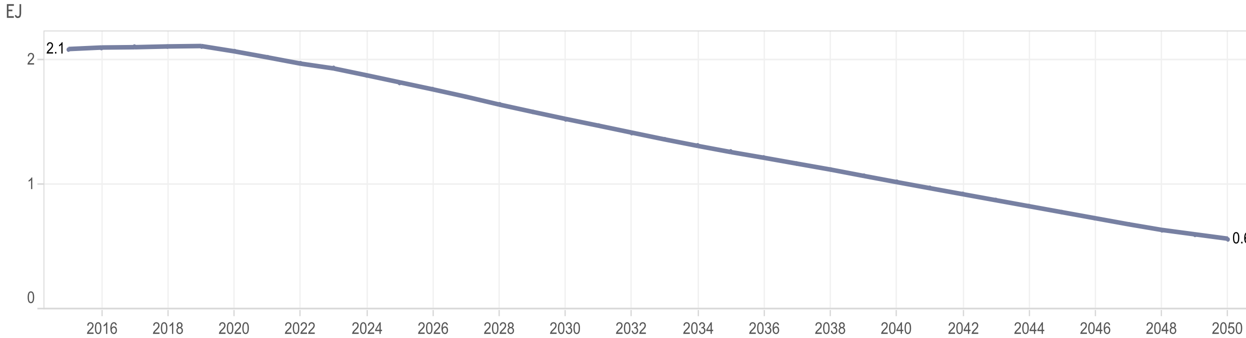
Transportation Demand - Liquid Fuels:

EJ



Industrial Demand - Solid Fuels:

EJ



B. Macroeconomic and Energy Security

Stability and Predictability

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

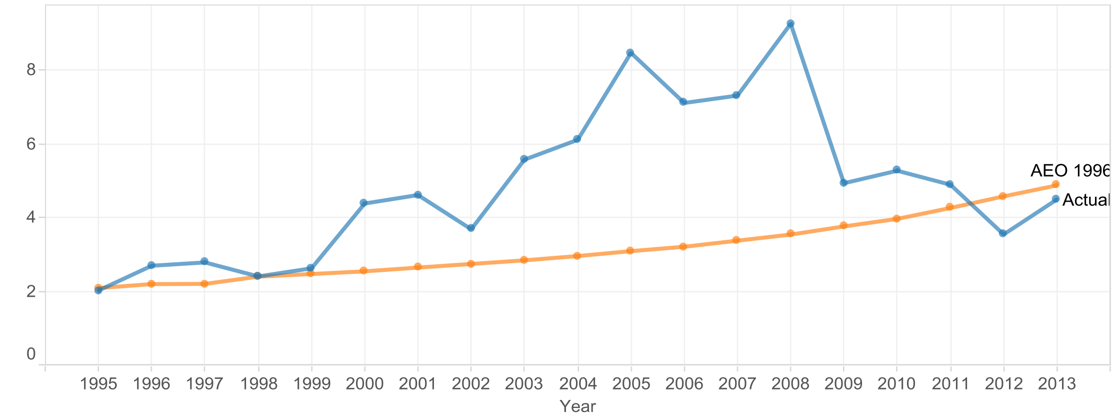
In the deeply decarbonized economy, energy costs are dominated by technology costs, which tend to be more stable and predictable. For electricity, the primary form of delivered energy in the 2050 low-carbon system, this is illustrated in Figure 14C, which shows actual average U.S. electricity rates over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

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

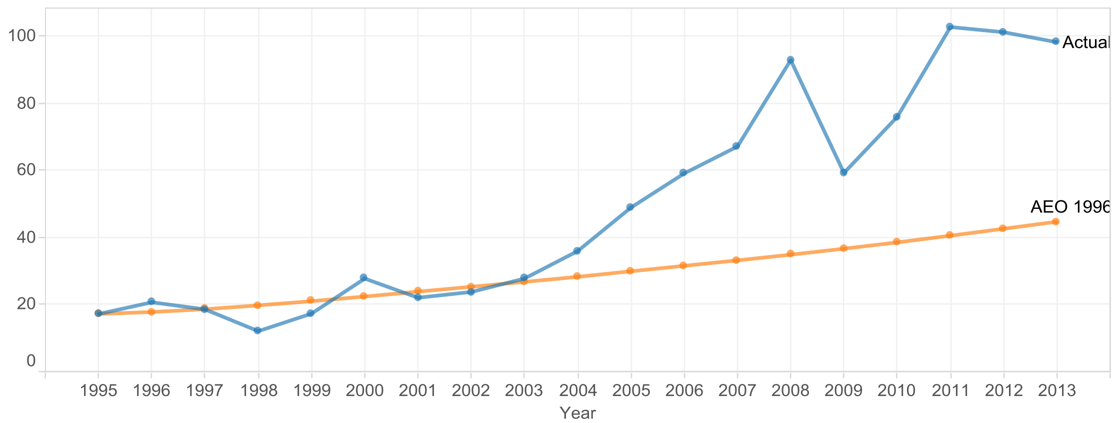
The technology-dominated costs of the deeply decarbonized system create a stable long-term environment for investors and more predictable energy costs for consumers. Overall energy investment will expand, driving vigorous competition within U.S. and global technology markets for equipment and infrastructure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

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

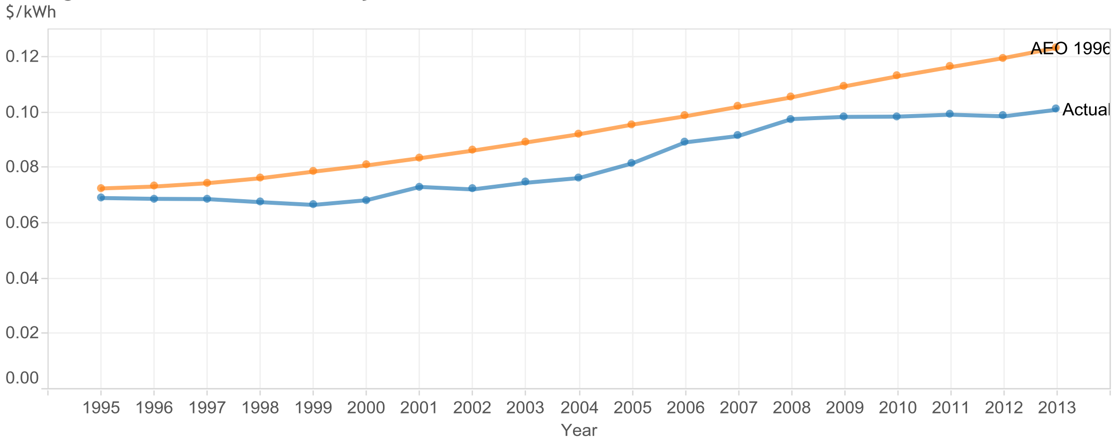
Natural Gas Actual vs. Projected:
$/MMBTU delivered to electricity generators



Crude Oil Actual vs. Projected:
$/barrel



Average Electric Rate Actual vs. Projected:
$/kWh



Source: (DOE, 1996; DOE, 2015)

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

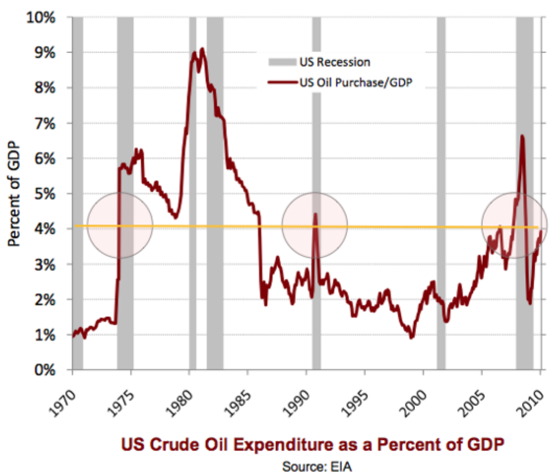
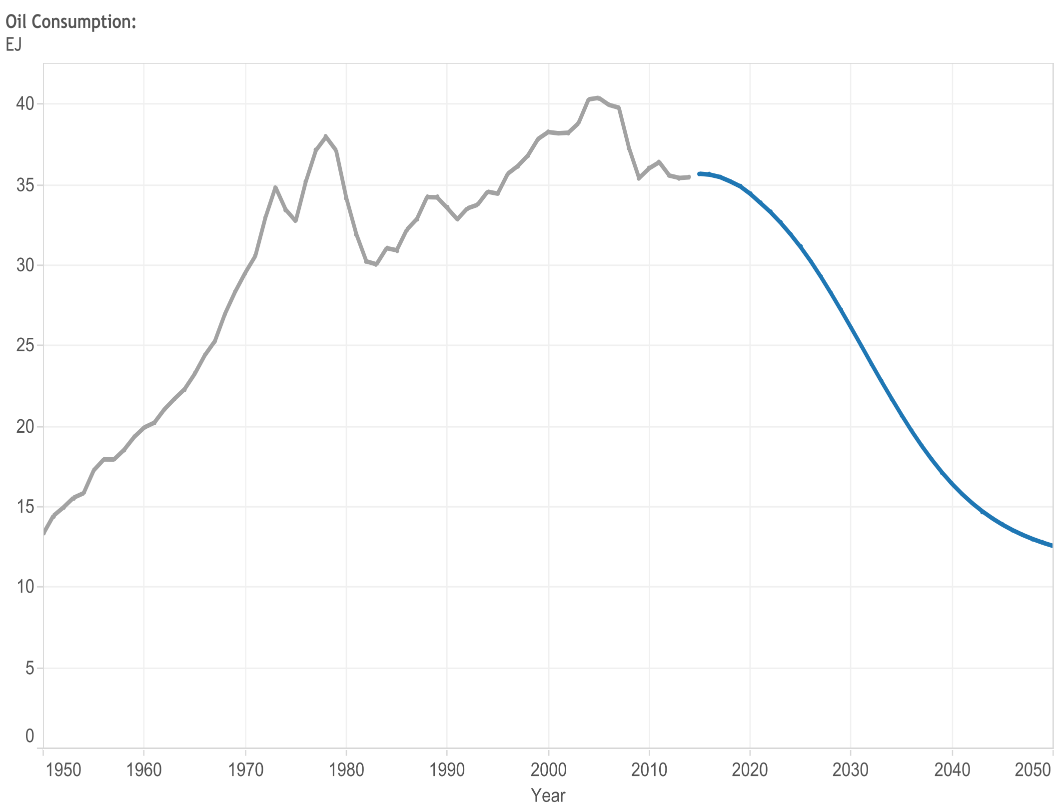


Figure 16. U.S. Oil Consumption, Historical 1950-2014 and Projected 2015-2050 for Deep Decarbonization, Mixed Case



Source: (DOE, 2015)

C. Widespread Economic Benefits

An Energy System with Many Winners

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

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

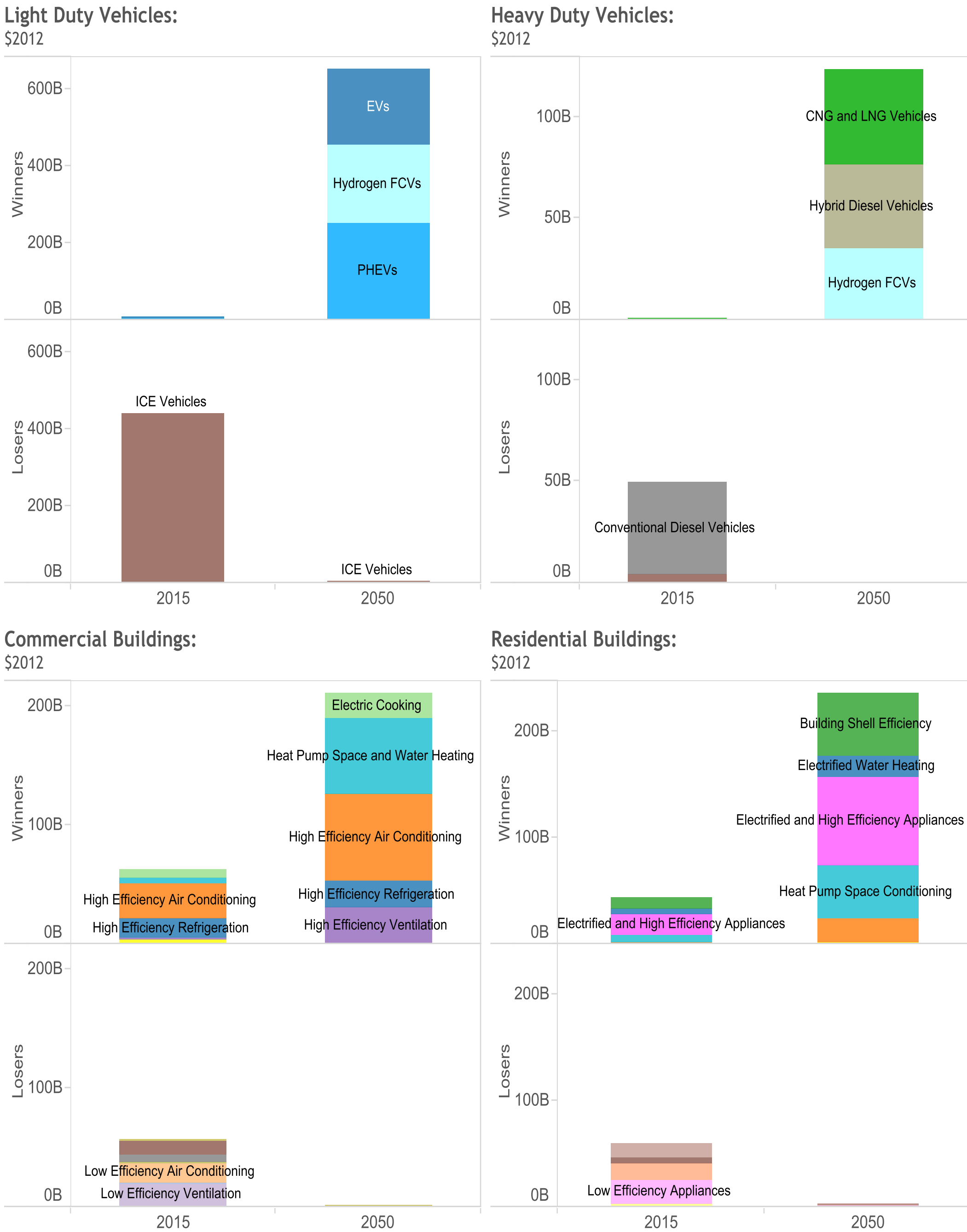
In **residential buildings** investment in clean technologies such as heat pump heating and air conditioning, high efficiency appliances, LED lighting, and building shell improvements will increase by a factor of six, from $35 billion annually today to $220 billion in 2050 (Figure 17B), while the low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

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

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

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

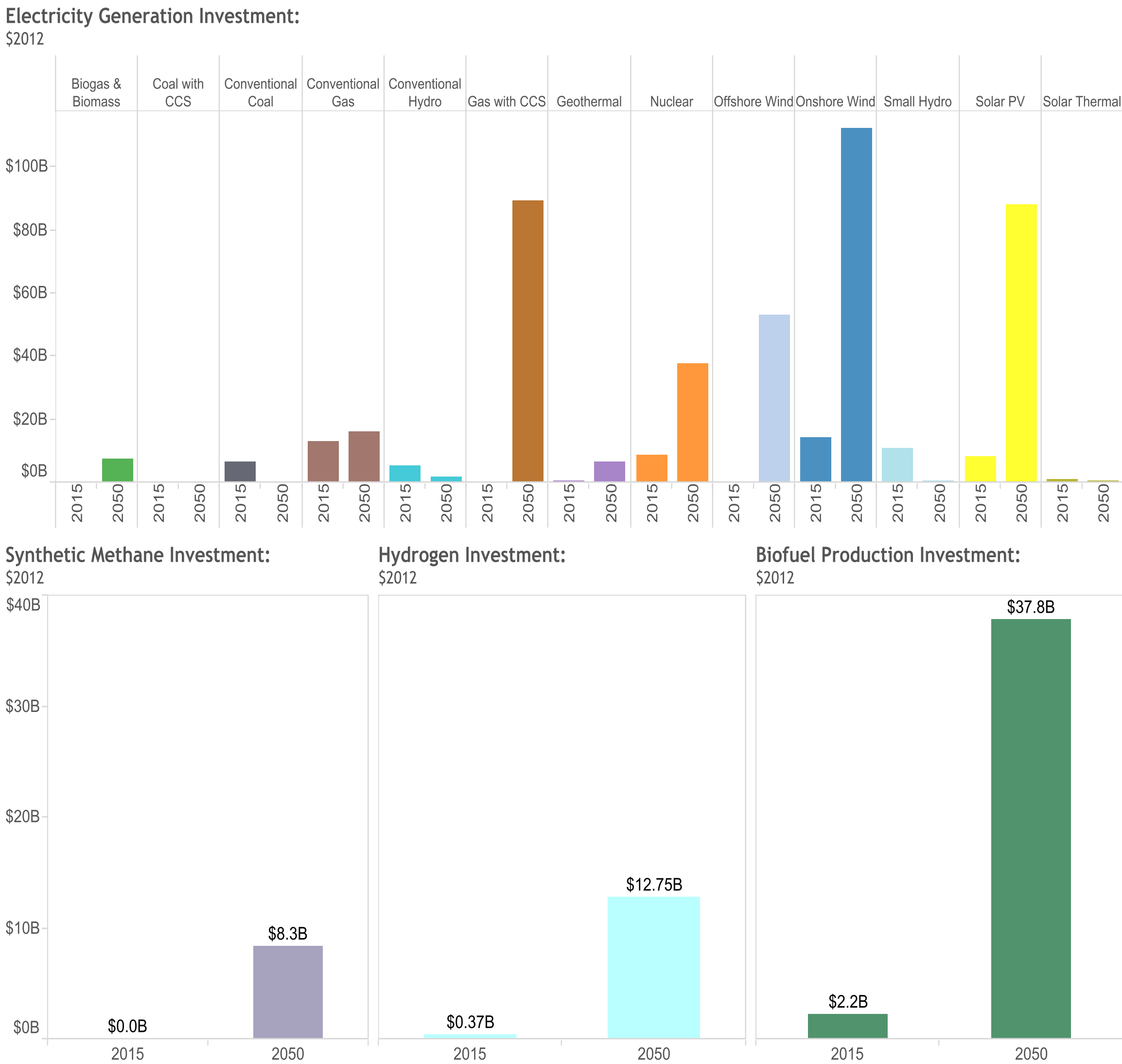
Figure 17. Annual Investment in Conventional and Low-Carbon Technologies in Buildings and Transportation, Current System versus Deeply Decarbonized System in 2050



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

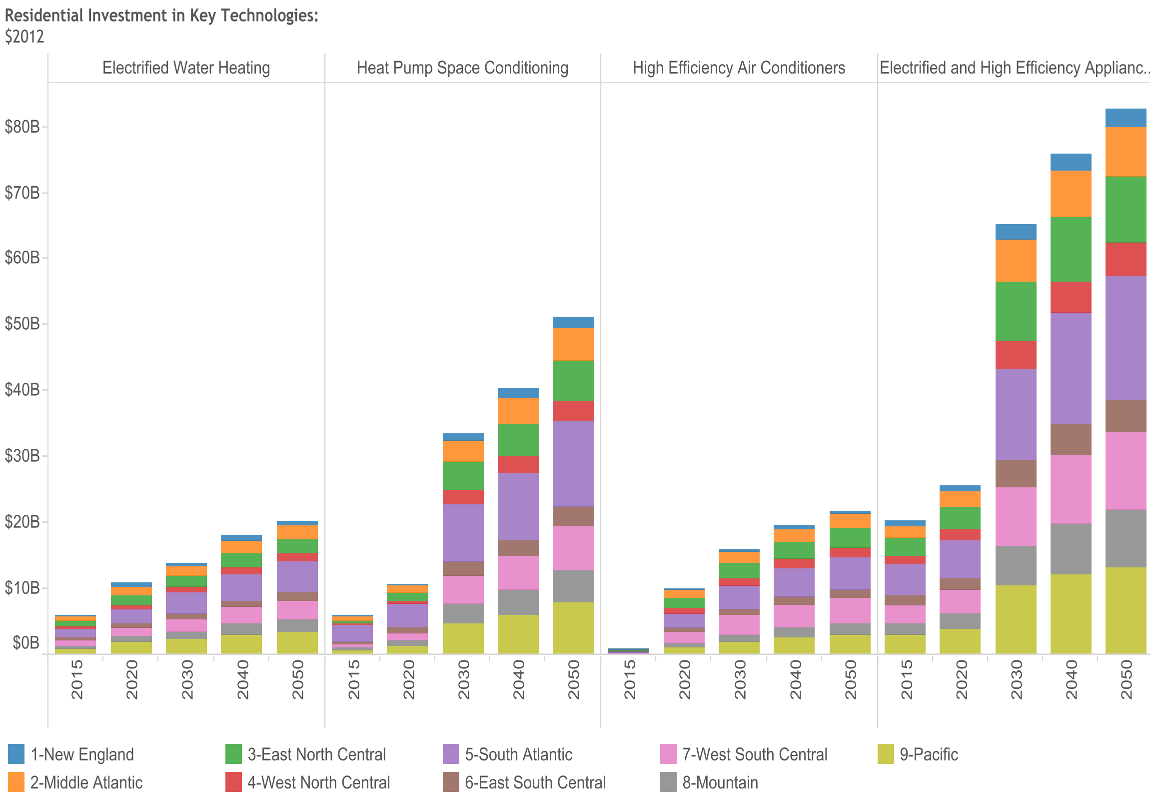
In **low-carbon fuels**, investment in production capacity for hydrogen and synthetic methane with grow from practically nothing today to more than $20 billion annually in 2050 (Figure 18B). Investment in biomass fuel production (renewable natural gas and renewable diesel) will grow from less than $200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

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



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

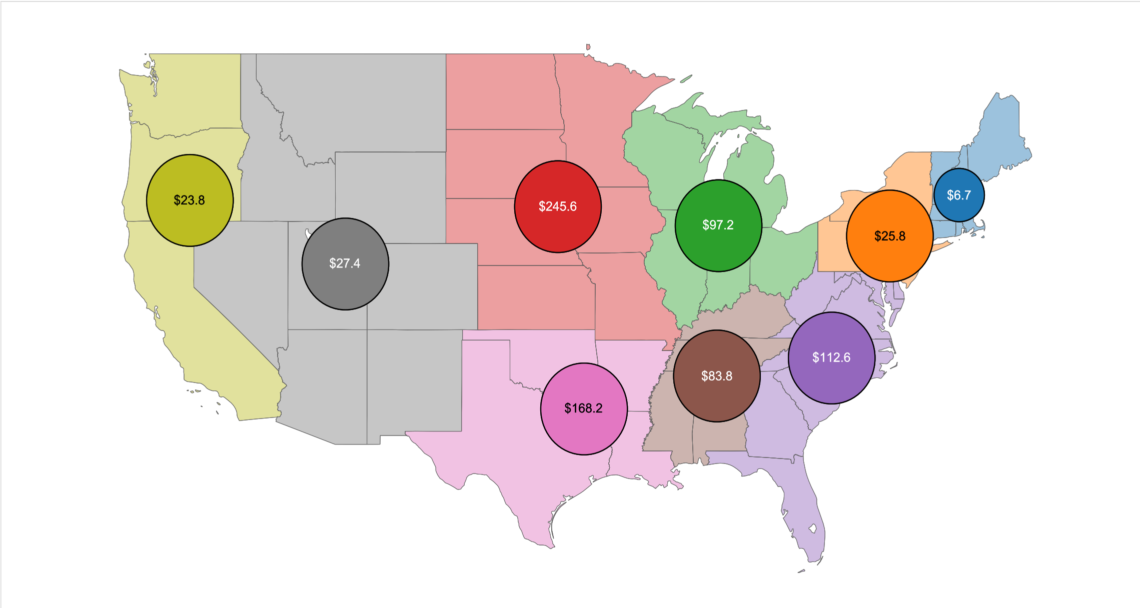
Figure 19. Annual Investment in High Efficiency Residential Technologies by Region, at 10-Year Intervals, for Mixed Case



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

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

Cumulative 2015-2050 Biomass Commodity Payments:
$2012B



Cumulative 2015-2050 Biofuel Production Investment:
$2012B

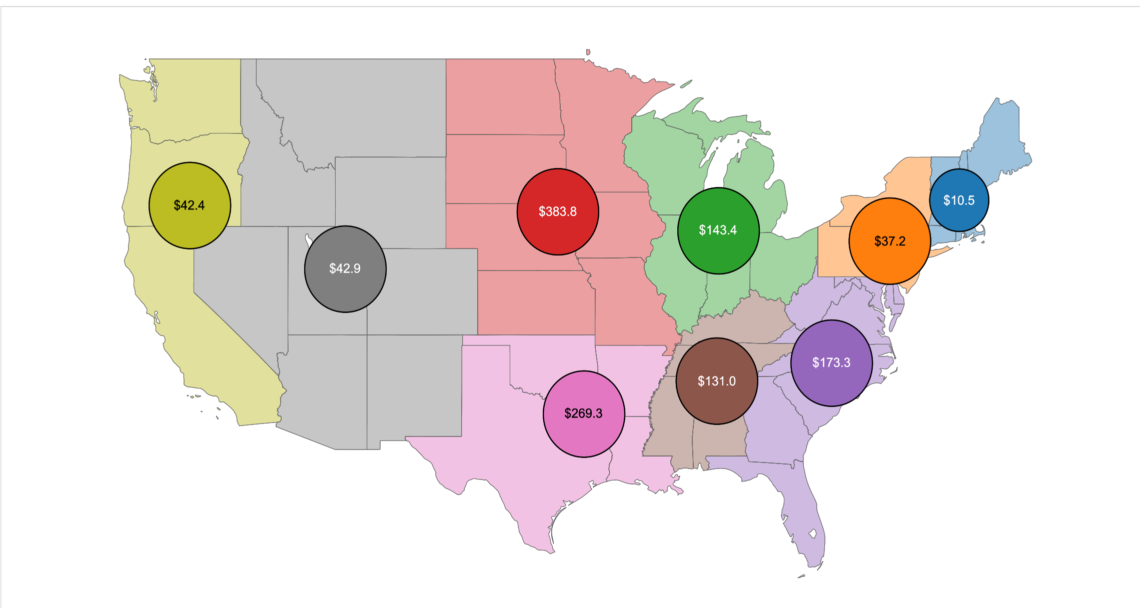
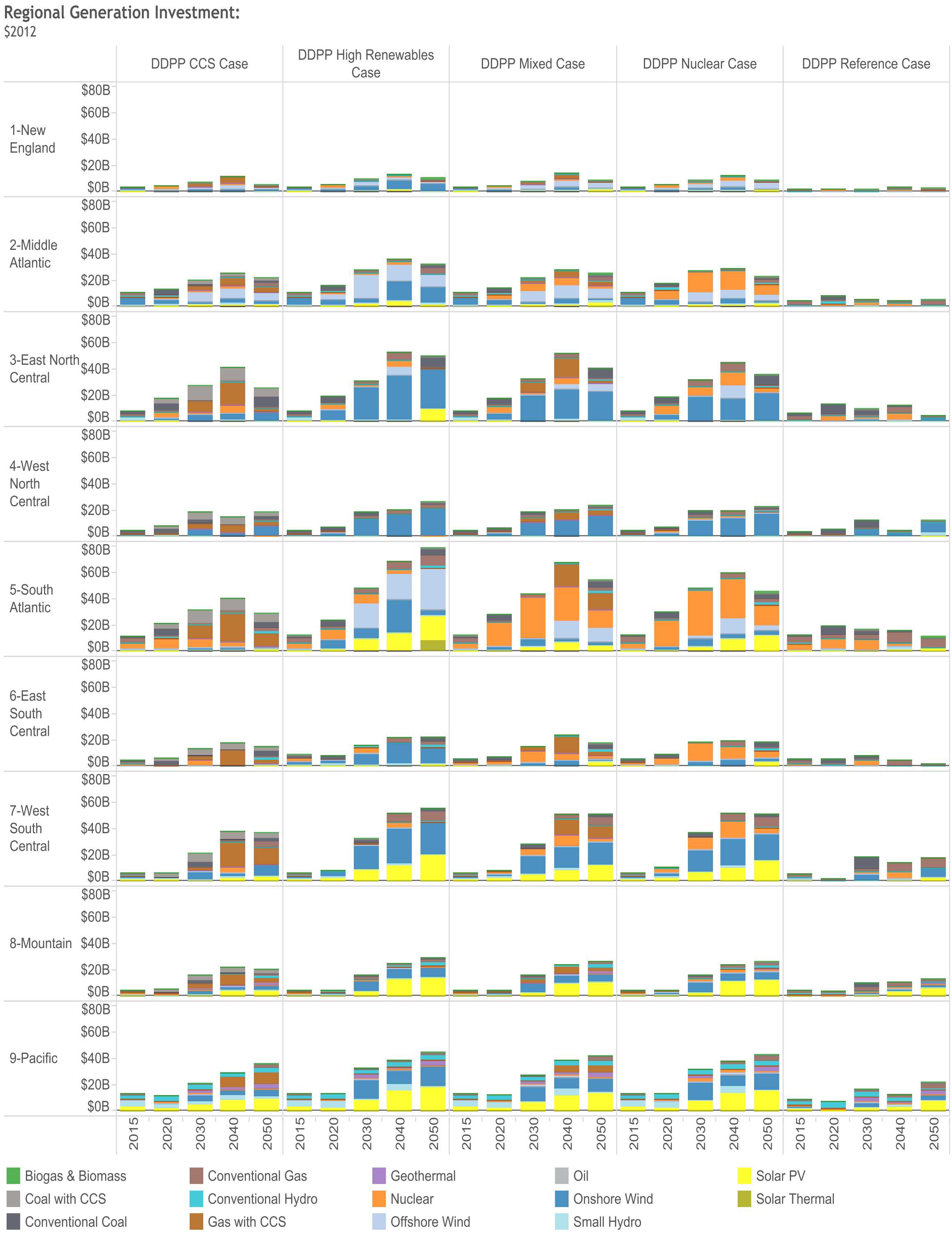


Figure 21. Annual Investment in Low-Carbon Generation by Region, at 10-Year Intervals, Reference Case and Four Deep Decarbonization Scenarios



D. Modernization, Competitiveness, and Jobs

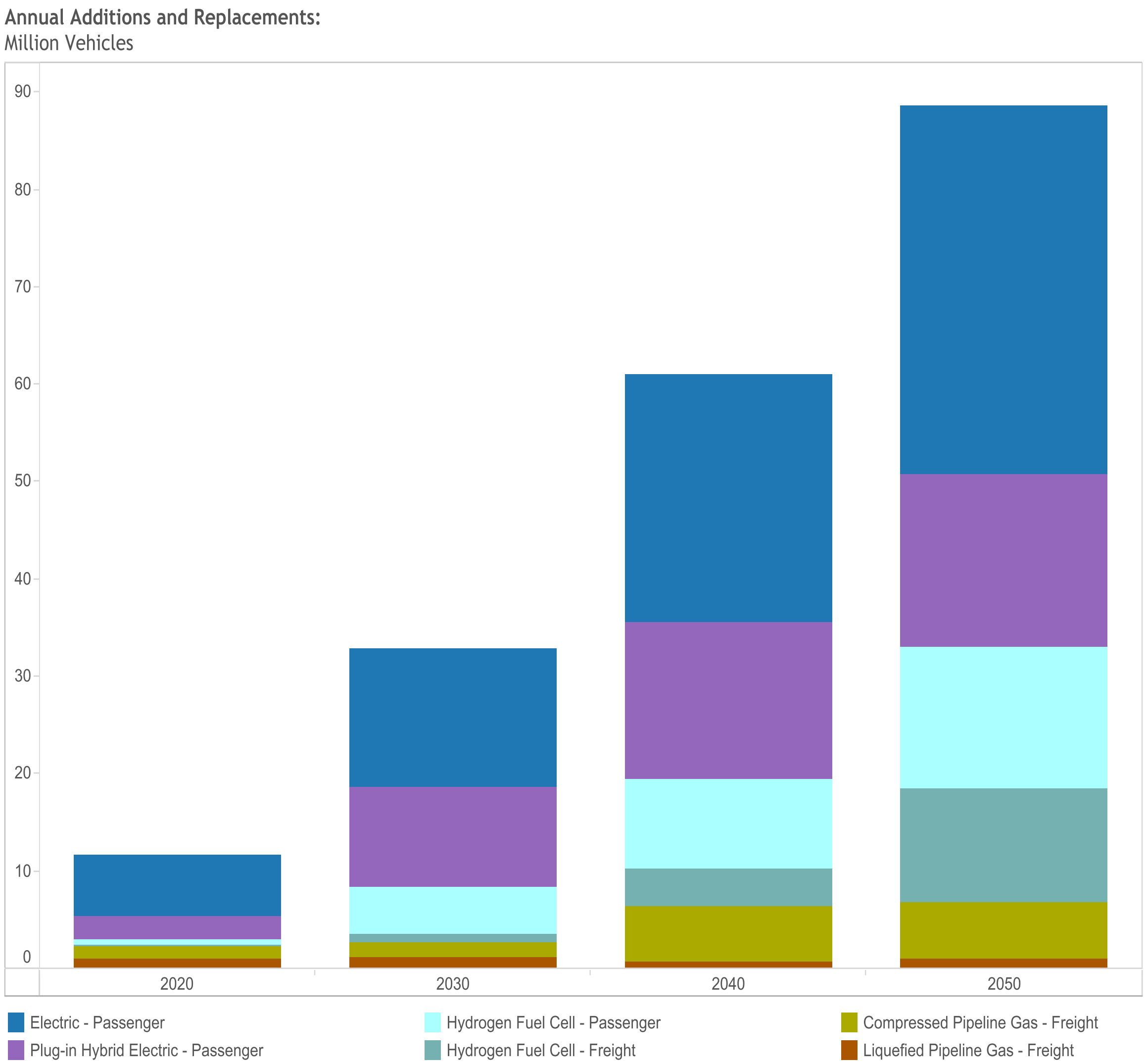
A High Tech Energy System

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

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

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

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



Source: *DDPP Global Synthesis Report 2015*

III. Energy Transition

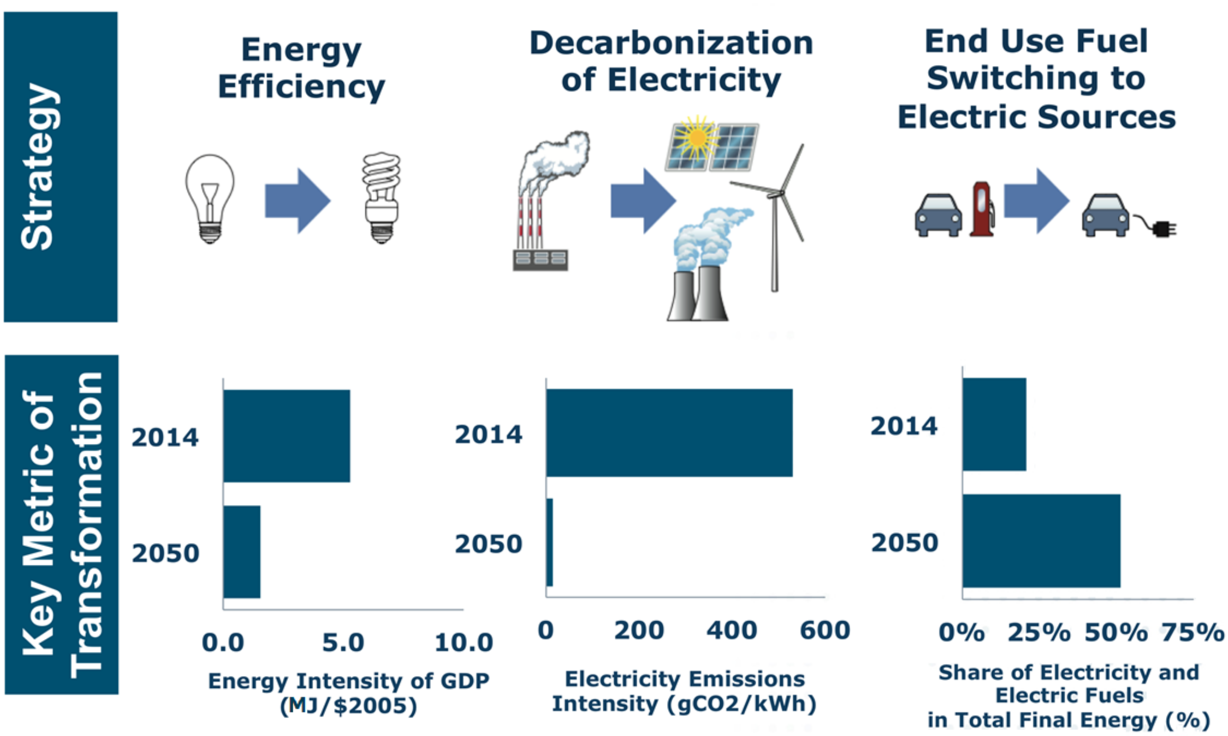
A. The Physical Transition: Metrics, Outcomes, Rates of Change

The Three Pillars

The transition to a low-carbon energy system rests on three pillars: (1) highly ***efficient end use*** of energy in buildings, transportation, and industry; (2) ***decarbonization*** of electricity and other fuels; and (3) ***fuel switching*** of end uses from high-carbon to low-carbon supplies, ***primarily electrification***. All three of these pillars are needed together to achieve the 2050 decarbonization goal.

Metrics for the three pillars are shown in Figure 23. The dramatic changes in these metrics demonstrate the extent of the low-carbon transformation required. The share of end-use energy from electricity or electrically-produced fuels such as hydrogen will need to increase from under 20% in 2010 to over 50% in 2050, displacing most fossil fuels. The carbon intensity of electricity will need to be reduced by a startling 97%, from more than 500 g CO_2/kWh in 2014 to less than 15 g CO_2/kWh in 2050. Energy intensity of GDP will need to decline by 70% over this period, with final energy use reduced by 20% from 68 to 54 EJ despite a forecast population increase of 40% and a 166% increase in GDP.

Figure 23. Three Pillars of Deep Decarbonization



Main 2050 Transitions by Sector

Scientists believe that limiting global warming to 2°C or less will require reaching net zero greenhouse gas emissions by around the year 2070. By 2050, that goal should be largely accomplished, and the stage set for moving to net zero emissions. This requires applying the “three pillars” strategies across the U.S. economy. Table 2 describes the transitions that must take place in each of the major sectors by 2050, along with key metrics indicating the extent of that transformation.

Table 2. Key Energy Transitions by Sector

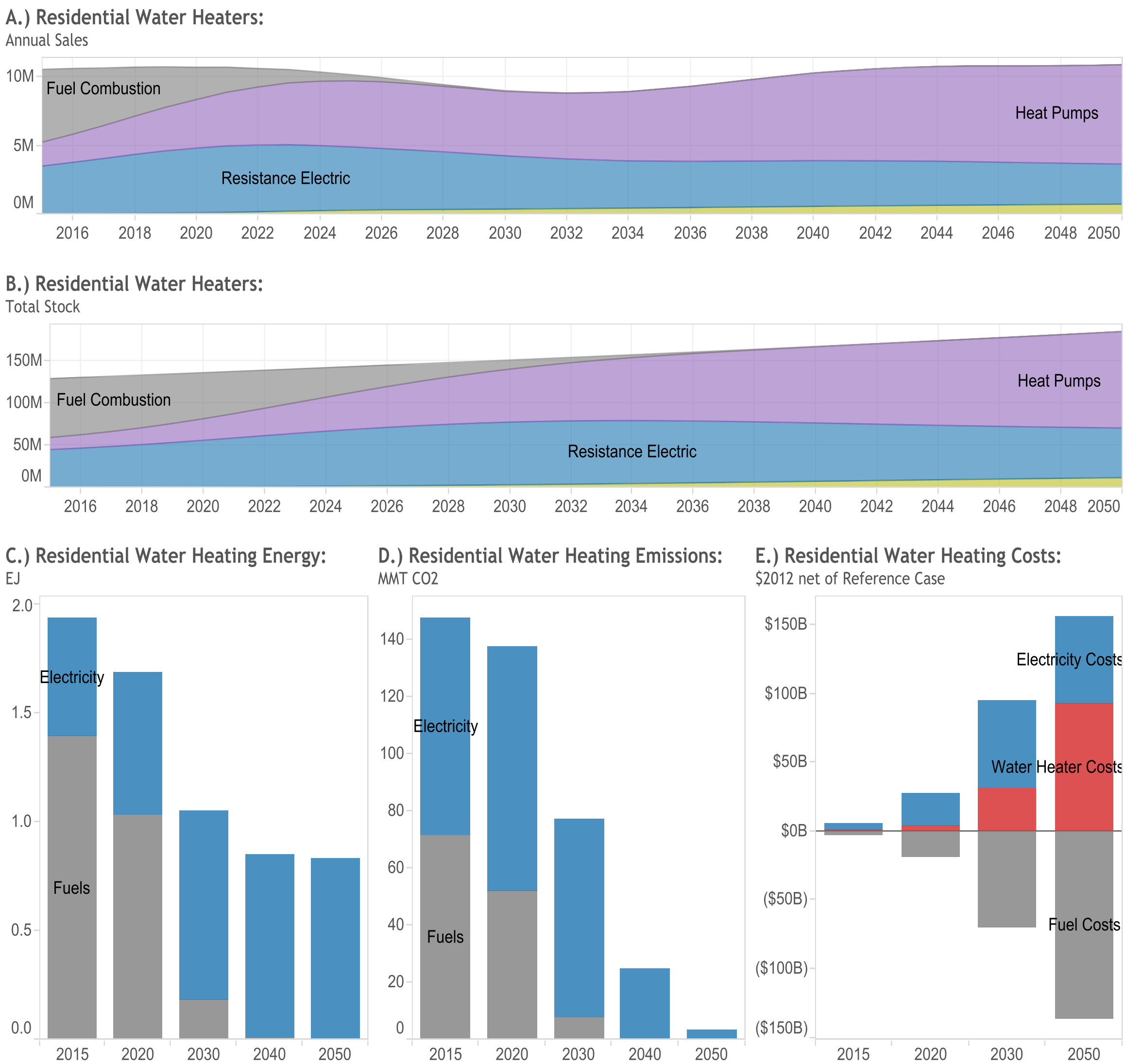
Sector	Current Energy System	Deep Decarbonized Energy System	Key Metrics in 2050
Electricity	Coal and natural gas dominated	Renewable, nuclear, or CCS	Double output while reducing CO_2/kWh 30x
Transportation	Oil dominated	Electricity, hydrogen, CNG, LNG, biodiesel	Fuel economy >100 mpg equivalent
Buildings	Natural gas and oil dominate heating	Electrification, end-use efficiency	Building energy use >90% electrified
Industry	Fossil fuel dominated	Electrification, CCS, efficiency, low-carbon fuels	Double efficiency, >40% electrification

Rates of Change

In addition to the key metrics that must be achieved by 2050, the rate at which current infrastructure and equipment must be replaced by low-carbon alternatives in order to achieve those targets can be specified. The U.S. analysis, taking into account equipment stocks, vintages, and economic lifetimes, yields benchmarks for the minimum required penetration rate of many technologies, from wind generators to fuel cell vehicles, at different points in time between now and 2050.

As an example, in the low-carbon transition for residential water heaters, units that directly combust fossil fuels are displaced by electric resistance heating and electric heat pumps when they come to replacement time. Figure 24A shows the share of annual sales of each technology, and Figure 24B shows the resultant mix of technologies in the stock over time, achieving 100% electric by 2040.b Figure 24C shows the final energy mix, which is all-electric by 2040. Figure 24D shows emissions approaching zero in 2050 as the carbon intensity of electricity is reduced over time. Figure 24E shows expected additional incremental cost of electric water heaters and electricity purchases, along with expected savings from avoided fuel purchases enabled by that equipment.

Figure 24. Residential Water Heater Transition, Mixed Case



B. Guidance for Policy

Five Principles of the Energy Transition

Five high-level observations on the low-carbon energy transition provide crucial touchstones for what policy should focus on if it is to achieve deep decarbonization. The observations arise from the results of the U.S. study, and are not a repetition of conventional wisdom. These principles of a low-carbon transition are unlikely to be incorporated into policy discussions unless there is a conscious effort to bring a 2050 perspective to bear on current decisions.

1. **"It's all about the transformation":** Deep decarbonization requires a sustained focus on transformation of the energy system by 2050. Policies that produce incremental improvements without facilitating transformation can result in dead ends for long-term emission reductions.

2. **Early retirement is not required, but timely replacement is:** Deep decarbonization can be achieved in the U.S. without retiring equipment before the end of its economic lifetime. However, when replacement time arrives, the new equipment must be consistent with the low-carbon transition path.

3. **Fundamentally new technologies are not required, but technical progress is:** Deep decarbonization can be achieved in the U.S. using existing commercial and near-commercial technologies. But policy must facilitate technical progress and volume production to keep transition costs low.

4. **Deep emission reductions require cross-sector coordination:** The further decarbonization proceeds, the more emissions reductions depend on interactions across sectors, e.g. transportation and electricity generation. Coordination and joint planning are required for best outcomes.

5. **Network supply of low-carbon energy requires a sustainable business model:** In a deeply decarbonized system, the majority of final energy is delivered through the electric grid and (decarbonized) natural gas pipeline. Policy makers must pay attention to the changing role of regulated utilities in the low-carbon transition, and the need for a sustainable business model.

"It's All About the Transformation"

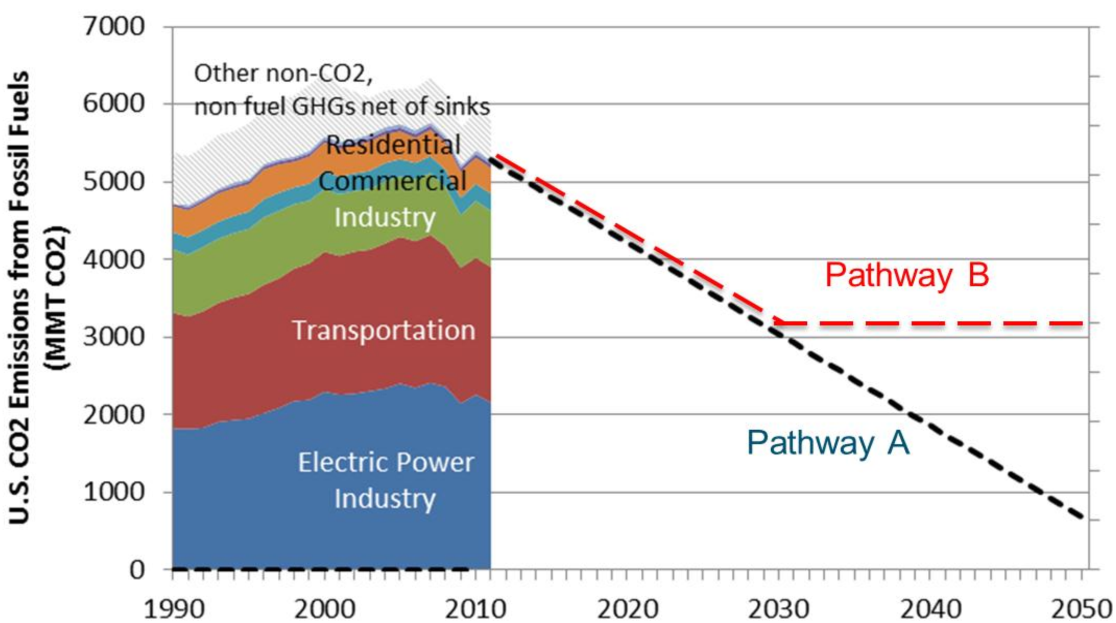
Deep decarbonization in the U.S. requires the economic intensity of GHG emissions to decrease 8% per year, and per capita emissions to decrease 5.5% per year. The U.S. analysis shows that these ambitious rates of change can be achieved technically and at an affordable cost, but it does required a sustained transformation of energy supply and demand infrastructure over the full period of time out to 2050 (and beyond, to net zero emissions by around 2070).

Policies that produce incremental improvements without facilitating transformation can result in technology lock-in and infrastructure build-outs that are dead ends from the standpoint of long-term emission reductions, meaning that economy-wide emissions decline for a period, but then reach a plateau beyond which further emission reductions don't occur or are difficult to achieve without early retirement.

A hypothetical dead-end emission trajectory situation is illustrated in Figure 25. Pathway A represents a linear trajectory from 2010 emissions of energy-related CO_2 to the 2050 target level. Pathway B represents policies that reduce emissions in the short-term but don't lead to deep decarbonization in the long-term.

Some examples of potential dead-ends include a focus on building energy efficiency without end-use electrification, improvement in internal combustion engine (ICE) economy without widespread deployment of electric or fuel cell LDVs, and a coal to conventional natural gas transition in electric generation without the necessary build-out of renewable, nuclear, or CCS generation.

Figure 25. Illustrative Deep Decarbonization Trajectory and "Dead End" Trajectory



Early Retirement Is Not Required, But Timely Replacement Is

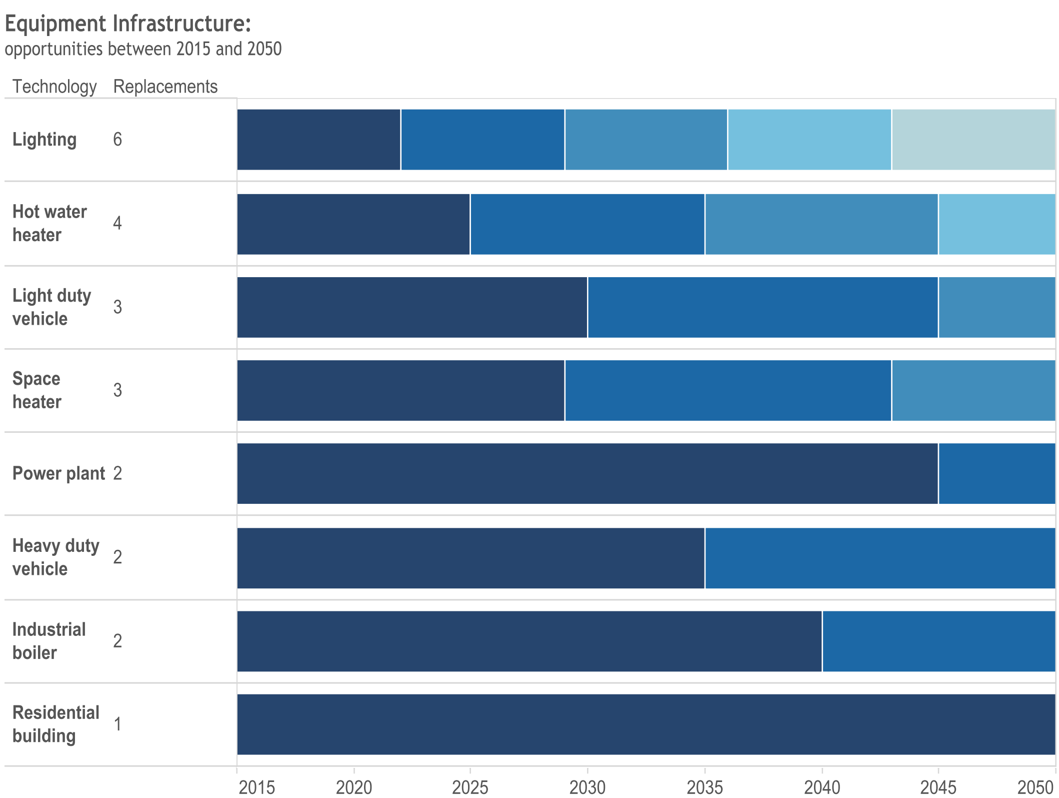
Deep decarbonization is fundamentally a sustained transition to efficient and low-carbon equipment and infrastructure. This can be achieved in the U.S. without retiring existing equipment and infrastructure before the end of its economic lifetime, which greatly reduces the expected cost of the transition.

However, the economic lifetime of most energy supply and end-use equipment is of the same order of magnitude as the time remaining between now and mid-century. As a consequence, there are four or fewer natural replacement cycles for most energy-related equipment, and for some of the most important types, such as electric power plants and industrial boilers, there is at most only one cycle. This is illustrated in Figure 26.

While early retirement can be avoided in the U.S. (in part because of the age of U.S. infrastructure, which is not necessarily universal across countries), it is also true that when replacement time arrives, the energy and emissions characteristics of the new equipment installed must be consistent with the low-carbon transition path.

Put differently, failure to replace retiring infrastructure and equipment with efficient and low-carbon successors will either lead to failure to achieve deep decarbonization by mid-century, or will subsequently require early retirements of the replacement equipment to meet the target.

Figure 26. Lifetimes Until Replacement for Key Equipment and Infrastructure



Fundamentally New Technologies Are Not Required, But Technical Progress Is

Deep decarbonization can be achieved in the U.S. using existing commercial and near-commercial technologies, meaning technologies that exist at significant scale in the field. Technologies that are *not required* in order for the U.S. to meet the 80% by 2050 target include such widely touted prospects as Gen IV nuclear, deep offshore wind, advanced geothermal, advanced cellulosic ethanol, advanced biodiesel, and CCS with greater than 90% capture rate. The development of some of these technologies may reduce costs and provide other benefits, but U.S. ability to reach the target does not depend on them. Table 3 illustrates the conservative assumptions about technology readiness underlying the U.S. deep decarbonization scenarios.

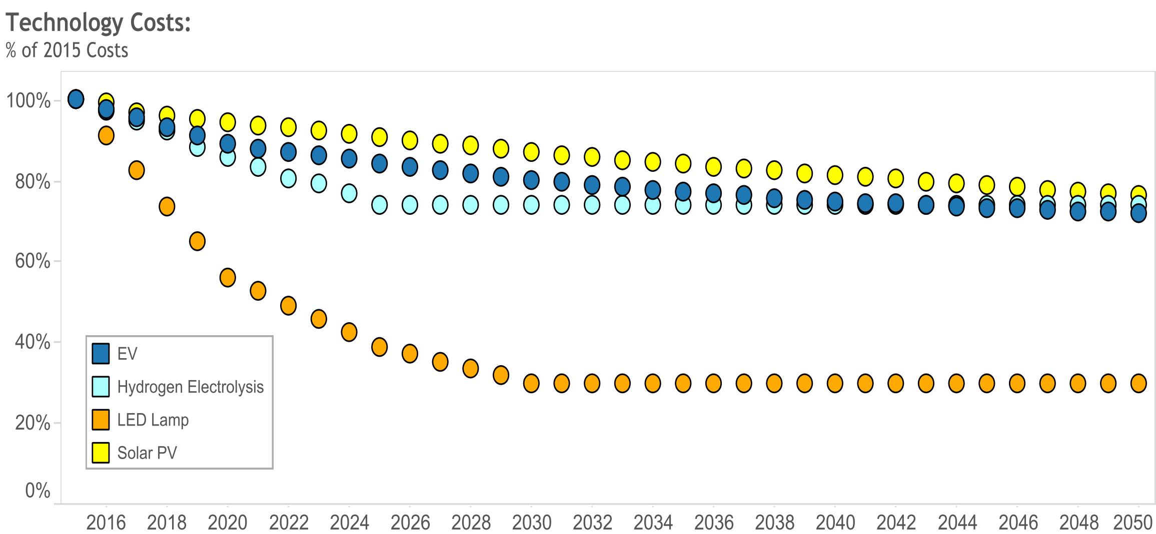
Table 3. Technologies Included in Four U.S. Deep Decarbonization Scenarios

Technology	Included in 2050 Scenario?			
	Mixed	Renewables	CCS	Nuclear
CCS for generation, 90% capture	Y	N	Y	N
CCS for generation, >90% capture	N	N	N	N
Nuclear Gen III	Y	Y	Y	Y
Nuclear Gen IV	N	N	N	N
Solar PV	Y	Y	Y	Y
Concentrating solar power	Y	Y	Y	Y
Onshore wind	Y	Y	Y	Y
Shallow offshore wind	Y	Y	Y	Y
Conventional geothermal	Y	Y	Y	Y
Deep offshore wind	N	N	N	N
Advanced geothermal	N	N	N	N
CCS for industry, 90% capture	Y	N	Y	N
CCS for industry, >90% capture	N	N	N	N
H_2 from electricity generation	Y	Y	N	Y
H_2 from natural gas reforming with CCS	N	N	Y	N
Continental scale H_2 distribution pipeline	N	N	N	N
Power-to-gas - SNG from electricity generation	Y	Y	N	N
Biomass conversion to SNG by AD or gasification	Y	Y	N	Y
Fischer-Tropsch liquid biofuels, 35% efficiency	N	N	Y	Y
Advanced cellulosic ethanol	N	N	N	N
Advanced biodiesel	N	N	N	N
Advanced bio-jet fuel	N	N	N	N
Biomass generation w CCS	N	N	N	N
Fuel cell LDVs	Y	N	N	Y
Battery electric LDVs	Y	Y	Y	Y
CNG passenger and light truck	N	N	N	N
LNG freight	Y	Y	Y	N
Fuel cell freight	N	N	N	Y
Heat pump HVAC	Y	Y	Y	Y
LED lighting	Y	Y	Y	Y
Heat pump electric water heat	Y	Y	Y	Y
Maximum efficiency shell for new buildings	Y	Y	Y	Y

Maximum efficiency shell for retrofits	N	N	N	N
Industrial process redesign	N	N	N	N
Manufactured product redesign	N	N	N	N

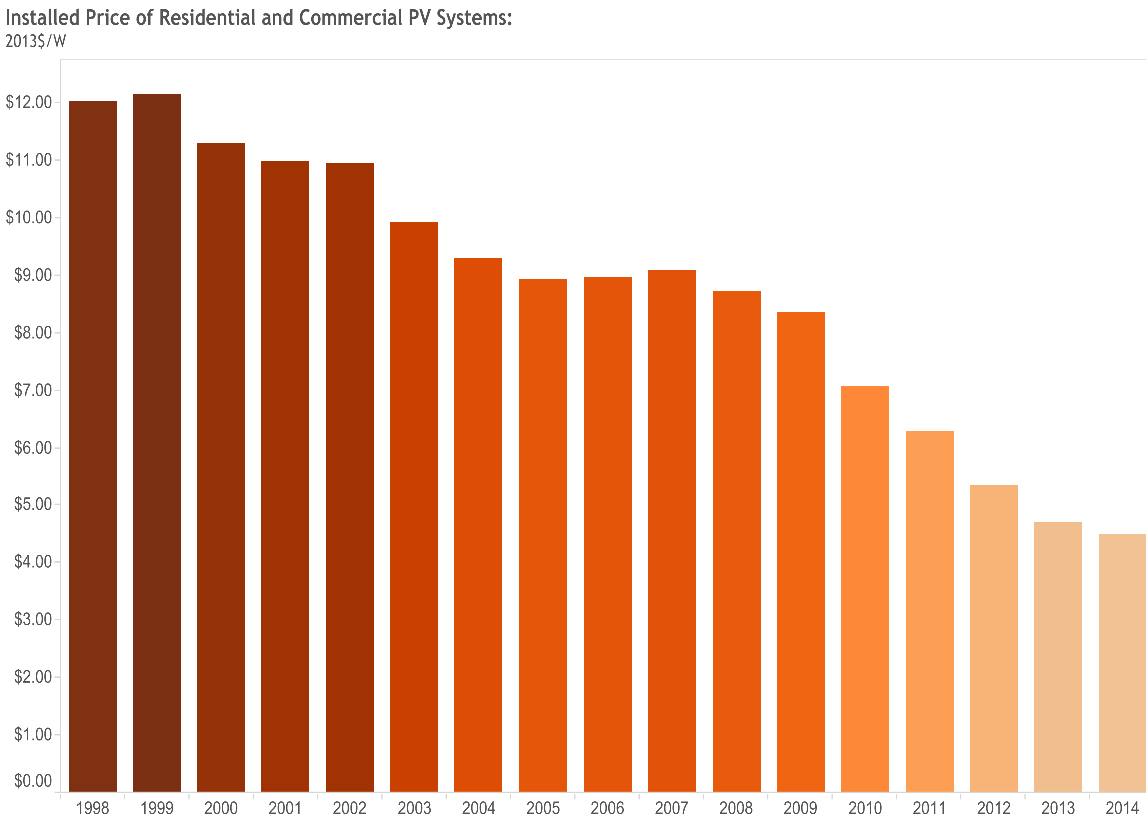
What is required, however, is steady progress in current technologies that facilitates rapid and widespread consumer adoption, high volume production, and corresponding price declines that keep transition costs low. As an illustration, Figure 27 shows cost trajectory assumptions in the U.S. study for key technologies such as solar PV, electric vehicles, LED lights, and hydrogen electrolysis. To achieve relatively low overall transition costs, the combination of R&D, market forces, and policy must result in cost reductions at least as significant as shown here, 20-30% below current for solar PV, EVs, and hydrogen electrolysis, and 70% for LED lights.

Figure 27. Technology Cost Trajectories Assumed for Solar PV, Electric Vehicles, Hydrogen Electrolysis, and LED Lamps, 2015-2050



Price declines assumed in the U.S. analysis over time as a function of technology maturity and market potential are not unreasonable. Falling cost trajectories as a result of technological learning that occurs as production volumes increase are common in many industries. For example, in the semiconductor industry "Moore's Law" has long been a widely recognized rule of thumb for projecting future prices as a function of cumulative global production. This phenomenon has also occurred in the energy industry, long ago in the case of many conventional technologies, and much more recently in the case of new low-carbon technologies. Figure 28 shows a 60% decline in historical prices of installed solar PV systems in the U.S. from 1998 to 2014.

Figure 28. Historical Prices for Installed Solar PV Systems, 1998-2014



Source: *(LBNL, 2015)*

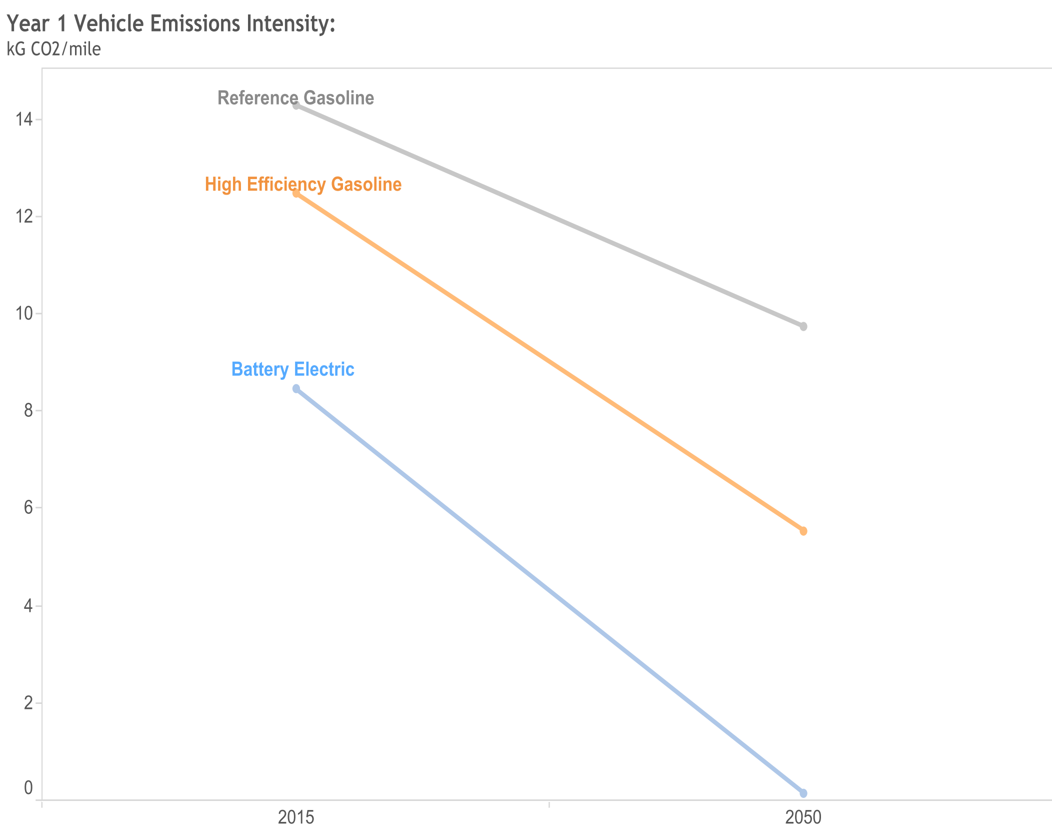
__Deep Emission Reductions Require Cross-Sector Coordination__

Decarbonization is an interplay between the carbon intensity of final energy supply and the fuel type and energy efficiency of end-use equipment. In early stages of decarbonization, the interactive impact between these factors on overall emissions is modest, and the effect of single-fuel strategies (e.g. higher efficiency use of the same fossil fuel supply) can be similar to that of fuel switching to lower carbon sources. As deep decarbonization proceeds, however, fuel switching to lower carbon sources becomes the paramount factor in lowering emissions.

This can be visualized in the case of LDVs (Figure 29). The difference in emissions intensity of efficient ICE vehicles and EVs on an average grid is significant but not overwhelming (around 30%) in 2015. By 2050, as grid electricity approaches full decarbonization, the difference is like night and day, with EV emission intensities 30 times lower. From this perspective, ICE-only emissions strategies are a dead end.

Achieving the full emissions benefit of parallel investments in supply side carbon intensity reduction and demand side fuel switching requires well-coordinated timing of deployment, for example ensuring the readiness of charging infrastructure for EVs in proportion to demand. This indicates the need for joint planning and well coordinated policy signals (pricing and/or quantity) across economic sectors that traditionally have had little to do with each other from either a market or regulatory perspective, such as electric power and transportation.

Figure 29. Vehicle Emission Intensities for Reference Case Gasoline Engine, High Efficiency Gasoline Engine, and Battery Electric Vehicle



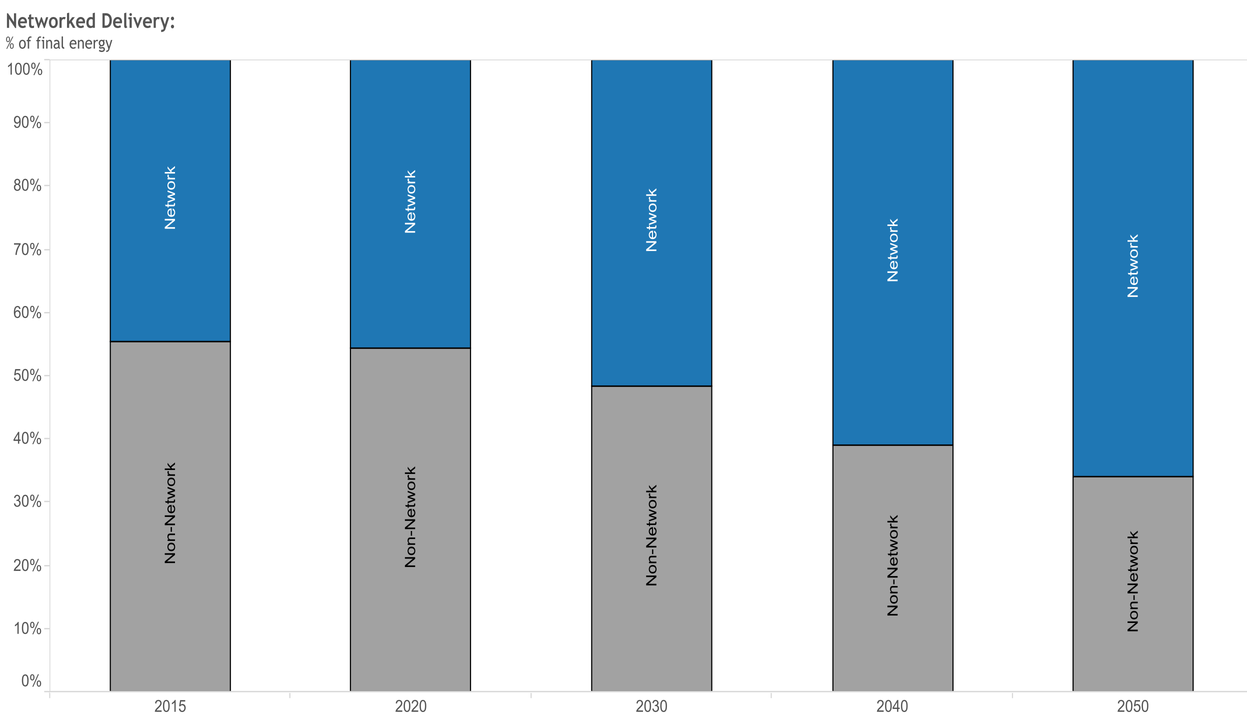
Network Supply of Low-Carbon Energy Requires a Sustainable Business Model

In a deeply decarbonized system, the majority of final energy will be delivered to end users either in the form of low-carbon electricity or partly decarbonized pipeline gas (Figure 30). This energy is supplied by network providers – the electric power grid and the natural gas pipeline. Network providers have traditionally been regulated (or public) electric and natural gas utilities.

The role of network providers in implementing low-carbon policies is potentially critical, since they would constitute the main institutional vehicles for acquiring most of the large, long-lived, high capital cost equipment and infrastructure required for deep decarbonization. Policy makers who currently pay little attention to utilities will need to readjust their focus to ensure that the regulatory signals relevant to procurement, rate-making, and cost allocation are compatible with the needs of the low-carbon transition.

The demands on regulated utilities will grow heavier as deep decarbonization proceeds, and the traditional balancing act between reliable service provision, environmental performance, and cost containment will become more critical to decarbonization outcomes. The current practices and business models of regulated utilities (and/or their unregulated suppliers) will be challenged – concrete examples being their adequacy for dealing with higher levels of solar PV distributed generation, and decreasing capacity factors for natural gas generators.

Figure 30. Final Energy Delivery, Network versus Non-Network Delivery to End User, Current and 2050 Deep Decarbonization



IV. Policy Pathways

The U.S. deep decarbonization analysis supports three fundamental conclusions regarding GHG mitigation policy:

- Achieving deep decarbonization of the U.S. energy system by mid-century is technically feasible and economically affordable. The policy question is not if deep decarbonization should be pursued, but how best to accomplish it.

- Deep decarbonization entails a transformation of energy supply and end-use infrastructure, in which incumbent technologies predicated on uncontrolled fossil fuel combustion are replaced by efficient and low-carbon technologies. The task of policy makers is to create conditions for that transformation.

- Most key infrastructure has an economic lifetime on the same order as the time remaining until mid-century. Near-term policy and investment decisions must be consistent with the transformation path, or else risk missing the target, stranded assets, and higher costs.

This chapter continues four sections to illuminate the considerations involved in constructing a successful policy approach to deep decarbonization:

Section A. What policies must accomplish. Policy formation must begin with an understanding of what policies must accomplish – the physical, financial, and institutional outcomes required by deep decarbonization.

Section B. The policy landscape. Effective policy requires fitting the available policy tools to the policy landscape, which differs by jurisdictional level, sector, and region.

Section C. Rethinking common assumptions. Effective policy needs to start with questions, observations, and analysis. It is important to be aware of the limitations of many conventional policy prescriptions and analytical approaches with regard to deep decarbonization.

Section D. Rethinking current policy. Current policies such as the Clean Power Plan, the Renewable Fuel Standard, CAFE standards, and building energy codes should be re-evaluated in terms of what will be required for deep decarbonization in the electricity, fuel supply, transportation, and building sectors.

A. What Policies Must Accomplish

Climate mitigation policies are not an end in themselves. Policy design must begin not as a theoretical exercise, but with an understanding of what policy needs to accomplish, namely the physical, financial, and institutional outcomes required by deep decarbonization. The key policy objectives emerging from the U.S. 2050 study are described in this section, beginning with the summary list below.

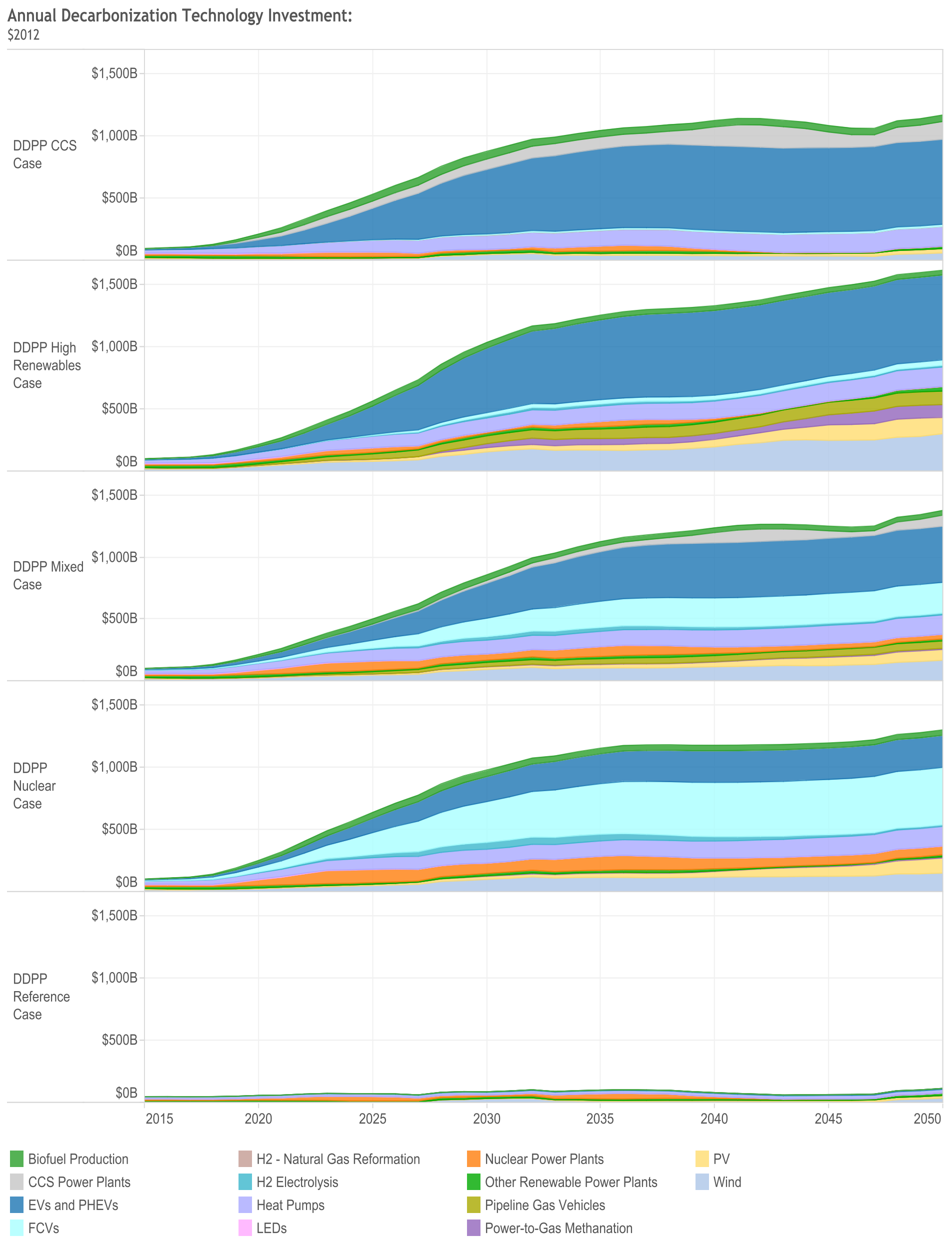
Key Policy Objectives

- Anticipate investment needs and build a suitable investment environment
- Incorporate future carbon consequences in current purchasing decisions
- Create stable drivers for sustained long-term transitions
- Develop institutional structures for coordination across sectors
- Integrate supply and demand-side planning and procurement
- Create the right kinds of competition
- Enable the required rates of consumer adoption
- Catalyze the needed cost reductions in key technologies
- Limit cost increases faced by consumers
- Minimize inequitable distributional effects

Anticipate Investment Needs and Build a Suitable Investment Environment

Across all U.S. deep decarbonization scenarios, the total annual investment requirement for low-carbon and efficient technologies rises from less than $100 billion today to over $1 trillion in about 20 years (Figure 31). This is not large relative to total investment in a much larger 2030s economy, and financial markets can readily supply this level of capital if returns are adequate and mechanisms are in place. To ensure that these conditions are met, investment needs must be anticipated and a suitable policy framework constructed. A policy framework that achieves the objectives laid out in the rest of this chapter will provide most of the enabling conditions for adequate investment.

Figure 31. Annual Investment Cost for Key Low-Carbon Technologies, All U.S. Deep Decarbonization Scenarios

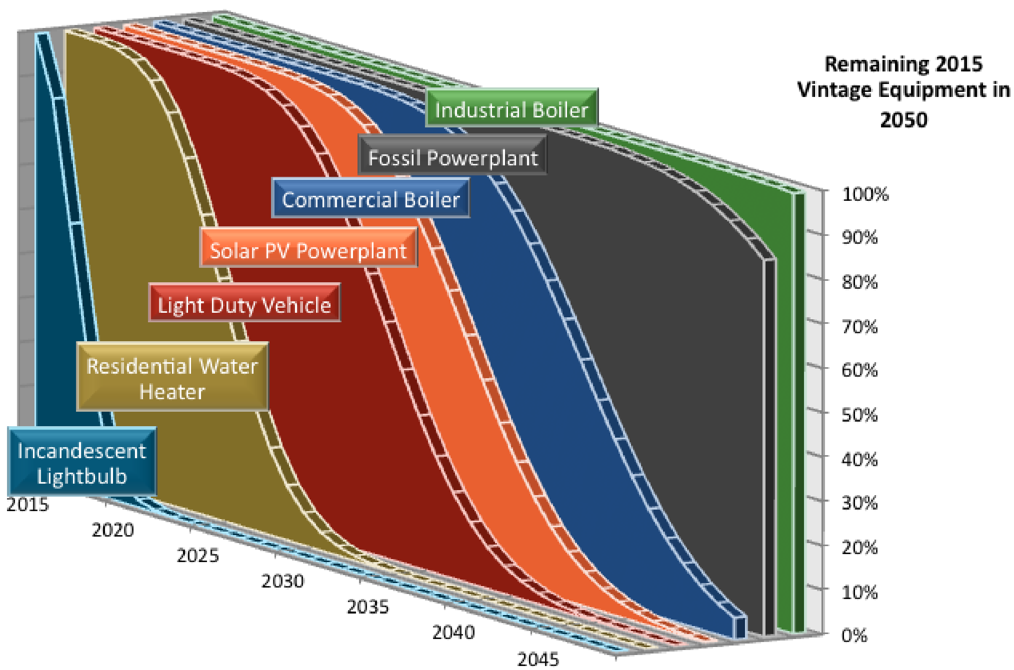


Incorporate Future Carbon Consequences In Current Purchasing Decisions

A key finding of the U.S. 2050 study is that deep decarbonization can be achieved by replacing existing equipment and infrastructure at the end of its economic lifetime, but that failure to replace it with sufficiently low-carbon equipment risks either missing emission reduction goals or early retirement. Much of the most important equipment and infrastructure is long-lived, with lifetimes on the order of the time remaining between now and 2050. Put differently, this means that for many kinds of equipment and infrastructure installed today, a substantial amount of it may still be in service at mid-century (Figure 32).

For a natural replacement strategy to succeed, current purchasing decisions for long-lived equipment and infrastructure must incorporate future carbon consequences. It is not obvious that currently proposed carbon pricing schemes will achieve this outcome, as the low-carbon replacements for many long-lived items – for example, electric industrial boilers – fall high on a marginal abatement cost curve based on current energy costs and electricity emissions intensities. "Working up the supply curve" based on a forward looking perspective could lead to emission reduction dead ends. The alternative needed is to incorporate back-casting into purchasing decisions, through pricing, emission standards, or other approaches.

Figure 32. Survival Curves for Equipment Important for Carbon Emissions

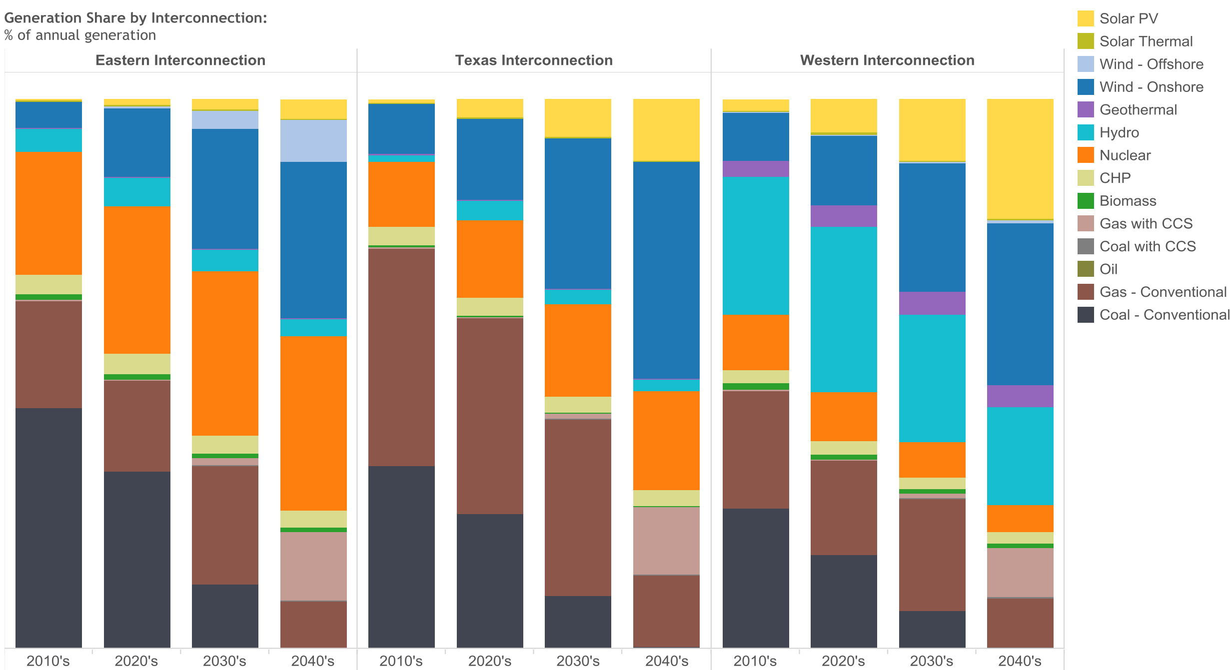


Create Stable Drivers for Sustained Long Term Transitions

A corollary to the need for timely replacement of infrastructure and equipment with low-carbon versions is the need for sustaining that approach over a time horizon of several decades. Decarbonization of the electricity sector provides a good example, as uncontrolled fossil generation is retired from the system and replaced with low-carbon generation (Figure 33).

Simultaneously expanding electricity supply and increasing the share of low-carbon generation implies not a one-time whirlwind of new purchases but a steady procurement process over three decades based on stable policies and stable incentives for investors, utilities, and developers of generation and transmission resources. It will also require consistent and streamlined treatment of siting and other regulatory processes. Ad hoc decision-making and inconsistent incentives will create serious obstacles to a sustained long-term transition.

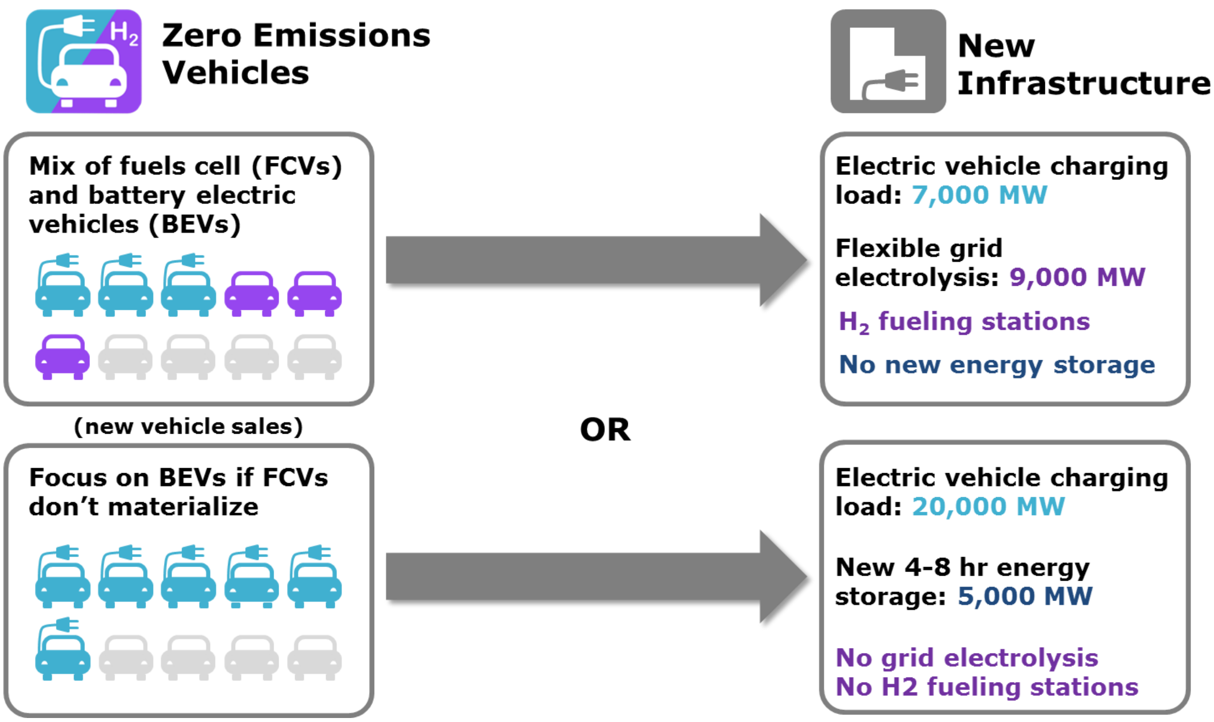
Figure 33. Generation Mix by Decade for the Three U.S. Interconnections



Develop Institutional Structures for Coordination Across Sectors

Cross-sector interactions will become increasingly important for both emissions reductions and costs in a low-carbon transition. Many cross-sector interactions that are of little significance in the current system will become central concerns in the future. For example, California will soon face decisions that link choices between fuel cell and electric vehicles with choices between hydrogen production and battery grid storage (Figure 34). Currently there is no shared institutional structure, either market or regulatory, to coordinate such interactions between the transportation and electricity sectors.

Figure 34. Pathways-Dependent Interactions Between Transportation and Electricity Balancing, Zero-Emission Vehicle (ZEV) Options for California

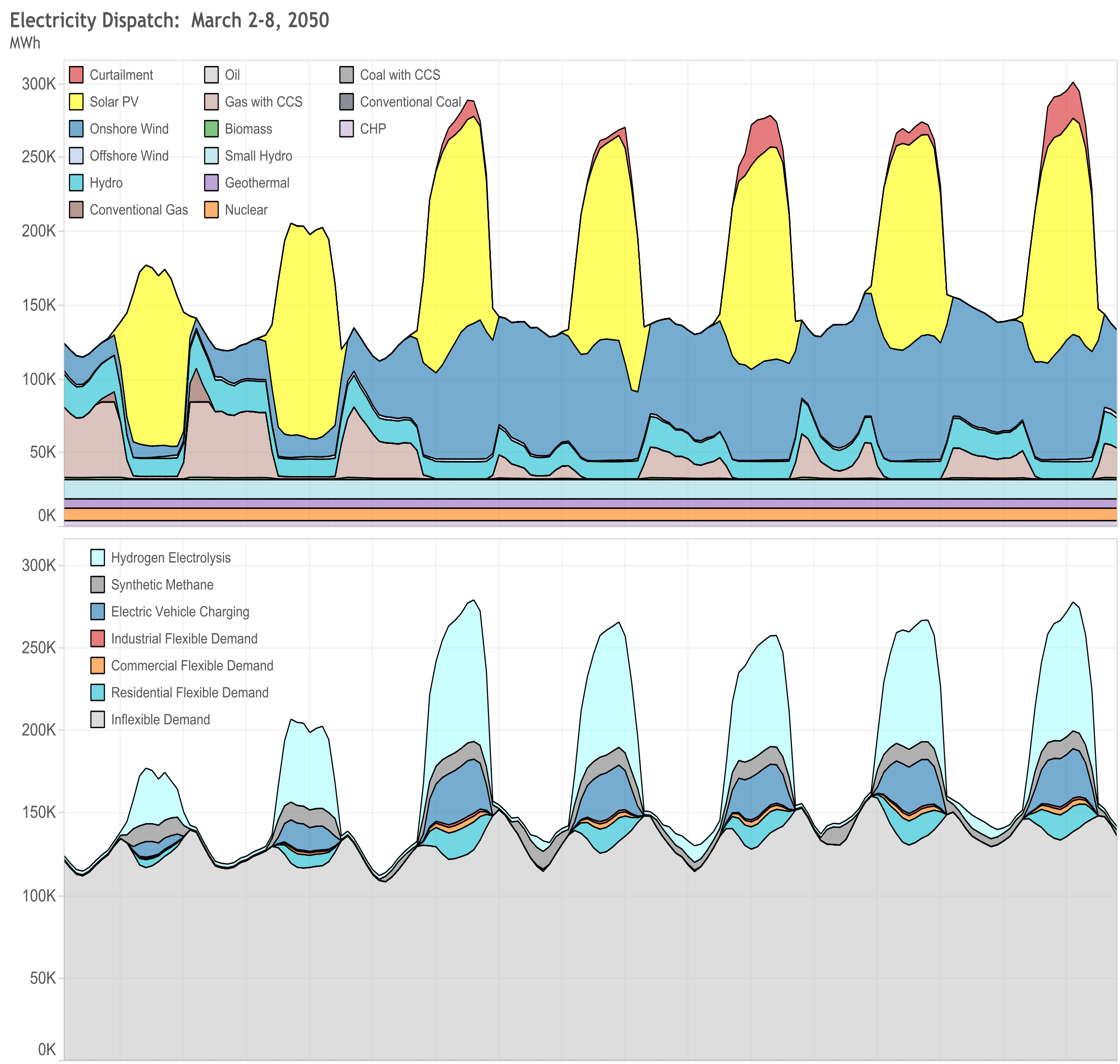


Source: (E3, 2015)

Integrate Supply and Demand-Side Planning and Procurement

A major challenge in cross-sector coordination comes when planning and procurement in a multi-sector system need to be closely integrated, as they would be in a deeply decarbonized electricity system comprising both supply-side generation and a variety of demand-side loads including transportation and fuel production. Maintaining reliability in a system with high penetration of inflexible generation (wind, solar, and baseload nuclear) requires correspondingly high levels of flexible demand (EV charging, hydrogen and SNG production, industrial and building loads) (Figure 35). The capability to provide demand-side flexibility at the required capacity, spatial, and time scales must be planned and procured in tandem with supply-side resources, and on the operational side wholesale electricity markets and reliability standards must be re-designed to work on both sides.

Figure 35. Electricity Dispatch in WECC, Generation and Load, March 2050, Mixed Case

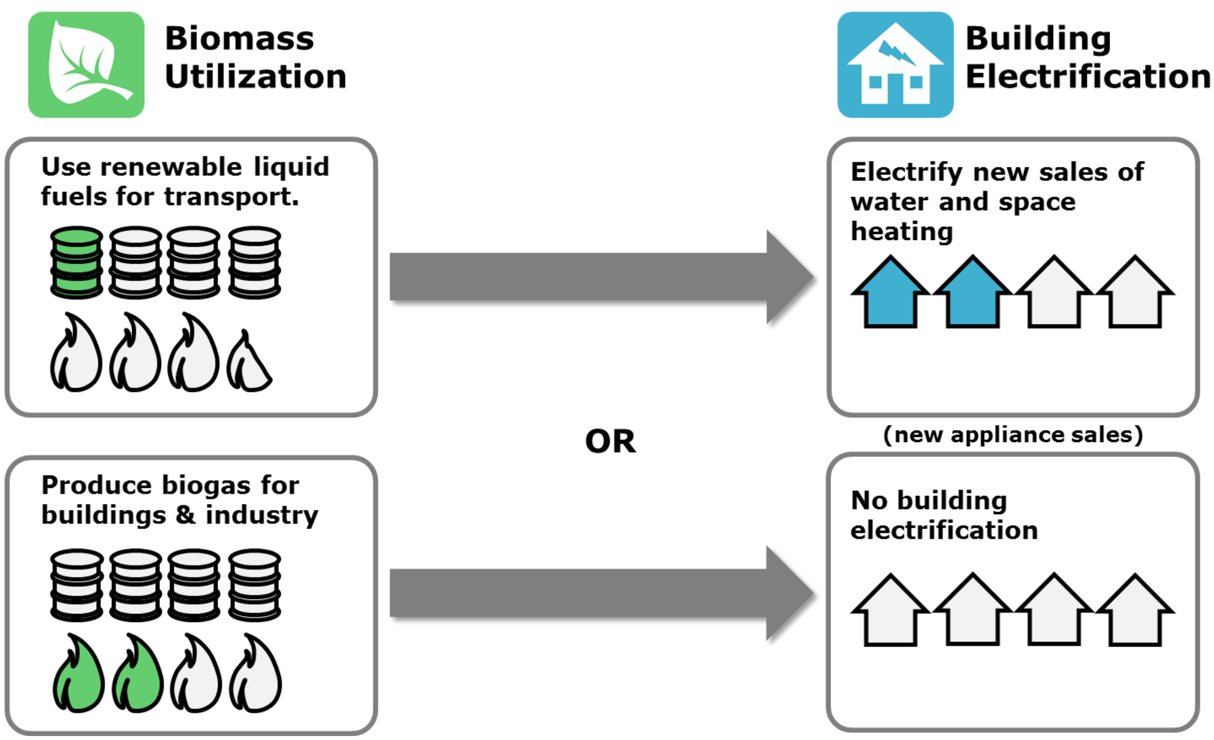


Create the Right Kinds of Competition

Competition among technologies is potentially an important way to drive innovation and reduce costs. However, unexamined conventional assumptions about what technologies might be in competition, for what applications, are likely to lead to the construction of policies and markets that result in unproductive competition. The development of long-term low-carbon pathways is essential to understanding what types of competition have value. For example, the U.S. 2050 study shows that the use of scarce biomass feedstocks to produce ethanol as a gasoline substitute is a misallocation of resources in the long run, since there are other ways (EVs, FCVs) to eliminate gasoline use from light-duty transportation. Policies that produce competition between ethanol and alternative vehicle technologies are unproductive from a deep decarbonization perspective.

Higher value uses of biomass lie in other applications, such as biodiesel to replace fossil diesel and renewable pipeline gas to replace fossil natural gas in building and industrial use. A "fork in the road" that California may confront in the 2020s is the unexpected tradeoff between allocation of biomass and the extent of building electrification (Figure 36). The competition implied in these pathway choices is between biodiesel and pipeline gas for use of biomass resources, and between building shell improvements and electrification for reducing emissions from building energy use. There is currently no institutional structure, either market or policy, for encouraging these kinds of competition (or for managing the cross-sector implications of how these competitions turn out).

Figure 36. Biofuel Pathway-Building Electrification Tradeoff, Options for California

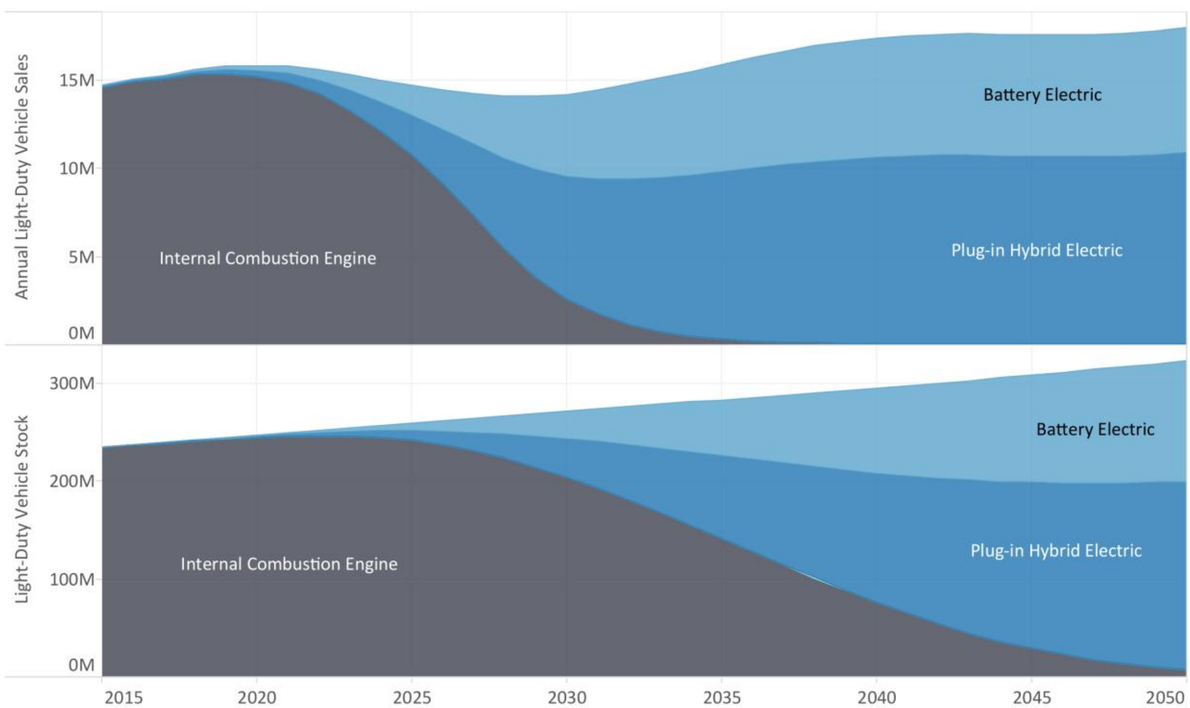


Source: (E3, 2015)

Enable the Required Rates of Consumer Adoption

The rate of energy supply side decarbonization – electricity and fuels – is amenable to control by a variety of policy, regulatory, and market mechanisms. On the other hand, the rate of demand-side adoption of efficient and electric end-use technologies, from buildings to industry to transportation, fundamentally involves consumer choices. Enabling the required rates of consumer adoption is a critical policy requirement. Deep decarbonization pathways analysis provides insight into the required adoption rates, for example in the light duty vehicle fleet (Figure 37). To achieve this level of adoption is likely to require a combination of upfront cost reductions, consumer incentives, and roll-out of a convenient fueling infrastructure coordinated with the share of alternative vehicles in the LDV fleet. Such strategies require working across industries – for example, with auto manufacturers and electric utilities – and need to be robust to changes in factors that affect consumer purchasing decisions, such as gasoline prices and interest rates.

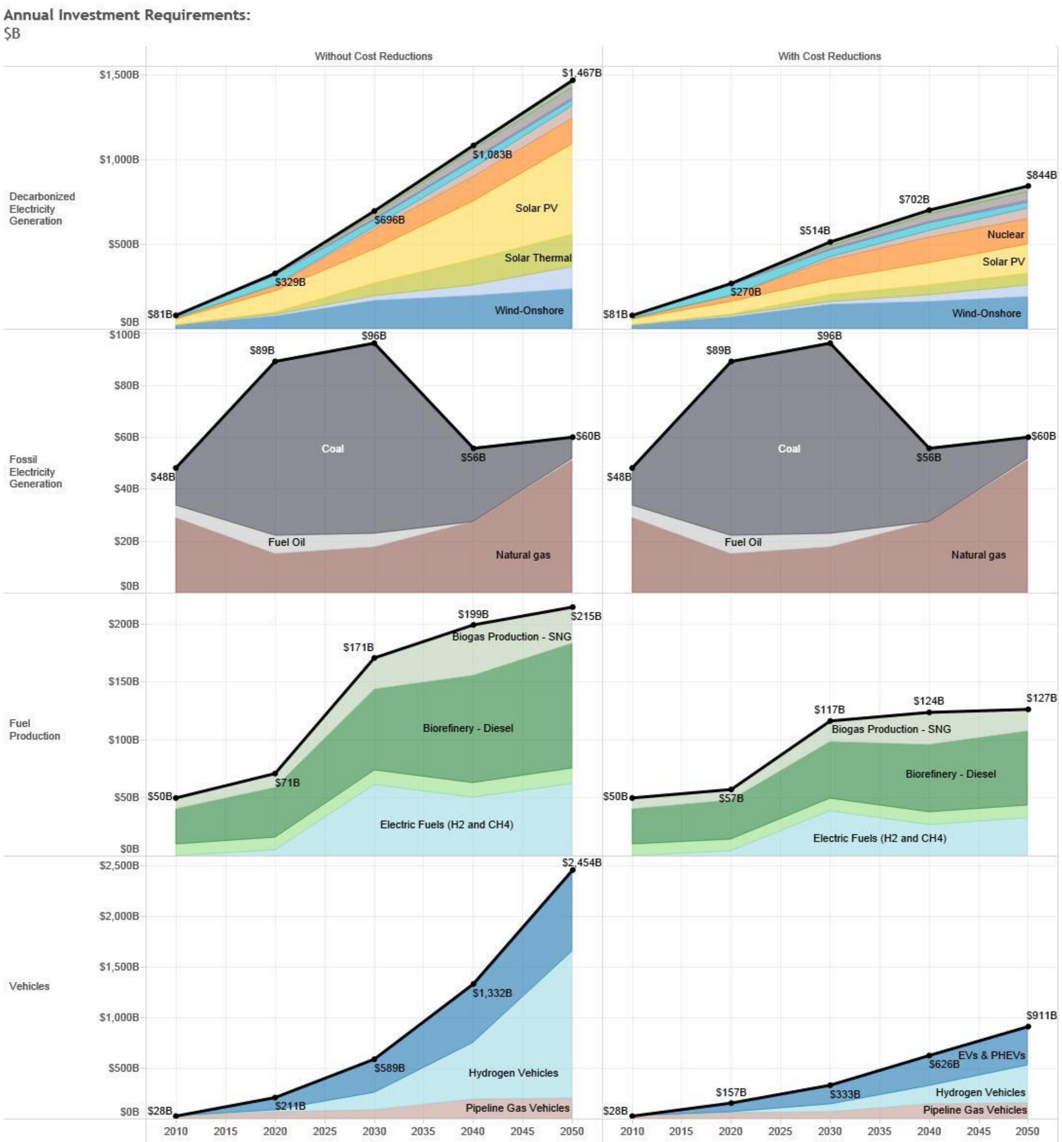
Figure 37. Light Duty Vehicle Sales and Total Stocks, 2015-2050, Deep Decarbonization High Renewables Case



Catalyze the Needed Cost Reductions In Key Technologies

Deep decarbonization is fundamentally the process of infrastructure transformation through the adoption of efficient and low-carbon technologies. Reducing investment requirements and upfront costs to consumers requires reducing the cost of the technologies themselves. Policy makers can catalyze the needed cost reductions by creating large markets for these technologies, leading to high production volumes and technological learning. Analysis of deep decarbonization pathways for the sixteen largest global emitting countries shows that learning-by-doing in large global markets for low-carbon generation, fuel production, and alternative vehicles potentially reduces annual investment costs, compared to stand-alone markets in the individual countries, by a factor of two (Figure 38). Coordinated RD&D and demonstration projects also play a role at earlier stages of technology development.

Figure 38. Annual Investment Cost for Low-Carbon Technologies With and Without Global Markets

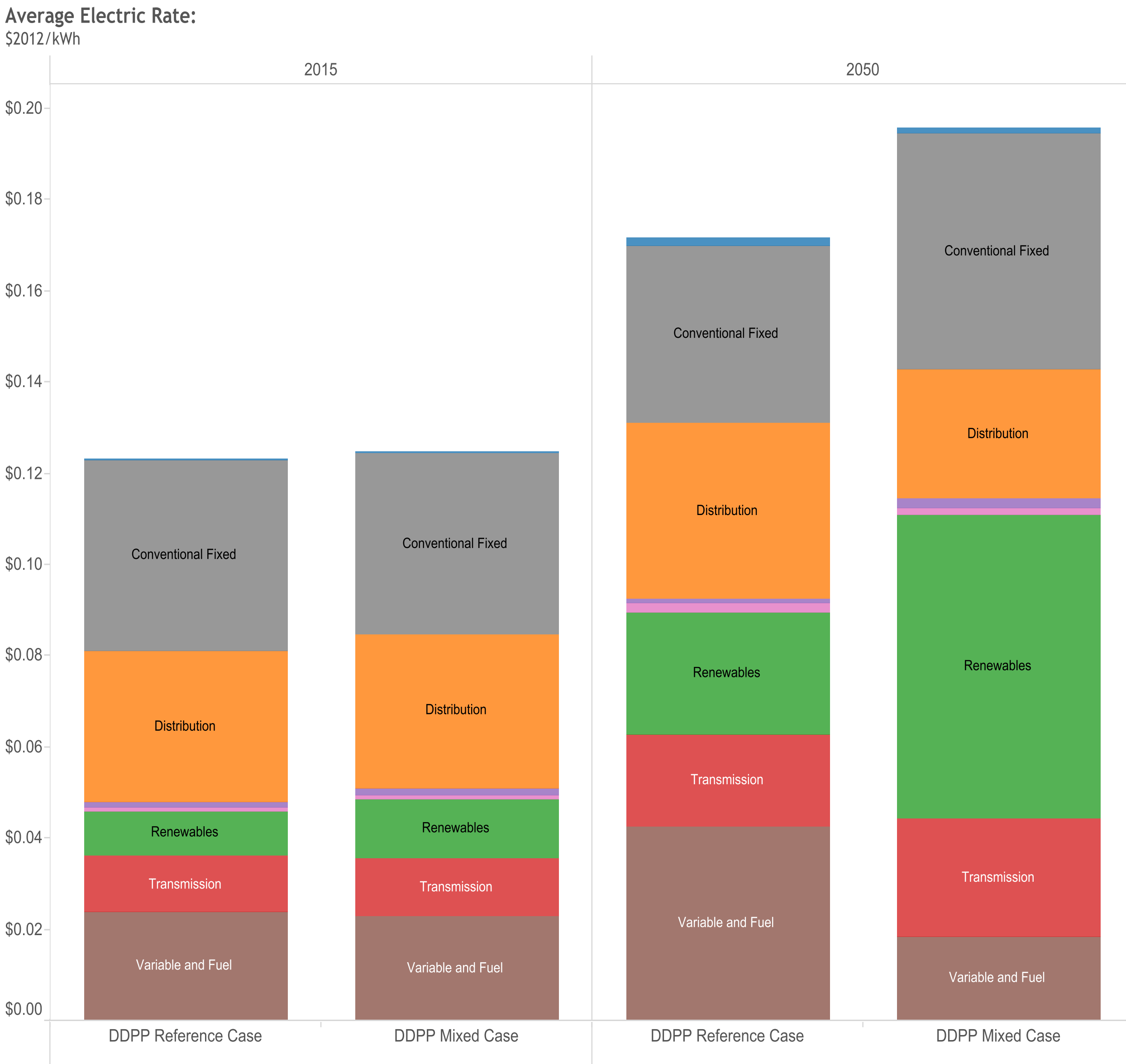


Source: (DDPP, 2015B)

Limit Cost Increases Faced by Consumers

Limiting the cost increases, and the rate of increases, faced by consumers is a key to the political sustainability of a low-carbon transition. Taking a long-term view can be helpful to policy makers in determining how to mitigate cost increases or make them more gradual. For example, in the U.S. 2050 mixed case, average retail electricity rates increase about 50% in real dollars, but if spread evenly over a 35-year period, this constitutes only a 1.6% average annual rate increase (Figure 39). Reference case rates during this period increase 1.1% per year, so the incremental increase in the decarbonized mixed case is 0.5% per year. Energy efficiency is a key to cost management, as reducing the amount of energy consumed to provide an energy service – for example, lighting a room or heating a building – can offset the effect of increased rates on the overall consumer bill.

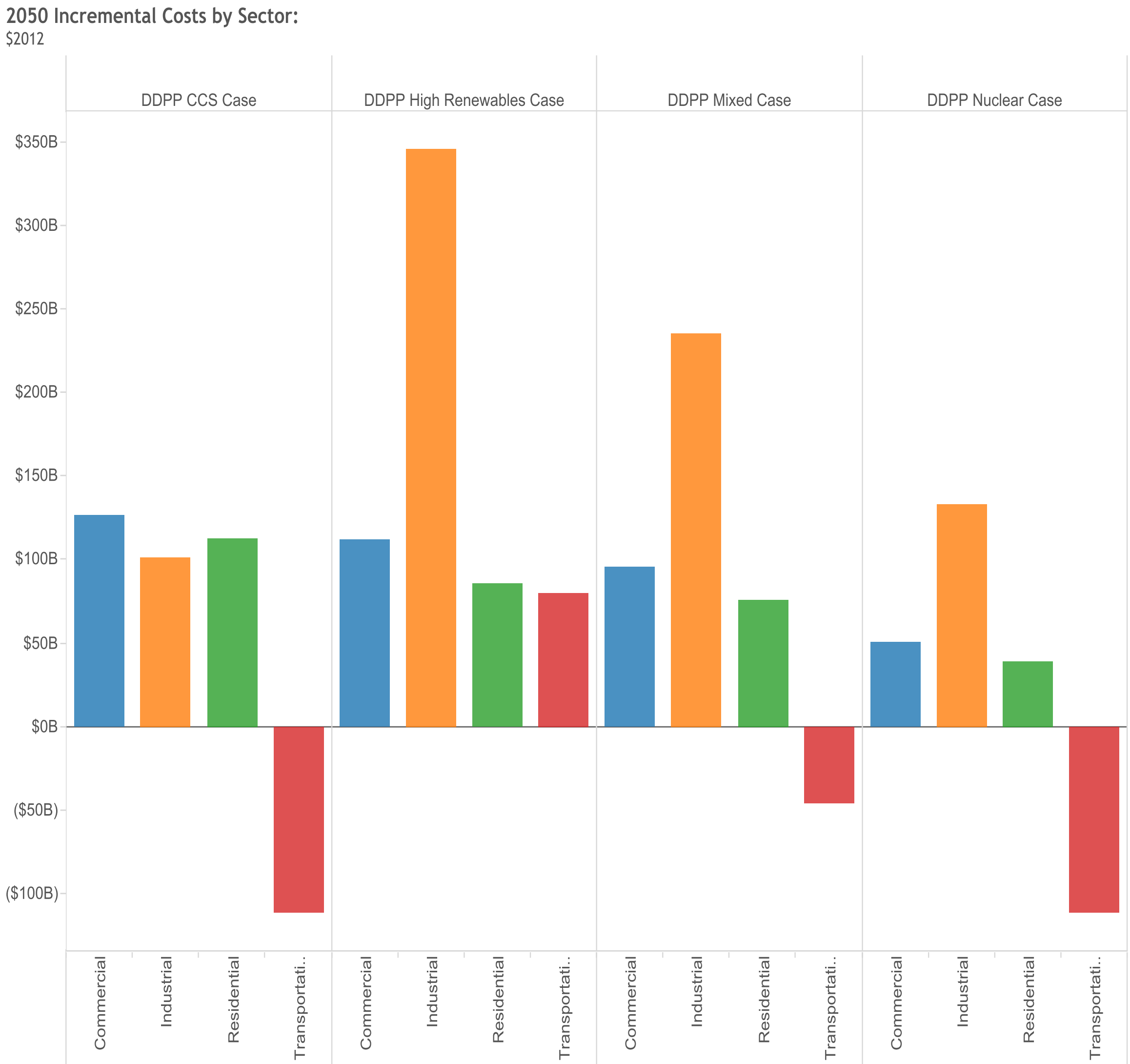
Figure 39. U.S. Average Retail Electricity Rates, Current and 2050 Deep Decarbonization Mixed Case



Minimize Inequitable Distributional Effects

Another requirement for the political sustainability of a low-carbon transition is minimizing inequitable distributional effects, whether these are regressive cost impacts on individuals as a function of income level, or differential costs across sectors or regions. There are many ways policy can address these impacts, for example cost allocation in utility ratemaking that maintains lower rates for low income customers. The low-carbon pathway pursued, with different technology transition strategies by sector and industry, can have major implications for the distribution of costs across sectors (Figure 40).

Figure 40. Net Costs by Sector in U.S. Deep Decarbonization Scenarios in 2050, Relative to Reference Case



B. Developing Deep Decarbonization Policy

Basic Guidance for Policy Makers

The key to deep decarbonization is a transformation of energy supply and end-use infrastructure. The question facing policy makers is not whether but how to undertake this transformation. Basic guidance for policy makers as they pursue this goal can be summarized in the following five points.

Identify clearly what policy must accomplish. As described in the previous section, creating the right policy instruments depends above all on being clear about what policy must accomplish, and using that as the test for its suitability. Many of the key objectives for deep decarbonization were described in the previous section – the physical, financial, and institutional needs of energy system transformation. Understanding these objectives will inform the kinds of economic and environmental regulations, markets and incentive structures, standards and RD&D programs required.

Have a plan. Deep decarbonization will not occur as a byproduct of undirected market activity. Planning is required to coordinate decarbonization measures within and across sectors, regions, and time periods. Deep decarbonization planning is necessarily a public-private partnership, across a wide range of activities – investment, manufacturing, interoperability standards, RD&D, etc.

Have a business model. In each domain of the energy transition there must be a workable business model that attracts investors, encourages innovation, and allows the providers of energy and equipment to make money and consumers to have options and control costs. Policy proposals that can't be expressed in terms of a viable business model are likely to be poor policies in practice. Thinking from a business perspective is an essential discipline for policy makers and analysts.

Prepare strategy for future choices. Many key pathways decisions will be made in the future, meaning that planning must be adaptable rather than rigid, and robust against uncertainty. A strategy for informing future choices includes such questions as what metrics will we use to decide? How can we generate the information we need? How shall we gauge risk? What is the point of no return? Having such a strategy is also a useful tool in the present.

Set a high bar for analysis. Many claims about the technical feasibility and cost of energy system changes and specific technologies and policies are based on analysis that is biased, poorly executed, or lacks rigor. Success in deep decarbonization requires policy makers to set a higher bar for the quality and relevance of analysis. This starts with having capable, technically competent advisors and asking the right questions.

Measures of Effective Policy

As a general and high-level diagnostic, some key characteristics of effective policy include the following:

- **Focused** on high priority areas, not spread overly thin
- **Workable** implementation strategy
- **Simple** to explain, clear messages

- **Coherent** across policy components, aligns incentives of key actors
- **Adaptive** to new information and actual results
- **Anticipatory** of future needs, impending forks in the road
- **Robust** to different failure modes, has alternatives

By contrast, ineffective policy is often based in poor analysis, ideology, or narrow self-interest, and will tend to be theoretical rather than empirical, hard to explain, lack a workable implementation plan, brittle, unprepared for problems that may emerge, and result in minimal GHG reductions for the cost and effort, or dead-end pathways that do not lead to deep decarbonization.

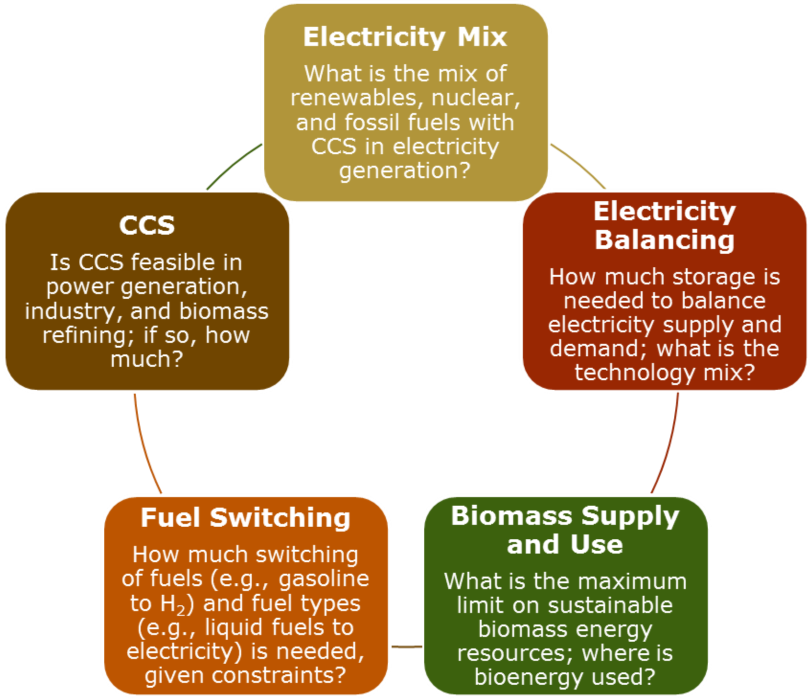
Two Transformations and Five Elements

Cut to its essentials, the U.S. study shows that the two main transformations required in the medium term are a high level of electricity decarbonization and a high share of alternative (electric or fuel cell) LDVs in new vehicle sales by 2030. During the same period, the groundwork needs to be laid for other transformations that will take place in bulk mostly after 2030 – high uptake of alternative HDVs, building and industrial electrification, decarbonized pipeline gas, low-carbon biofuels, and large scale flexible loads such as hydrogen production for electricity balancing.

Reflecting on what is required to substantially decarbonize electricity and new LDVs by 2030 reveals some of the complexities of the policy challenge. First, the kinds of government action needed in these two areas are fundamentally different. Electricity carbon intensity can be directly controlled by regulatory action, which for success must also maintain reliability, limit costs, meet other environmental standards (e.g., water, land use), and provide a viable business path for utilities and the power industry. Alternative LDV uptake depends on consumer adoption, in which the role of government is less direct – e.g., establishing markets, incentives, operability standards, manufacturing partnerships, and fueling infrastructures.

Second, technology choices, investment decisions, and policy design in generation and LDVs cannot be made independently of those in other domains of the low-carbon transition. The U.S. study identifies five fundamental elements of deeply decarbonized energy systems (Figure 41) – generation, electricity balancing, fuel switching, CCS, and biofuels – where the choice of pathway in one area can profoundly affect the options in others. For example, balancing solutions in a highly renewable generation mix will be very different from those in a high CCS mix.

Figure 41. Five Interacting Elements that Determine a Deep Decarbonization Pathway



Addressing the interdependence and contingency implied by these relationships will require government to anticipate and plan for future choices – for example, through RD&D, sectoral benchmarks, market discovery, and new institutional arrangements that cross jurisdictional silos. It will also require boldness by the private sector, which must bootstrap markets, attract investment, test new technologies, improve products, and gain consumer confidence on a short timeline.

The Policy Toolkit

Policy can attempt to reduce GHG emissions in many different ways, both direct and indirect, using a varied set of tools. It can set limits on emissions or emission intensities. It can create price signals to incorporate externality costs and influence purchasing decisions. It can directly require the adoption of efficient and low-carbon technologies, or it can provide incentives for investment in them, or consumer adoption of them. It can encourage the development or improvement of such technologies. Some common types of policy tools and examples of how they are used to affect GHG emissions, along with observations on their implications, are shown in Table 4.

Table 4. Some Common Types of Policy Tools for Energy and Climate Policy

Policy Tool	Example	Comment
Carbon target	U.S. Copenhagen commitment, California 2030 target	Provides clarity about end point, gives coherence to policies
Pricing mechanisms	Carbon tax, cap & trade, time of use pricing for electricity	Useful if price is right level, stable, actionable, equitable
Technology mandates	Renewable portfolio standard, EV sales requirements	Cost control and consumer adoption critical to success
Minimum standards	Building energy efficiency codes, emission intensity standard, CPP	Corrects market failures, requires cost control

Tax incentives and subsidies	Investment tax credit, federal loan guarantees	Subject to political change, challenge is consistency
RD&D support	DOE Sun Shot, California EPIC	Effective if well-targeted, consistent, adequate in scale
Consumer incentives	Utility rebates for customer purchase of LED lights	Standard tool for EE, can provide cost savings to society
Public-private partnerships	Energy Star labeling, manufacturing partnerships	Can be fraught (e.g. FutureGen) but many success stories
Decarbonization pathways analysis	US 2050 DDPP analysis	Keeps long-term transformation visible, illuminates choices

The Policy Landscape

Having identified what policy must accomplish for deep decarbonization to be achieved – the long-term objectives for policy – the effective formation of policy will require understanding the policy tools available, the policy landscape, and how these fit best together. It goes without saying that policy landscapes will change over time as technologies, costs, and political environments change. A key principle of sound policy in the energy arena is that policies must be empirically-based and adaptive as conditions change. Actual results must be compared to intended outcomes, and policies adjusted accordingly.

Key elements of the energy policy landscape include energy markets, governmental jurisdictions, sectoral characteristics, and state/regional conditions. Each of these topics is highly complex and the subject of a large literature, with many volumes of published law and regulation as well as economic, legal, and policy analysis. For the purposes of guiding deep decarbonization policy formation at a general level, a few broad observations on the policy landscape are helpful.

Energy Markets Are Fragmented and Imperfect

Electricity and natural gas distribution have the characteristics of natural monopolies, requiring public ownership or regulated private ownership to avoid monopoly abuses of consumers. Allocation of costs in these domains is a regulated process, not a direct market function. Wholesale markets and transmission in these domains also require sophisticated regulatory oversight to avoid abuse of consumers, often resulting in market distorting measures such as price caps.

Fossil fuel supply markets are fragmented geographically – only oil is a truly global market – and local supplies are often treated as strategic resources or local champion industries by governments, with many non-competitive implications. Both fossil and non-fossil energy supplies receive market-distorting subsidies. Environmental and social externalities of fossil fuel supply and use are well-documented and large, but difficult to quantify with precision and to incorporate in market prices. Information in both the supply and demand side of energy markets is highly asymmetric. Consumers and producers have very different access to information. Very little about energy markets can be approximated as ideal.

Sector Characteristics Determine the Suitability of Policy Instruments

The efficacy of policy instruments in achieving emission reductions depends on how well they match the characteristics of the market segment, sector, or industry to which they are applied. In general, four key characteristics will determine likely outcomes: (A) the expected payback period on investments; (B) the sophistication of market participants and their access to market information; (C) the presence of readily available substitute products; and (D) the ability to mitigate regressive distributional cost impacts of the policy.

Consider the application of four types of policy instruments commonly proposed for mitigation of GHG emissions: (1) price signals that incorporate externality costs such as a carbon tax or equivalent price from cap and trade; (2) incentives and subsidies; (3) minimum technology performance or content standards and other forms of direct regulation, and (4) RD&D support. An illustrative mapping of these instruments onto sector/industry characteristics is shown in Table 5. Emissions pricing is generally seen as the most economically efficient approach to GHG mitigation. However, conditions to generate an efficient market response to a tax or other emissions price signal are often not present. Incentives, such as tax credits and consumer rebates, are considered less economically efficient but are also less restrictive than minimum standards or other forms of direct regulation. Incentives change upfront costs faced by investors and consumers, and can be effective when payback periods exceed market participant willingness to wait for a return on investment. In addition, under circumstances in which the distributional impacts of an emissions tax are difficult to mitigate, incentives can be an effective alternative strategy.

Minimum standards are a common response in situations with serious market failures, including lack of transparent market information and/or consumers with limited knowledge. Finally, for new or underdeveloped industries, characterized by very long payback periods on investments and few substitute products, government support for RD&D is often necessary to encourage technology development.

Table 5. Matching Industry/Market Segment/Sector Characteristics to Policy Types

Industry/market segment/sector example	Willingness to see a relatively long payback period on investment?	Sophisticated buyers with access to transparent market information?	Many substitute products?	Ability to mitigate regressive distributional cost impacts of emissions price?	Suitable Policy Instruments
1) Utility investment in electricity generation	**Yes**	**Yes**	**Yes**	**Yes**	Emissions tax
2) Consumer purchase of EVs/PHEVs/FCVs	**No**	**Yes**	**Yes**	**Difficult**	Incentives & minimum standards
3) Consumer purchase of efficient/electric appliances	**No**	**No**	**Yes**	**Yes**	Incentives
4) Homeowner purchase of energy efficient building	**No**	**No**	**No**	**Yes**	Minimum standards
5) Business development of emerging technologies	**No**	**N/A**	**No**	**N/A**	Research & development support

"Energy Policy" Is Divided Across Federal, State, and Local Jurisdictions

The constitutional separation of state and federal jurisdictions is a defining feature the U.S. energy system. The state role is at least as important as the federal role in the U.S. energy system, and likely to grow even more important under in a transition away from an oil-based energy economy to one based on low-carbon infrastructure. States have the strongest jurisdictional levers over infrastructure investment decisions underlying the "three pillars" of supply decarbonization, energy efficiency, and fuel switching: state public utility commissions over utility procurement and rate making; state building codes and incentive programs over building energy use; state policies on fuel emission standards, transit system investment, and alternative vehicles in the transportation sector. California's ability to single-handedly set and control the outcome of statewide GHG emission targets is one indicator of a state's jurisdictional prerogatives in shaping its energy system and integrating carbon policies across its supply and demand-side components.

This is not to say that the federal role is unimportant, including potentially in cross-cutting areas such as a national carbon price and trade policies that encourage large global markets in low-carbon technologies. Some current important sectoral roles include setting vehicle and appliance efficiency standards, R&D, tax and incentive policies, biofuels, and FERC's role in regulating hydropower and electric and natural gas transmission and wholesale markets. EPA may be most important federal agency in providing drivers for a low-carbon transition, but the actions taken in response to these drivers lie mostly under state control.

An example of a policy ensemble acting across all levels from federal to local, based on their different jurisdictional authorities, is given below in Table 6 for the case of electricity generation.

Table 6. Generation Decarbonization Policy Approaches

Assessment	• 2050 requirement: reduce emissions intensity 30x while doubling generation • Uncontrolled coal is out, even CCS coal limited in quantity due to residual emissions & storage rate limits • Some natural gas for balancing, budget depends on gas use elsewhere in economy • New operating and procurement environment for power sector with high penetrations of intermittent renewables
Policy challenges	• Encouraging regional approach to generation and transmission for CO_2 compliance (e.g. CPP) • Market design for low-carbon operations, including flexible demand and gas generation with very low capacity factors • Mechanisms that simultaneously eliminate uncontrolled coal, reduce uncontrolled natural gas, and expand low-carbon generation
Federal	• CO_2 price through tax or cap and trade • Nuclear waste policy • CCS demonstration, rules for transport and storage • Extension of investment tax credit and production tax credit • Anticipatory site assessment on federal land (e.g. DRECP)

	• Wholesale market design consistent with decarbonization and regionalization
State	• CO_2 price through tax or cap and trade • Renewable portfolio standards • Emissions performance standards • Distributed PV policy with sustainable business model • Utility business model • Incorporate generation planning in larger portfolios (e.g. flexible load) • Regional integration of electricity planning and operations • Rate design consistent with decarbonization • Statewide anticipatory site assessment
Local	• Site permitting • Local incentives/financing for distributed energy resources

Energy Systems Have Strong Regional Identities

Energy systems have regional identities, in terms of both physical features and political economy, that affect the policy landscape for decarbonization. Location-specific resource endowments of fossil fuels and hydroelectric potential have shaped regional energy supply systems. Regional climate has shaped construction practices and building energy requirements, and regional patterns of settlement have shaped transportation options and fuel demand. Other physical patterns – renewable resource endowments, water availability, transmission distance, land use constraints, sub-surface geologic resources – may become increasingly prominent in shaping energy options and costs going forward.

Resource endowments have created regional industries (for example, oil production in Texas and Alaska, and coal production in West Virginia and Wyoming) with strong historical legacies, ties to local economies, and influence over policy. Regional energy supply systems are significant sources of employment and tax revenues, and these characteristics are good predictors of political positions taken by state representatives in Congress vis-à-vis energy and carbon policy. In some regions (for example, the southeastern US) electric utilities have extraordinary influence over a range of policy issues at the state level, from acceptance of nuclear power and its fuel cycle, to the adoption of renewable portfolio standards, to the existence of utility energy efficiency programs and/or the application of cost-effectiveness tests that determine the scope and effectiveness of such programs.

Regional energy characteristics will affect the cost and difficulty of the low-carbon transition, with distributional implications. Policies that are tied to relative changes – for example, fixed percentage reductions below a given year's emissions – may be relatively lower cost for states that have done little to date, as they still have potential low hanging fruit options, such as basic energy efficiency measures, to contain costs. On the other hand, policies that are tied to absolute targets, for example 1.7 tonnes CO_2 per capita in each state in 2050, may be more challenging for current high per capita emitting states.

A different aspect of regional energy identity can be seen in the wide range of state by state prices and expenditures for energy, shown for 2012 in

Table 7. Even ignoring data from Hawaii, an island that imports most of its energy supplies, there is a factor of two spread in average energy prices, a factor of three in energy expenditures per capita, and a factor of eight in energy expenditures as a percentage of GDP. Beyond simply underscoring regional variation, some interesting patterns emerge, with the highest energy prices generally in states that are not fossil fuel producers and the lowest in those that are. Yet the states with lowest energy prices also tend to have the highest expenditures on energy per capita and as a share of GDP. Demonstrating how deep decarbonization could benefit consumers in these states could be valuable in lowering political barriers to a low-carbon transition.

Table 7. Energy Prices and Expenditures Ranked by State, 2012 (EIA data)

Table E15. Energy Prices and Expenditures, Ranked by State, 2012

2012 RANKINGS

	Prices		Expenditures [a]		Energy Expenditures per Person		Energy Expenditures as Percent of Current-Dollar GDP [b]	
Rank	State	Dollars per Million Btu	State	Million Dollars	State	Dollars	State	Percent
1	Hawaii	40.04	Texas	155,921	Alaska	10,484	Louisiana	16.2
2	Vermont	29.11	California	136,364	North Dakota	10,049	North Dakota	15.3
3	New Hampshire	28.35	Florida	66,876	Wyoming	9,828	Mississippi	15.1
4	Connecticut	28.25	New York	65,134	Louisiana	8,544	Alaska	14.8
5	Rhode Island	26.35	Pennsylvania	53,954	Texas	5,983	Wyoming	14.7
6	Massachusetts	26.04	Ohio	49,326	Hawaii	5,608	Montana	13.5
7	Arizona	25.98	Illinois	48,091	South Dakota	5,598	Alabama	13.2
8	District of Columbia	25.83	Georgia	40,144	Montana	5,443	Maine	13.0
9	Florida	25.41	New Jersey	39,426	Nebraska	5,440	Kentucky	12.9
10	Maryland	25.41	Louisiana	39,322	Iowa	5,339	West Virginia	12.7
11	Alaska	25.33	Michigan	39,315	Maine	5,270	Arkansas	12.4
12	New York	25.24	North Carolina	36,204	Oklahoma	5,168	Oklahoma	12.3
13	California	24.70	Virginia	35,135	Mississippi	5,132	South Carolina	11.9
14	Delaware	24.64	Indiana	32,267	Kentucky	5,125	Vermont	11.6
15	New Jersey	24.11	Tennessee	28,636	Alabama	5,042	Idaho	11.5
16	North Carolina	23.69	Washington	27,570	Vermont	5,041	Texas	11.2
17	Nevada	23.47	Massachusetts	26,317	Kansas	4,944	New Mexico	11.1
18	Virginia	23.05	Missouri	26,146	Indiana	4,935	South Dakota	11.0
19	New Mexico	22.95	Alabama	24,291	West Virginia	4,757	Indiana	10.8
20	Maine	22.92	Minnesota	24,159	Arkansas	4,618	Iowa	10.8
21	Pennsylvania	22.73	Wisconsin	23,871	Minnesota	4,491	Hawaii	10.8
22	Missouri	22.50	Arizona	22,759	South Carolina	4,458	Tennessee	10.3
23	Oregon	22.28	Maryland	22,595	New Hampshire	4,447	Kansas	10.3
24	Tennessee	21.97	Kentucky	22,447	New Jersey	4,446	Nebraska	10.1
25	Montana	21.93	South Carolina	21,057	Tennessee	4,436	Missouri	10.1
26	Colorado	21.71	Oklahoma	19,719	Delaware	4,377	Michigan	9.8
27	South Carolina	21.67	Colorado	19,456	Missouri	4,340	Ohio	9.7
28	Georgia	21.60	Iowa	16,419	Virginia	4,292	Georgia	9.3
29	Washington	21.45	Mississippi	15,327	New Mexico	4,285	Wisconsin	9.1
30	Michigan	21.39	Connecticut	15,051	Ohio	4,269	New Hampshire	9.1
31	Wisconsin	21.05	Oregon	14,918	Pennsylvania	4,227	Pennsylvania	9.0
32	Kansas	20.90	Kansas	14,265	Idaho	4,215	Florida	8.6
33	Utah	20.82	Arkansas	13,623	Connecticut	4,190	Arizona	8.5
34	West Virginia	20.79	Utah	10,579	Wisconsin	4,170	Minnesota	8.2
35	Kentucky	20.65	Nebraska	10,093	Georgia	4,049	Utah	8.1
36	South Dakota	20.54	Nevada	9,982	Washington	3,998	North Carolina	7.9
37	Mississippi	20.46	New Mexico	8,928	Michigan	3,978	Virginia	7.9
38	Ohio	20.37	West Virginia	8,833	Massachusetts	3,960	New Jersey	7.8
39	Oklahoma	20.12	Hawaii	7,796	Maryland	3,839	Oregon	7.5
40	Minnesota	19.99	Alaska	7,656	Oregon	3,825	Nevada	7.5
41	Idaho	19.87	North Dakota	7,048	Colorado	3,749	Rhode Island	7.4
42	Arkansas	19.87	Maine	7,001	Illinois	3,737	Washington	7.3
43	Alabama	19.74	Idaho	6,725	North Carolina	3,714	Maryland	7.1
44	Nebraska	19.63	New Hampshire	5,877	Utah	3,706	Colorado	7.1
45	Illinois	19.10	Wyoming	5,667	Nevada	3,624	Illinois	6.9
46	Texas	18.82	Montana	5,473	California	3,589	California	6.8
47	Wyoming	18.51	South Dakota	4,669	Rhode Island	3,568	Connecticut	6.6
48	North Dakota	18.14	Delaware	4,014	Arizona	3,474	Massachusetts	6.5
49	Indiana	17.86	Rhode Island	3,748	Florida	3,461	Delaware	6.1
50	Iowa	17.82	Vermont	3,155	District of Columbia	3,398	New York	5.4
51	Louisiana	15.54	District of Columbia	2,152	New York	3,327	District of Columbia	2.0
	United States	21.65	United States	1,355,677	United States	4,319	United States	8.6

[a] The U.S. total includes $175 million of coal coke net imports, which are not allocated to the states.
[b] GDP = Gross domestic product.
Note: Rankings are based on unrounded data.

Web Page: All data are available at http://www.eia.gov/state/seds/seds-data-complete.cfm.
Sources: Data sources, estimation procedures, and assumptions are described in the Technical Notes.

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Low-carbon policies need to account for and leverage the physical and political economic realities of regional systems. Standards used to promote efficient building shells, air-conditioners, and electric heat pumps cannot be "one size fits all," but appropriately formulated for climate zones to avoid waste and frustration at the state level. In rural areas of the U.S., the main providers of electricity are the more than 900 rural electric co-ops, which have been beneficiaries of low cost federal hydroelectric power since the New Deal. The same federal policy vehicles offer an opportunity to support decarbonized electricity supplies for rural co-ops.

C. Policy Frames in Context

Effective policy begins with questions, observations, and rigorous analysis. Accepting unexamined assumptions can lead to ineffective or counterproductive policies. Many common policy frames and analytical approaches used in energy and climate policy were developed in the context of incremental changes to fossil fuel-dominated energy systems, not an energy transformation. Below is a preliminary look through the lens of deep decarbonization at the uses and limitations of a few widely applied conceptual approaches in guiding the energy transition.

Carbon price. Economists generally see carbon pricing as the foundational policy approach for reducing GHG emissions, by incorporating an externality cost into fossil fuel prices to eliminate a market failure. This premise has been accepted in the policy community to the extent that other approaches are often referred to as "complementary policies." There are energy market segments in which a carbon price may indeed provide a useful signal to sophisticated market players. For example, in industry, a carbon price might lead industries with different cost structures to adopt quite different responses – fuel switching, energy efficiency, CCS, process changes, dematerialization, and product redesign. These can be efficient outcomes that would be difficult to achieve solely through regulatory means. From the standpoint of deep decarbonization, however, establishing carbon pricing as the primary or only policy instrument has some important potential drawbacks.

(1) Carbon prices are an unstable price signal for attracting large-scale, long-term capital investment, which is essential to deep decarbonization. Because carbon prices are fundamentally tied to the price of fossil fuels either through a carbon tax or cap and trade, they are also tied to the rise and fall of those notoriously volatile prices. Consumers ultimately bear the costs of technology procured to supply energy to them, and there is a tradeoff between downward pressure due to competition, and upward pressure due to risk. For example, a potential wind energy developer facing only a carbon price and selling into a wholesale electricity market must make a very complex investment and return calculation, including such factors as long-term forecasts of carbon prices, natural gas prices, construction of other renewable and non-renewable generation in order to estimate system-level curtailment, construction of transmission to estimate local curtailment, permitting cost uncertainty, etc. These uncertainties impose high risks on investors, and will be reflected in a high premium on the cost of capital.

(2) Carbon prices are consistent with a "low-hanging fruit" policy that procures carbon reductions sequentially on the basis of marginal abatement cost (MAC). However, deep decarbonization requires systemic changes in which measures with high apparent MACs must occur in tandem with those with lower MACs.

(3) Carbon prices are likely to be capped, for political reasons, at levels too low to catalyze the transformations required for deep decarbonization. Carbon prices remain linked to analytically unsound expectations ("$20/ton"). Actual or implied prices greater than these expectations are often assumed to imply negative economic impacts, even though marginal carbon costs are actually a poor indicator of the impact on energy system costs.

(4) Price signals are very imperfectly refracted through fragmented energy markets, many segments of which are highly inelastic with regard to price. This can contribute to impacts on low-income consumers that must be counteracted by other policies, which may themselves not be politically feasible or easily implementable.

(5) Carbon pricing can contribute to an unfavorable political environment by creating an impression among the public of climate policy as a cost only, rather than as a physical transformation that can provide widespread economic benefits and a hopeful vision of the future.

Marginal abatement cost. Marginal abatement cost is seen as a complement to carbon pricing, by providing a sequence of abatement actions ordered by increasing cost ($/ton) and thus has figured prominently in climate policy discussions and analysis approaches. Increasing carbon prices, achieved through a mechanism such as a carbon tax or cap-and-trade, are often assumed to lead in practice to an orderly progression of abatement in the real economy, following the MAC curve. Most common energy system and integrated assessment models used for climate policy use MAC curves as the basis of their optimizations, determining the technology deployment resulting from a given carbon price. The MAC concept can be problematic from a deep decarbonization perspective for the following reasons.

(1) MAC is defined as the marginal cost of a decarbonization measure divided by the marginal emissions reductions from that measure; both of these factors are analytically ambiguous in a real-world energy system, because they are path dependent. Emission reductions are system responses that involve cross-measure and cross-sector interactions – for example, the emissions reduction impact of an EV depends both on the EV and on the emissions intensity of the grid – and thus are not a single-valued function of the measure. Thus the MAC of two identical EVs with identical costs is different depending on the electricity emissions intensity, either as a function of location or time. Especially in the case of deep decarbonization, involving many measures over long periods of time, there is no unique MAC curve – there are many different MAC curves depending on the order of deployment.

(2) The pairing of MAC with carbon pricing has long been at the heart of climate policy discussions, as it offers the prospect of a concise approach in which price reflects marginal benefit and is set equal to marginal cost. This creates the prospect of a smooth sequential climb up the MAC curve as carbon price increases. However, the U.S. analysis shows that deep decarbonization requires transformations in which multiple physical elements must change in tandem to achieve emissions goals. Some of these changes will have MACs – however ambiguous – that are quite different from each other. MAC based procurement, even if it were meaningfully defined – could well cause essential components to either be delayed or omitted.

(3) Attempts to make practical use of MAC curves, such as the iconic McKinsey curve, have succeeded in focusing policymakers on concrete actions needed to decarbonize, but have also demonstrated how hard it is to assign globally or nationally meaningful values to MAC. MACs based on global averages have little utility in specific locations where the underlying costs and emissions characteristics are very different. It's hard to imagine a policymaker even having the purview to decide between, say, variable speed motors versus micro-hydro generation, much less deciding on the basis of a MAC. These curves had an instructional value at a certain stage in the policy discussion, but they serve as a poor guide to practical energy-system decision making.

Social cost of carbon. The climate policy discussion often takes place in a cost-benefit framing, in which the costs of emissions mitigation are juxtaposed against the cost of economic damages from climate change. The marginal damage associated with a marginal emission is sometimes referred to as the social cost of carbon (SCC). SCC plays a useful role in regulatory decision making at the federal level, where it provides a non-zero proxy for the public benefits of reducing GHG emissions, for example in the setting of appliance standards. However, as an overall framework for climate policy SCC is problematic.

(1) The problem analytically with SCC is that future damages are fundamentally unknowable, since the relationships between emissions, radiative forcing, and climate response are uncertain and may be highly non-linear, and the economic consequences of the climate response depend on unknown tipping points. This is compounded by the problem of time scales and discounting of future damages.

(2) The cost-benefit framing for climate policy is not appropriate in situations in which societies are already committed to deep decarbonization, because it limits ambition to the level of the SCC, rather than whatever is required to achieve deep decarbonization. Once the transformational commitment is made, policy should be informed by the system costs of alternative pathways within an energy context. Fundamentally, the SCC was intended to guide “how much” mitigation is economically appropriate. Unfortunately, its application to decisions on “how” reductions may be achieved, once their level is established, is limited.

D. Rethinking Current Policy

The current ensemble of energy and climate policies in the U.S. has reduced GHG emissions and laid important groundwork for future reductions. Federal CAFE standards and appliance efficiency standards, and state level RPS and building standards, for example, have reduced energy use and carbon intensities relative to what would otherwise have occurred.

The circumstances shaping the ambition and effectiveness of these policies have varied: changes in technology costs; accommodating political reality in Washington or in state capitals; adjusting to national or regional economic conditions; pursuing the mandates of executive branch agencies; setting or following legal precedents; building political coalitions around common interests.

In most cases, policies were designed to work within a particular policy environment in the pursuit of short-term goals, generally incremental rather than transformational. While this can be a valid response to circumstances, the policy community must be aware of the difference between what is tactically expedient and what is required for the U.S. to be on the path to deep decarbonization.

This section provides a deep decarbonization perspective on four key areas of the energy transition and the current policy vehicles being used to advance them. The goal is not to criticize current policy, or to comment on the details of policy mechanisms, but to point out broad directions that must be followed to be consistent with achieving deep decarbonization and meeting U.S. commitments under the UNFCCC:

- **Electricity decarbonization** and the Clean Power Plan
- **Fuel decarbonization** and the Renewable Fuel Standard
- **Transportation energy** and CAFE standards
- **Building electrification and** energy codes and standards

Electricity Decarbonization and the Clean Power Plan

The federal Clean Power Plan proposes to use the EPA's authority under the Clean Air Act Sections 111.b and 111.d to regulate GHG emissions from power plants. It is intended by its advocates primarily to inhibit the construction of new non-CCS coal power plants, and to reduce emissions from existing uncontrolled coal plants, both of which are important steps. However, the statutory language of the CAA has dictated the CPP approach to a great extent, as the CPP was designed largely around the need to withstand federal judicial review, rather than from an electricity system perspective. Three important features of the CPP as currently proposed are the level of ambition for emission reduction targets, emphasis on state implementation plans, and the use of demand-side measures as flexibility mechanisms for compliance.

From the deep decarbonization perspective, for the CPP to serve as a driver of deep electricity decarbonization will require a significant evolution from its current form, or augmentation by complementary policies at the federal and state levels, which it is important that the CPP not undermine. Key priorities for electricity policy going forward as identified by the U.S. 2050 study include the following:

- **Drive near-complete decarbonization.** The U.S. study shows that generation emission intensities must be 30 times lower than current levels by 2050. This allows only a very low level of non-CCS fossil generation by mid-century, equivalent to less than 5% of total generation from uncontrolled natural gas plants. Across all scenarios, very high levels of near-zero carbon generation are required. While non-CCS natural gas generation can be important for renewable integration, in a deeply decarbonized system it can only be operated infrequently. With regard to the CPP, policies that drive a "natural gas transition" without also driving a great expansion of renewable, nuclear, or CCS generation, will not achieve the needed emission levels in the long run. State policies such as RPS may continue to be the most important driver of generation mix.

- **Encourage regional integration.** The U.S. study shows that the need for diversity of load and generation for balancing demand with supply in a low-carbon electricity system increases with the level of inflexible generation such as renewables and baseload nuclear. Expanding the locus of electricity planning and operations beyond present-day balancing authorities (aka utility control areas) to the regional scale will be essential for limiting cost and reserve requirements. Greater regional integration is a negative-cost, no-regrets policy priority in both the short and long term. The proposed version of the CPP provides few incentives for regional integration, and could provide counter-incentives in some cases.

- **Promote electrification.** The U.S. study shows that one pillar of deep decarbonization is a high level of electrification of transportation and buildings. Energy efficiency policies as currently practiced may work at cross-purposes to electrification. For this reason, the flexibility mechanisms in the proposed version of the CPP could be counterproductive. In general, energy policy should encourage coordinated planning on both the demand and supply side (see below on flexibility), but should avoid treating energy efficiency and supply decarbonization as interchangeable.

- **Enable flexible loads.** The U.S. study shows that flexible loads (i.e. those that are not "must-serve" on an hourly basis) constitute a large share of electricity demand in many deep decarbonization scenarios, and are essential to reliability and controlling cost by making use of generation that would otherwise be curtailed. In the future, demand will need to be fully integrated into electricity sector planning processes, as the procurement of generating capacity and flexible load will be inextricably linked. Policy has to address institutional and regulatory design for ownership, interconnection, and cost allocation for flexible load.

- **Redesign wholesale markets.** The U.S. study shows that nearly all generation will have near-zero operating cost in a deeply decarbonized electricity system, and that the function of markets will be the allocation of capacity and flexibility costs. This situation is drastic departure from the history of electricity markets, in which the cost of energy supply was the primary economic concern, and in which a strict dichotomy between generation and demand was the norm. The new normal will require market design innovation – in which FERC could play a leading role – to address the temporal and spatial allocation of capacity investments on both the supply and demand side. Market designs will need to be robust to large shares of flexible demand, rationalize direct-access and bundled demand, and allow differentiated levels of electricity reliability.

- **Anticipate siting requirements.** The U.S. study shows a large increase in renewable generation will be required in all cases, including high nuclear and high CCS scenarios. In combination with a need for increased intra- and inter-regional transmission, there will be significant land use requirements. Positive outcomes in terms of ecosystem, water, and cultural impacts require long-term anticipatory signals to renewable developers based on science and stakeholder based site assessments far in advance of need. The federal-state joint Desert Renewable Energy Conservation Plan provides a potential model for anticipatory planning.

Fuel Decarbonization and the Renewable Fuel Standard

The Renewable Fuel Standard, administered by the federal EPA, mandates a minimum quantity of "renewable fuel" in the transportation fuel mix. From its beginnings in the Energy Policy Act of 2005, bolstered by arguments about energy independence, RFS targets have grown over time. The target for 2022 is 36 billion gallons, equivalent to more than one-fourth of current gasoline consumption. While "renewable fuels" include a variety of alternatives to gasoline and diesel, including electricity, the RFS has served primarily as a vehicle for adding corn-based ethanol to the country's gasoline mix, along with some sugar cane-based ethanol imported from Brazil. There are valid scientific concerns about the carbon benefits of these fuels, especially when indirect land use change is taken into account. The RFS in practice has been shaped as much by a desire to provide farm subsidies to politically important states as by strategic thinking about decarbonized fuels.

From the deep decarbonization perspective, for the RFS to serve as a key driver of fuel decarbonization will require major changes in its present form. Key priorities for low-carbon fuel policy going forward as identified by the U.S. 2050 study include the following:

- **Encourage the development of fuels produced from electricity.** The U.S. study shows that electrically produced fuels such as hydrogen and synthetic natural gas have high value as fuel substitutes under all scenarios and can provide demand flexibility for electricity sector balancing. The RFS should be expanded to include hydrogen and SNG, and to facilitate their incorporation into the pipeline gas mix, including RD&D and regulations related to safety, blend criteria, purity requirements, and interconnection protocols from production to pipeline.

- **Redirect biomass resources toward high value uses.** The U.S. study shows that the best use of limited biomass resources is to replace fuels that lack other technical alternatives. Most biofuel is currently ethanol, which is used as a gasoline substitute in passenger cars. However, passenger cars have several viable technical alternatives, including electric vehicles, plug-in hybrids, and fuel cell vehicles. Across all scenarios, prioritizing the use of scarce biomass resources as a substitute either for diesel fuel (mostly for freight), jet fuel, or natural gas (mostly for industry) has a much greater carbon benefit. Policies that promote competition between biofuels and electricity or hydrogen for light duty vehicle use are not consistent with deep decarbonization.

- **Move away from biofuels with marginal emissions benefits.** The U.S. study shows that combustion fuels with only slightly lower lifecycle GHG emissions than their fossil alternatives – for example, corn ethanol substituted for gasoline – cannot play a significant part in long-term mitigation. As with non-CCS natural gas power generation, well before mid-century emissions constraints will be too stringent to permit such fuels to play a large role in the energy system. Policy should emphasize bioenergy with near zero lifecycle carbon, when feedstocks, fuel production, and fuel transportation are taken into account, including a strong constraint on indirect land use change. In the short term, reforming the RFS to include a multiplier for per-unit emissions reductions could provide better incentives for using biomass feedstocks with low fossil fuel inputs such as miscanthus and switchgrass.

- **Create a glide path for reducing existing biofuels.** The U.S. study shows that gasoline demand will decline, even in the reference case, due to increased LDV efficiency. Changing the definition of RFS to a percentage of final demand, instead of an absolute volume, and expanding the definition to include the replacement of fossil natural gas, would lead to reductions of corn-ethanol even without its explicit retirement from RFS.

Transportation Energy and CAFE Standards

The federal Corporate Average Fuel Economy (CAFE) standards set the requirements for fuel economy for passenger cars and light trucks. After stagnating at 27 mpg for over 20 years, new rules starting in 2011 have steadily raised the standard at a rate of about 2 mpg per year, with a target of 54 mpg in 2025. This change was catalyzed by California's Pavley standards for vehicle GHG emissions, which were upheld in 2007 by the U.S. Supreme Court. In return for California dropping separate standards for vehicles sold in the state, the Obama Administration adopted new rules for CAFE broadly consistent with California's. Coming on the heels of the federal bailout of the auto industry in the wake of the 2008 financial crisis, the Administration was in a strong position to make demands on an auto industry that had resisted fuel economy improvements for decades.

From a deep decarbonization perspective, CAFE as envisioned out to 2025 is generally consistent the direction required for the U.S. LDV fleet. In addition to essentially doubling fuel economy in internal combustion engine LDVs, CAFE provides extra incentives for electric, fuel cell, and hybrid vehicles. CAFE will be revisited in 2018, and likely face resistance to continuing the upward targets, even though the levels set for the 2020s will only be equivalent to those already achieved in Europe and Japan a decade earlier. To follow a deep decarbonization path beyond the mid-2020s, not only must CAFE maintain its existing targets, it must become more aggressive in transforming the vehicle fleet, in combination with complementary policies at the state level. Key priorities for transportation energy policy going forward as identified by the U.S. 2050 study include the following:

Make CAFE standards more aggressive. The U.S. study shows that average fuel economy for LDVs will need to be over 100 mpg equivalent across all scenarios by 2050, meaning that these levels will need to be achieved in new models before 2040. Future CAFE updates should unambiguously set increasing targets over time consistent with this transformation.

Facilitate a rapid transformation of the LDV fleet. The U.S. study shows that by 2030, the majority of new LDV sales must be either electric, fuel cell, or plug-in hybrid vehicles, and that allowing for slow turnover of stocks virtually the entire fleet must be composed of these vehicles by 2040. Achieving this transformation within about two average vehicle lifetimes will require policy support for high levels of consumer adoption, partnerships with auto manufacturers, and close coordination with electricity and/or hydrogen providers.

Build the necessary infrastructure. Fueling/charging infrastructure requirements must be anticipated and met in coordination with the expansion of low-carbon vehicle fleets. For EVs, of this must take place at the state level, where electric utility planning must account for growing electric vehicle loads at the distribution level. In the case of FCVs, development of hydrogen fueling infrastructure is a top priority for RD&D and pilot projects. Federal involvement will be required if hydrogen transport requires the development of a new transmission pipeline infrastructure.

Create large markets to bring down costs. The DDPP Synthesis Report investment study shows that technological learning has the potential to greatly reduce the incremental capital costs of electric, fuel cell, and plug-in hybrid vehicles. To take advantage of learning, large markets with high production volumes must be developed. These markets can be facilitated by regional collaborations within the U.S., and by U.S. climate and trade policy at the global level.

Develop technologies for low-carbon freight and air transport. The U.S. study shows that multiple options exist for low-carbon freight and air transport fuels, including biodiesel, fuel cells, and compressed and liquefied pipeline gas containing various mixes of natural gas, synthetic natural gas, and hydrogen. Recent proposed EPA rules that drive efficiency improvements for existing diesel and jet engines while also encouraging RD&D and technology competition in these areas is a positive step.

Building Electrification and Energy Codes and Standards

Building energy policy is primarily focused on energy efficiency, with the minimum energy efficiency of dozens of kinds of appliances and end-use equipment ranging from motors to light bulbs to refrigerators regulated by federal standards, while building energy efficiency in areas such as insulation and glazing is regulated by state codes. These are augmented by the federal EnergyStar program, a partnership of DOE and EPA, which provides a high-efficiency certification for products that improve substantially on minimum standards, and by state-level programs, carried out either through state offices, non-profit agencies, or utilities – that provide incentives to consumers to purchase energy efficient products. A fundamental element of codes, standards, and incentives at both the federal and state level is that they are typically set based on cost-effectiveness tests.

Despite some major gaps – weakness or absence of energy efficiency policies in some states, difficulties in developing effective policies for retrofitting existing buildings even in the most advanced states – energy efficiency has been perhaps the most sustained success story for clean energy over the decades since the oil crises of the 1970s first spawned widespread energy consciousness in the US. However, from the deep decarbonization perspective, some of the fundamental paradigms that have made these programs successful in the past will need to be reoriented going forward, requiring significant policy innovation in both state and federal codes and standards.

- **Focus on reducing carbon emissions, not primary energy use.** Reducing carbon is not only a function of improving energy efficiency, but also removing carbon from energy supplies. In some cases, emission reductions may entail increasing primary energy use from a low-carbon source relative to a more efficient use of primary energy from a higher carbon supply. This is a departure from a longstanding paradigm of energy efficiency policy – from a time when oil imports were a central concern – which sought always to maximize source Btu efficiency as a mechanism to achieve both cost savings and energy security.

- **Develop incentives for fuel switching.** The U.S. study shows that fuel switching becomes the most important measure on the demand side as electricity and fuel supplies are decarbonized. Current codes and standards are oriented toward improving the efficiency of an existing fuel use, rather than providing incentives to switch fuels. Developing fuel-switching incentives will require a fundamental rethinking of the scope and priority areas of energy efficiency policy.

- **Rethink cost-effectiveness.** Societally optimal fuel switching likely outpaces the current analysis framework for cost effectiveness, suggesting the need for a new planning framework that takes carbon emissions, energy consumption, and demand flexibility into account.

- **Make better use of advanced meter data.** Currently, vast quantities of building energy data are being collected by utilities, but this data is generally not being used to develop targeted programs to improve building energy performance. Policies ranging from privacy protection to enabling third-party providers are needed to take advantage of this data to mobilize advanced technology and expand the adoption of cost-effective energy efficiency and fuel switching. Targeting customers with large potential benefits from fuel switching – for example, electric heat pumps – can create a pool of early adopters, expand markets, and catalyze cost reductions.

- **Make an early decision on the fate of gas use in buildings.** The U.S. study shows that fossil natural gas use in buildings must be almost completely eliminated by mid-century, and replaced either by decarbonized pipeline gas or electricity. Since building energy demand can be met entirely by electricity, while industrial uses still require combustion fuels, avoiding competition for scarce biomass and electricity derived pipeline gas may mean the end of gas use in buildings. If this is the case, rapid reduction in building gas use will threaten new investments in pipeline infrastructure. To avoid stranded assets, it is important for policy to create a context for early decisions on the fate of gas in buildings, starting with permitting of gas supplies to new structures.

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