Achieving Carbon Neutrality in the United States
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U.S. Deep Decarbonization Pathways Project

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Introduction

This white paper describes pathways by which the United States can achieve carbon neutrality by mid-century. It expands on the SDSN’s *Pathways to Deep Decarbonization in the United States* (2014) and *Policy Implications of Deep Decarbonization in the United States* (2015), which examined the requirements for reducing GHG emissions by 80% below 1990 levels by 2050. The earlier studies were conducted in concert with similar studies for other high-emitting countries by the country research teams of the Deep Decarbonization Pathways Project, also sponsored by the SDSN. The emissions reduction pathways developed were consistent with the Paris Agreement’s calls for “holding the increase in the global average temperature to well below 2°C above pre-industrial levels.”

Recent observations of climate change have led to a growing consensus that even a 2°C increase may be too high to avoid dangerous impacts. Some scientists assert that staying well below 1.5°C, with a return to 1°C or less by the end of the century, will be necessary to avoid irreversible changes to the climate system. A recent report by the IPCC indicates that staying below 1.5°C will require reaching net-zero emissions of CO₂ globally by 2050 or earlier. Following the scientific evidence, jurisdictions around the world have begun to adopt more aggressive emissions targets, for example California’s executive order calling for the state to achieve carbon neutrality by 2045 and net negative emissions after that. This white paper describes what meeting such a target would mean for the United States as a whole.

*Figure 1. (L) Global CO₂ emissions trajectories consistent with limiting warming to 1.5°C or less. (Source: IPCC, Global Warming of 1.5°C) (R) Trajectories for returning warming to less than 1°C by 2100 (Source: Hansen et. al, 2017).*

Achieving carbon neutrality in the United States by mid-century requires a monumental transformation, from an economy based largely on unchecked fossil fuel combustion to one based on decarbonized energy sources, in thirty years or less. Yet, as this study will demonstrate, from a technical and cost perspective this is a much more achievable outcome than many might think. We know enough at present to chart a clear course to
carbon neutrality and anticipate many of the choices and tradeoffs that will arise along the way. For policy-makers, the key to a successful zero carbon transition lies in creating a policy environment that drives the necessary changes in the physical infrastructure of the U.S. while also addressing challenges in areas such as cross-sector coordination, employment and land use. Because of the diversity of U.S. society, the complex structure of its energy system, and the constitutional division of authority across different levels of government, the institutional challenges are significant. Creating policies that work in and across sectors and jurisdictions will require participatory planning processes in which decision-makers and stakeholders are well-informed about the nature of the transitions ahead. Helping to provide that information is the purpose of this white paper.

The transition to carbon neutrality in the United States over the next three decades entails simultaneous transitions in many domains, including infrastructure, energy economy, policy, land use, and employment. This report focuses on the first two domains. The infrastructure and energy economy transitions were modeled by the authors, and are discussed in Chapter 1. Policy actions by decade are discussed in Chapter 2 along with some general policy considerations.
Chapter One: The Infrastructure Transition

Pathways to carbon neutrality

This white paper describes pathways by which the United States can reach carbon neutrality by mid-century, based on detailed modeling of the required changes in technology and infrastructure, and associated costs. The authors modeled these pathways for the U.S. for each year from 2020 to 2050, following a straight line trajectory in net CO₂ emissions from energy and industry (E&I) from the current level of about 5 billion metric tons to zero in mid-century (Figure 2). This trajectory represents a 4% per year reduction in net emissions after 2020, with cumulative emissions for the U.S. during the 2020 to 2050 period of 78 billion metric tons of CO₂. An alternative pathway was also modeled that reached negative net E&I CO₂ emissions of -500 million metric tons in 2050, with cumulative emissions of 72 billion tons.

Figure 2 Emissions Trajectory, Annual CO₂ and Cumulative CO₂

The pathways described here are for reductions in CO₂ from the use of fossil fuel for energy and for industrial processes and feedstocks, which constitutes more than 80% of current U.S. greenhouse gas (GHG) emissions. This study does not include the land CO₂ sink or emissions of non-CO₂ greenhouse gases such as methane and nitrous oxide. Published values from studies of the potential for mitigation of these emissions were combined with our modeled results for E&I to obtain economy-wide CO₂e emissions for comparative purposes. Table 1 shows that for current levels of the land CO₂ sink (about -750 Mt) and non-CO₂ GHGs (about +1250 Mt), there would still be residual emissions of +500 Mt CO₂e in a “carbon neutral” E&I scenario. A 50% increase in the land sink (to -1125 Mt) combined with a 10% decrease in non-CO₂ GHGs (to +1125 Mt) – both of
which are generally considered to be ambitious levels of mitigation – would be required to bring total GHG emissions to zero. Alternatively, negative net E&I emissions could result in zero or net negative total GHGs. This illustrates the importance of mitigation in other areas in addition to eliminating net fossil fuel emissions from energy and industry for achieving stability or drawdown of current atmospheric CO$_2$e concentrations.

Table 1. U.S. GHGs in 2050, based on modeled trajectories for energy and industrial CO$_2$ and published estimates for mitigation of land sink and non-CO$_2$ GHGs (all values in Mt CO$_2$e).

<table>
<thead>
<tr>
<th>Energy and industrial CO$_2$</th>
<th>Net land CO$_2$ sink</th>
<th>Non-CO$_2$ GHGs</th>
<th>Total GHG emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-750</td>
<td>+1250</td>
<td>+500</td>
</tr>
<tr>
<td>0</td>
<td>-1125</td>
<td>+1125</td>
<td>0</td>
</tr>
<tr>
<td>-500</td>
<td>-750</td>
<td>+1250</td>
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<tr>
<td>-500</td>
<td>-1125</td>
<td>+1125</td>
<td>-500</td>
</tr>
</tbody>
</table>

Scenarios

Our analysis models the transition to net-zero E&I CO$_2$ emissions in 2050 (and in one case, to -500 Mt) and addresses questions about technical feasibility, resource constraints, infrastructure buildout rates, and costs. A feasible pathway for this transition must successfully meet the challenges of integrating high levels of variable renewable energy (VRE), producing low carbon fuels from biomass and electricity, decarbonizing difficult applications such as industry, aviation, and freight transport, and incorporating carbon capture, utilization, and storage (CCUS) into the overall E&I system.

We developed scenarios to explore different pathways to the mid-century target, as demonstrated in previous work of the US DDPP. Scenarios were modeled using two sophisticated analysis tools, EnergyPATHWAYS and RIO, which provide a high level of sectoral, temporal, and geographic detail to ensure the scenarios account for such things as the inertia of infrastructure stocks and the hour-to-hour dynamics of the electricity system. Combining the two tools generates demand for energy services and industrial feedstocks and produces the least-cost supply of energy to satisfy this demand while addressing carbon, policy, and reliability constraints.

The carbon-neutral and carbon-negative scenarios were required to meet the same demand for energy services for daily life and industrial production as a business-as-usual reference case based on the Department of Energy’s long-term forecast, Annual Energy Outlook (AEO). All scenarios use AEO assumptions for population, GDP, and industrial production. The modeling assumes only technologies that are commercial or have been demonstrated at a large pilot scale. The central case is the case that reaches zero net E&I CO$_2$ emissions in 2050 at the lowest net cost. Other scenarios, described later, test the robustness of the central case to societal preferences and environmental or resource limits that constrain the decarbonization options available.
Four Pillars of Decarbonization

*Figure 3 Four main strategies of deep decarbonization, comparison of current vs. 2050 central case*

The transition from a high-carbon to a low-carbon energy system is based on three main strategies: (1) *using energy more efficiently* (2) *decarbonizing electricity*; and (3) *switching* from fuel combustion in end uses to *electricity* (Figure 3). Achieving net-zero or net-negative E&I emissions requires an additional strategy: (4) *carbon capture*. Key benchmarks in each of these areas that must be reached in 2050 include: carbon intensity of electricity reduced 95%; electricity’s share of end-use energy tripled, from 20% to 60%; per capita energy use reduced 40%, with energy intensity of GDP reduced two-thirds. Carbon capture reaches 800 Mt CO₂ per year in 2050, up from negligible levels today. Since the emissions reduction impacts of these strategies are multiplicative, they must be simultaneously applied to achieve their full potential. Thus, successful implementation requires economy-wide coordination across all sectors of the four foundational strategies.

**Infrastructure transition**

Figure 4 illustrates the energy system transformation resulting from the application of these strategies. The two Sankey diagrams represent the forms of primary energy used, on the left side of the figure, and then through conversion processes to final energy consumption, on the right side of the figure, for the current system and the 2050 carbon neutral system (central case). In the carbon neutral system, both primary and final energy use are lower than in today’s system, representing 65% and 73% of the 2020 values respectively, despite 30 years of rising energy service demand due to higher population and GDP.
The shares of coal, oil, and natural gas in the primary energy supply decrease dramatically from today’s level, replaced by wind, solar, and biomass. Coal is eliminated altogether, while natural gas (75% reduction) and petroleum (70% reduction) play limited roles supporting industrial uses and feedstocks, and targeted transportation applications. A small amount of natural gas for use in power plants that operate at low capacity factors is needed to ensure reliability for the high-VRE electricity system. Low-carbon electricity and fuels replace fossil fuels in most final energy uses. Conversion processes that play a minimal role today – biomass refining, and the production of hydrogen and synthetic fuels from electricity – become essential in the decarbonized energy system. CO₂ emissions from residual fossil fuel use are captured directly or offset.
The transformed energy flows of a deeply decarbonized economy are enabled by an infrastructure transition over the next three decades that implements the four pillars. Low-emitting, high-efficiency, and electricity-consuming technologies largely replace high-emitting, low-efficiency, and fossil-fuel consuming technologies. Figure 5 illustrates this transition for three sectors that together comprise about two-thirds of current E&I CO₂ emissions: electric power generation, on-road vehicles including light-duty vehicles, and space and water heating in buildings.

**Figure 5 Infrastructure transition for power generation, on-road vehicles and residential heating**

Large additions of renewables drive electricity decarbonization. By 2050, generation capacity increases by 3000 GW with virtually all of the net increase coming from wind and solar. Coal capacity is fully retired. A sustained transition in demand-side technologies enables both the efficiency and electrification strategies, as represented by both light-duty vehicles and residential space heating. By 2050, out of 280 million cars and light trucks, more than 260 million are battery electric vehicles, almost entirely replacing internal combustion vehicles with more efficient electric alternatives. Eighty percent of medium- and heavy-duty trucks are battery-electric or hydrogen-powered vehicles. In residential buildings, electric heat pumps constitute 110 million out of 140 million space heating units, and 80 million out of 150 million water heating units, with electric resistance heaters comprising most of the remainder. This enables residential buildings to heat with the lowest-cost source of decarbonized energy, renewables-based electricity.
Electricity from VRE is the least-cost form of primary energy in a decarbonized system. The energy economy as a whole is organized around using VRE to the maximum extent possible, leveraging traditional loads, newly electrified loads, fuel production, and carbon capture. In the central case, the generation mix is 90% wind and solar. Reliable operation of a very-high VRE electricity system requires a multi-pronged approach to balancing supply and demand in real-time in comparison to conventional systems. A suite of different resources play different roles, depending on the time scale of the imbalance and whether there is an energy deficit or surplus. The most cost-effective means of addressing these imbalances is a combination of thermal generation for reliable capacity, plus transmission, energy storage, and flexible loads that integrate generation and demand with fuel production.

Figure 6 illustrates the problem conceptually for representative days in three months of the year. The left panel of the figure shows non-thermal net load, meaning gross load minus renewables output. The negative values indicate there is more renewable output than electrical load. High VRE systems designed to provide sufficient energy in high-demand parts of the year will over-generate at other periods, both within a day and over the year. The remaining hours in which renewable output is insufficient to meet demand are due to especially high load (e.g., August late afternoons with high cooling demand), low renewable output, or a combination (e.g., December evenings with high electric heating demand and comparatively low renewable output).

The middle panel shows how different non-thermal balancing resources are employed to address the oversupply of renewable energy. Some level of curtailment of wind and solar is economic, but too much is not. Batteries can economically time-shift renewable generation from surplus to deficit periods over a day; battery capacity increases to 200
GW with an average duration of about 7 hours. However, batteries are not cost-effective for balancing on longer time scales. Flexible end-use loads (e.g., EVs and water heaters) are similarly valuable for short-term balancing but not over longer durations. Large, industrial-scale flexible loads can address energy surpluses lasting periods of days to months. These loads produce useful products from generation that would otherwise be curtailed and support integration of very high levels of VRE. Electrolysis of water simultaneously balances the system and produces valuable fuels (hydrogen, and synthetic hydrocarbons made with hydrogen) for applications that are difficult to electrify. Flex-fuel boilers use electricity during periods of overgeneration. Other large industrial loads such as desalination could also potentially operate flexibly.

Transmission enables VRE-dominated systems to take advantage of geographically diverse load and generation profiles. In carbon neutral cases, inter-regional transmission capacity approximately doubles (130 GW in the central case, an 80% increase). Most transmission is built to connect wind-rich and wind-poor regions, generally from the wind belt in the center of the U.S. toward the Southeast and Mid-Atlantic.

The right panel of Figure 6 shows “residual load,” which is what remains of net load after deploying all the non-thermal balancing loads in the middle panel. The contrast between the left and middle panels and the right panel illustrates how the provision of capacity (MW) in a decarbonized electricity system is fundamentally separate from the provision of energy (MWh). The system is designed around supplying as much low-cost VRE as possible, with non-thermal balancing loads to utilize surplus electricity. Dispatchable capacity is needed to address the residual reliability needs of the system. The capacity resource that pairs best with a high VRE system is gas-fired capacity, due to its low capital cost. Gas capacity ramps up and down to support the whole system in the limited hours where there is a need for generation beyond VRE, hydro, and nuclear. Hydro, followed by nuclear, ramp down after gas-fired capacity to maintain as much zero-carbon generation on the system as operating constraints allow.

Figure 7 shows the requirements for gas-fired capacity in ensuring a reliable system even with very-high levels of VRE. The gas fleet in the central case is nearly 600 GW, comparable to 500 GW today, providing the bulk of the dispatchable capacity for the system. Since this capacity runs very infrequently, on average about 5% of the time, the lowest capital cost plants are preferred. The much higher capital cost of CCS and nuclear plants makes them uneconomic for such low utilization rates, and at the same time, they are uncompetitive with VRE for supply energy in bulk. To remain within carbon constraints, gas plants without carbon capture either burn natural gas and those emissions are offset elsewhere in the E&I system, or they burn zero-carbon fuels such as renewable natural gas.
Decarbonizing the Remaining Fuels in the System

A decarbonized electricity system delivers 60% of final energy demand in a carbon neutral economy. The remaining 40% must be met with fuels, particularly in applications where: volumetric or gravimetric energy density requirements make electrification difficult (e.g., aviation); high process temperatures are needed; in thermal power generation to provide reliability; and in industrial feedstocks where hydrocarbons are required. Figure 8 shows the continued need for some fuels in the central case by 2050. A decarbonized grid meets final energy demand for electricity while also producing synthetic fuels, based on hydrogen from electrolysis.
There are three strategies for meeting residual fuel demand in a carbon-neutral system: (1) efficiency and conservation, (2) drop-in carbon-neutral fuels, and (3) post-combustion carbon capture or “offsetting” with negative emissions in another location. Figure 8 shows the deployment of the three strategies in the central case. The final energy panel shows a decline in demand for all fuels. Efficiency and conservation are essential for minimizing fuel demand and cost but alone are insufficient for reaching carbon neutrality.

Drop-in fuels are derived from three sources: biomass, by the Fischer-Tropsch process; electricity, by electrolysis; and natural gas, by steam methane reforming (SMR) or auto-thermal reforming (ATR) with carbon capture. All sources have potential resource constraints: the quantity of sustainable biomass feedstock, the land requirements for renewable electricity, and the injection rate for sequestered CO₂. Their relative costs depend on primary energy cost, transport cost, end-use efficiency, and carbon content. All have increasing costs with volume; thus, a mix of drop-in fuels and combustion of some fossil fuels with emissions offsetting elsewhere in the system results in the lowest cost. As the figure shows, biomass’s share of primary energy rises as it increasingly is used to produce hydrogen, drop-in long-hydrocarbon fuels, and steam. Hydrogen, derived from biomass, electrolysis, and natural gas, is used to create drop-in transportation fuels utilizing roughly 40% of the 800 Mt of carbon captured in 2050 for the central case. This
carbon is captured from industrial processes, biofuel refining, and hydrogen production from natural gas. The remaining capture carbon is geologically sequestered.

Among fossil fuels, natural gas is the last fossil fuel to be replaced in a least-cost system because it is the least expensive on an energy basis and has the lowest carbon content. Carbon capture and offsetting both have a role in addressing the emissions from the limited combustion of fossil fuels. Post-combustion “end-of-pipe” capture is cost-effective for concentrated, high volume CO₂ streams from sources like bulk chemicals and cement. Offsetting is used for small and widely dispersed sources that are not economic to capture directly; this is accomplished by bioenergy with CCS (BECCS) or direct air capture (DAC). When renewables are higher cost, SMR or ATR with carbon capture displaces electrolysis for the production of hydrogen and synthetic hydrocarbons. With high oil prices, liquid fuels are replaced by drop-in carbon-neutral alternatives. With low oil prices, emissions offsetting is more cost-effective for some applications.

In contrast to the pathways to an optimal electricity mix, which is robust across a wide range of sensitivities, there is much greater uncertainty about the optimal mix of fuels for a net-zero E&I system. There are many technically feasible fuel pathways for carbon neutrality, but the optimal pathway will be determined by future fossil fuel price trajectories, the cost and potential of biomass and geologic sequestration, and the level of achievable efficiency and conservation.

**Cost**

The net energy system cost of reaching carbon neutrality in the central case is $140 billion in 2050, representing about ~0.4% of forecast GDP for that year (Figure 9). Net cost is the difference in the costs of supplying and using energy in the central case compared to the reference case, along with the net cost of reducing or offsetting non-energy industrial process emissions. Our analysis only assesses the energy costs of the transition to carbon neutrality and does not count the economic benefits of avoided climate change and other energy-related environmental and public health impacts, which have been described elsewhere.

The black line in Figure 9 represents the net cost of the central case. The net cost is a result of a large swing in gross costs, with roughly $950 billion in spending on efficient and low-carbon technologies enabling savings of $800 billion in fossil fuel costs. Put another way, deep decarbonization represents a shift from an E&I system that is dominated by variable costs to a system with much higher capital expenditures and low variable costs. At 0.4% of 2050 GDP, the incremental cost of decarbonization for the central case is a remarkable decline, given that a few years ago, analysts were calculating a net cost of about 2% of GDP for an 80% by 2050 scenario. Ongoing cost decreases in solar, wind, and EV batteries have driven these lower cost estimates.
Historical total U.S. spending on energy has ranged between 6% and 13% of GDP from 1970 to the present (Figure 10). In the reference case, this is projected to decline to 3.8% in 2050. Under the central case, deep decarbonization of the E&I system also declines, although not as quickly as the reference case, reaching 4.2% of GDP in 2050. Incremental capital investment will average $500B per year for decarbonization, which represents about 8% of the current U.S. capital investment, which totals $6T, in all sectors. This suggests that finance is unlikely to present a barrier if policies to limit risk and allow cost recovery are in place.
Alternative pathways

The central case represents the least-cost system based on the least-constrained pathway to carbon-neutrality. However, future resource limitations or societal preferences may place constraints on economically preferred options that require other, higher-cost alternatives to be used. We developed other scenarios to explore the impact of these potential constraints on technology choices and costs:

- **Limited land**: biomass supply limited to 50% of central case value, and land area of onshore wind and utility-scale solar limited to 50% of central case value. Limited availability of biomass and onshore VRE requires more nuclear, offshore wind and sequestered carbon.

- **Delayed electrification**: consumer adoption of electrified end-use technologies such as electric vehicles and heat pumps delayed by 15 years relative to the central case. This necessitates more electric fuels, biomass, land, and carbon sequestration. It also requires more electricity generation, to meet the demand for electric fuels.

- **Low demand**: energy service demand in key end-uses reduced 20-40% below AEO levels, to reflect high levels of conservation. Lower service demand requirements result in less energy, infrastructure, cost, land, sequestered carbon.

- **100% renewable primary energy (100% RE)**: uses no fossil fuel, including for feedstocks, resulting in net E&I emissions of -350 Mt CO₂ in 2050. Displacing all fossil fuel use requires more electricity, electric fuels, biomass, and land.

- **Net negative**: the least-cost cost case that produces net E&I emissions of -500 Mt. Requires greater uses of negative emissions technologies and more carbon sequestration.

Each of the alternative pathways limits the availability of cost-effective decarbonization measures or requires more stringent emission reductions, and as a result, incurs higher costs than the central case as shown in Figure 11. The range of cost across cases in 2050 is 0.4% to 0.9% of GDP. The net negative case, with a much higher emissions reduction ambition, is 0.5% and the 100% RE case is 0.9%. While these alternative pathways come at a cost premium, falling costs of low-carbon technologies result in lower 2050 costs for these cases than recent net cost estimates, including the authors’ previous estimates of 2% of GDP for an 80% reduction by 2050.

A common result across the alternative pathways is that the lowest cost approach to decarbonization is by organizing the energy system around deploying large amounts of

![Figure 11. Energy System Cost of Alternative Pathways](image-url)
VRE. The left panel of Figure 11 shows the 2050 generation mix is 90% or more wind and solar for all cases except in the limited land case, which despite land constraints that make new nuclear generation economic, still has an 80% VRE system. Falling wind and solar costs will make these resources the cheapest source of zero-carbon energy, and even under a range of potential future pathways, these resources are likely to be the dominant supplier of electrical generation. Just as with the central case, the most cost-effective approach to a reliable VRE system is a combination of flexible loads, storage and a large gas-fired thermal fleet that runs infrequently. The right panel of Figure 11 illustrates this is even true in the 100% RE case, where the gas-fleet runs less frequently and burns drop-in zero-carbon fuels but is still part of the least-cost supply portfolio.

Figure 11. 2050 Generation and Dispatchable Capacity

The Pathway to Fuel Decarbonization is Varied and Less Certain

In contrast to the similarity of the electricity-generation mix across cases, the fuel mix differs widely as a function of resource constraints and price sensitivities (Figure 12). The 100% RE case is the only scenario with significant decarbonization of pipeline gas. The delayed electrification case creates significantly higher biomass use, to supply decarbonized fuels that make up a greater share of final energy demand. The limited land case utilizes effectively all available biomass, and SMR or ATR with carbon capture displaces electrolysis for production of hydrogen and synthetic hydrocarbons on account of less available low-cost VRE to run electrolyzers. The net negative case utilizes the same approach as the central case, but with greater utilization of biomass and VRE primary energy to produce zero-carbon drop-in fuels. This scenario depends more heavily on carbon capture both to support fuel production and achieve the emissions target.
Figure 12 Primary Energy and Final Energy Blend Shares

Our results demonstrate that there are many possible fuel pathways for carbon neutrality, but the optimal pathway will be uncertain until future fossil fuel price trajectories, the level of electrification, and the cost and potential of biomass and geologic sequestration are better understood.

Carbon Capture Plays a Critical Role in Net-Zero Systems

All carbon neutral and net negative scenarios require carbon capture, which can occur at three points in the fuel lifecycle: in making the fuel, in the exhaust stream from combusting the fuel, or from the air once it is released to the atmosphere (E&I capture does not include photosynthetic capture in the land sink or biofuels). Once captured, the CO2 can be geologically sequestered or used to make zero-carbon fuels (Figure 13). Even the 100% RE case, which uses no fossil fuels, requires about 650 Mt/y of carbon capture in 2050 to capture industrial process emissions (e.g., from cement manufacturing) and to provide the carbon for renewable fuel production. All captured carbon in this case is utilized and none is stored. The central case captures 800 Mt/y from industrial processes, biofuel refining, and hydrogen production from natural gas. Of this, 40% is used to make liquid fuels, and 60% is geologically sequestered.
BECCS and DAC are used as negative emissions technologies (NETs) to offset uncaptured CO$_2$ emissions from small and distributed point sources for which CCS and low carbon fuels are uneconomic. In contrast to some modeling studies, we find that the most economic form of BECCS is not in power plants but in biorefineries, as solar and wind are a lower-cost alternative in electric generation, but biofuels are competitive for fuel production. The delayed electrification case relies heavily on BECCS, utilizing the captured carbon to support synthetic fuel production to support high residual fuel demand. The net negative case has a comparable level of BECCS, but geologically sequesters a greater share of carbon. A low fuel price sensitivity on the central case captures almost 20% more carbon, as it becomes economic to offset more fuel use. In this sensitivity, nearly more than 80% of captured carbon is sequestered to support offsetting.

Bioenergy and DAC are most economic when tightly coupled to the E&I system, where they can be flexibly used for fuels and products (e.g., plastics) or sequestration as circumstances warrant. DAC costs are strongly dependent on energy costs, which can be minimized by flexible operation in locations with high capacity-factor renewable generation. BECCS is resource-limited both in sequestration potential and biomass feedstocks. DAC also faces sequestration injection limits as well as high costs in general, especially where its input energy has not been decarbonized. For these reasons, NETs remain complementary components of a low-cost decarbonization strategy, and it is highly uneconomic to achieve carbon neutrality through a strategy of continuing high levels of gross CO$_2$ emissions from burning fossil fuels that are offset by NETs.
Tradeoffs Across Scenarios

The scale and pace of infrastructure buildout and demands on the land potentially entail competition among social, environmental, and economic priorities. Our scenarios illustrate the effect of these tradeoffs, as limiting technology choices in one area requires compensating changes in other areas to reach the same carbon goal. If consumer adoption of electric end-use technologies is delayed, more decarbonized fuels are required, resulting in higher land requirements for biomass feedstocks and the siting of renewable generation to produce electric fuels. The 100% renewable primary energy case has the highest land requirements for these purposes, as well as the highest cost of any scenario. The low demand case has the lowest land requirements and cost but requires a high level of societal commitment to conservation. When siting and biomass were constrained in the low land case, nuclear power, natural gas use, and carbon sequestration all grew substantially, raising different social acceptance issues. Given that such tradeoffs can be anticipated in a transition to carbon neutrality, analyses, and processes that help the public and decision-makers to engage with choices and understand their consequences are essential. Recent work in California, where conflicts between renewables siting, biodiversity conservation, and agriculture have already emerged, points to the potential of geospatial planning to help reconcile competing land uses in large scale wind, solar, and transmission buildouts.
Chapter Two: The Policy Transition

From Pathways to Policies

The previous chapter describes the infrastructure transition required to achieve carbon neutrality in the United States, and its implications for energy costs and the economy as a whole. This chapter addresses the question “how do we make use of this information in developing policy?” It does not prescribe policy details or draft legislative language, which are the responsibility of policy makers and stakeholders across levels of government throughout the U.S. Instead, it offers observations based on the modeling results to assist policy makers and stakeholders regarding: what policy needs to accomplish to achieve the physical transformation and recommendations for making effective policy.

Key Actions by Decade lays out the concrete goals and actions that policy makers and stakeholders will need to undertake to achieve carbon neutrality. It addresses the questions:

- What changes in the physical infrastructure are required, by what year? What are the key benchmarks?
- What investment decisions can be made with confidence now, and what decisions are contingent on future developments?

Next, we describe Recommendations for Making Policies to drive a low-carbon transition. This addresses the following questions:

- What are best practices for making effective policy for decarbonization?
- What are considerations for choosing policy tools to transition energy and infrastructure?

Finally, we conclude with a summary of the key transitions that are entailed in reaching carbon neutrality by mid-century.
Key Actions by Decade

The pathways modeling provides a clear set of targets and timelines to guide policy making and implementation. These are summarized in Table 2 then described in more detail below. The key actions required in each decade are highlighted, based on their importance for achieving carbon neutrality by mid-century. The key actions are accompanied by explicit quantitative benchmarks for the physical outcomes that must be reached in each sector. The list is not exhaustive, and it does not prescribe the policy mechanisms by which the outcomes are to be achieved. It does, however, describe the physical results that must be reached by certain points in time for the U.S. to be on a least-cost carbon neutral trajectory.
### Table 2. Key actions by decade for achieving carbon neutrality in the United States by 2050, with quantitative indicators.

<table>
<thead>
<tr>
<th>Sector</th>
<th>Indicator</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light duty vehicles</td>
<td>Electric vehicle share</td>
<td>&gt;50% of sales</td>
<td>100% of sales</td>
<td>100% of fleet</td>
</tr>
<tr>
<td>Medium duty vehicles</td>
<td>Electric and fuel cell vehicle share</td>
<td>&gt;40% of sales</td>
<td>&gt;80% of sales</td>
<td></td>
</tr>
<tr>
<td>Heavy duty vehicles</td>
<td>Electric and fuel cell vehicle share</td>
<td>&gt;30% of sales</td>
<td>&gt;60% of sales</td>
<td></td>
</tr>
<tr>
<td>Residential buildings</td>
<td>Electric space/water heating share</td>
<td>&gt;60% of sales</td>
<td>100% of sales</td>
<td></td>
</tr>
<tr>
<td>Commercial buildings</td>
<td>Electric space/water heating share</td>
<td>&gt;60% of sales</td>
<td>100% of sales</td>
<td></td>
</tr>
<tr>
<td>Electricity generation</td>
<td>Generation to meet new electric loads</td>
<td></td>
<td>&gt;2x current level (~8000 TWh/y)</td>
<td></td>
</tr>
<tr>
<td>Electricity emissions</td>
<td>Carbon intensity</td>
<td>60% below current</td>
<td>80% below current</td>
<td>&gt;95% below current</td>
</tr>
<tr>
<td>Coal power</td>
<td>Share of total generation</td>
<td>&lt;1% of total generation</td>
<td>no coal generation</td>
<td></td>
</tr>
<tr>
<td>Renewable power</td>
<td>Wind and solar capacity</td>
<td>3.5x current (~500 GW)</td>
<td>10x current (~1500 GW)</td>
<td>2500 GW total capacity</td>
</tr>
<tr>
<td>Natural gas power</td>
<td>Capacity</td>
<td>current capacity (~400 GW)</td>
<td>current capacity (~400 GW)</td>
<td>current capacity (~400 GW)</td>
</tr>
<tr>
<td>Nuclear power</td>
<td>Generation</td>
<td>current generation (~800 TWh/y)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity storage</td>
<td>Capacity (diurnal storage)</td>
<td>&gt;20 GW</td>
<td>&gt;100 GW</td>
<td></td>
</tr>
<tr>
<td>Transmission</td>
<td>Inter-regional capacity</td>
<td></td>
<td></td>
<td>3x current</td>
</tr>
<tr>
<td>Electricity markets</td>
<td>Wholesale market reforms</td>
<td>Low capacity factor generation</td>
<td>Industrial scale flexible demand</td>
<td></td>
</tr>
<tr>
<td>Electrolysis</td>
<td>Capacity</td>
<td>&gt;20 GW</td>
<td>&gt;100 GW</td>
<td></td>
</tr>
<tr>
<td>Biofuels</td>
<td>Million bbls per day zero carbon biofuel</td>
<td></td>
<td></td>
<td>&gt;2 MBD</td>
</tr>
<tr>
<td>Fossil fuels</td>
<td>Infrastructure to transport fossil fuels</td>
<td>no new oil &amp; gas pipelines</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon capture &amp; storage</td>
<td>CCS capacity large industrial facilities</td>
<td>&gt;250 MMT/year CO₂ sequestered</td>
<td>&gt;500 MMT/year CO₂ sequestered</td>
<td></td>
</tr>
<tr>
<td>NETs (negative emissions tech)</td>
<td>DAC and BECCS capacity</td>
<td>Deployed commercially</td>
<td>Deployed at full scale required</td>
<td></td>
</tr>
</tbody>
</table>

**Key Actions by Sector, 2020-2030**

The key actions by sector for 2020-2030 are robust across many different technology pathways and cost assumptions. They form the basis of a common set of near to medium
term policy priorities for all proponents of decarbonization, regardless of specific preferred long-term pathways.

**Electricity.** Electricity must be rapidly decarbonized while generation expands to accommodate new electric end uses. This requires parallel action on several different fronts in this decade.

- **Reduce the carbon intensity of electricity to 60%** below its current level by 2030.
- **Ramp up the construction of wind and solar generation** to reach 3.5 times the current capacity by 2030, which means adding on average at least 20 GW of wind and 25 GW of solar (including rooftop) per year.
- **Reinforce the transmission system** to accommodate delivery of renewable generation from areas with high resource quality to distant load centers.
- **Increase storage capacity.** Add at least 20 GW of diurnal storage to help accommodate renewable intermittency, especially solar.
- **Switch from coal to gas in electricity system dispatch.** Reduce coal generation to less than 1% of the generation mix.
- **Allow new natural gas power plants to be built to replace retiring plants.** The current capacity of natural gas generation needs to be maintained for reliability.
- **Maintain the existing nuclear fleet** to the extent circumstances allow, in order to limit the rate of new renewable and transmission construction required.
- **Initiate electricity wholesale market reforms** to prepare for a changing mix of electric loads and resources and address emerging issues in operations and cost allocation.

**Fuels.** Begin a concerted move away from fossil fuels, replacing these with electricity where possible and otherwise with biofuels and electric fuels.

- **Begin large-scale shift from fossil fuels to electricity.** The key fuels policy is replacing fossil fuel end-use technologies in transportation and buildings (see below).
- **Stop developing new infrastructure to transport fossil fuels,** for example oil and gas pipelines, LNG terminals, and coal terminals, as these will rapidly become stranded assets.
- **Pilot and further develop new fuel technologies** that need to be deployed at large scale after 2030, including electrolysis, power to gas, power to liquids, and advanced biofuels.

**Transportation.** Begin large-scale electrification of transportation, replacing gasoline and diesel use in vehicles of all kinds (personal, commercial, and freight) with low carbon electricity.

- **Rapidly increase the electric vehicle share** of new light duty vehicle sales (e.g. cars, SUVs, light trucks) to at least 50% by 2030.
- **Rapidly increase the electric and fuel cell vehicle share** of new medium duty vehicle sales (e.g. buses, delivery trucks) to at least 40% by 2030.
- **Rapidly increase the electric and fuel cell vehicle share** of new heavy duty vehicle sales (e.g. long-haul freight trucks) to at least 30% by 2030.
Buildings. Begin large-scale electrification of fossil fuel end uses in buildings, replacing oil and natural gas with electricity.

- **Increase the electric heat pump share of space and water heating** equipment in residential buildings to at least 60% of sales.
- **Increase the electric heat pump share of space and water heating** equipment in commercial buildings to at least 60% of sales.

Industries

- **Begin building carbon capture** on a large pilot or limited commercial scale for large industrial facilities with concentrated CO₂ streams.
- **Begin development of low-carbon feedstocks** for industrial products based on biomass, electric fuels, or carbon capture.

Key Actions by Sector, 2030-2040

Electricity. Continue to decarbonize electricity while expanding generation for newly electrified end uses. This requires the following:

- **Reduce the carbon intensity of electricity to 80%** below its current level by 2040.
- **Accelerate the rate of new construction of wind and solar generation** to an average of at least 35 GW of wind and 60 GW of solar per year during 2030-2040 in order reach 10 times current renewable capacity (~1500 GW) by 2040.
- **Continue expanding the transmission system** to accommodate delivery of renewable generation from areas with high resource quality to distant load centers.
- **Increase storage capacity** by at least 100 GW of diurnal storage above the present level to help accommodate renewable intermittency.
- **Continue to allow new natural gas power plants to be built to replace retiring plants**, maintaining current capacity for reliability.
- **Maintain existing nuclear fleet** to the extent circumstances allow.
- **Deploy fossil power plants capable of 100% carbon capture** if they are economic.

Fuels. Continue to replace uncaptured fossil fuel combustion with electricity where possible and otherwise with biofuels and electric fuels.

- **Begin large scale buildout of electrolysis** capacity for producing hydrogen, reaching at least 20 GW by 2040.
- **Begin large commercial-scale production of biodiesel and bio-jet fuel** during the 2030 to 2040 period.
- **Further develop new fuel technologies** needed in bulk after 2040 including power to gas, power to liquids, and advanced biofuels.

Transportation. Complete electrification of the vehicle fleet in all vehicle classes.

- **Achieve 100% electric vehicle share of new light duty vehicle sales** (e.g. cars, SUVs, light trucks) by 2040.
- **Achieve 80% electric and fuel cell vehicle share of new medium duty vehicle sales** (e.g. buses, delivery trucks) by 2040.
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- Achieve 60% electric and fuel cell vehicle share of new heavy duty vehicle sales (e.g. long-haul freight trucks) by 2040.

Buildings. Continue large-scale electrification of fossil fuel end uses in buildings, replacing oil and natural gas with electricity.
- Achieve 100% electric heat pump sales share of new space and water heating equipment in residential buildings by 2040.
- Achieve 100% electric heat pump sales share of space and water heating equipment in commercial buildings by 2040.

Industry
- Rapidly expand carbon capture to large commercial scale for industrial facilities, reaching 250 million tons of CO₂ per year by 2040.

Key Actions by Sector, 2040-2050

Electricity. Complete the decarbonization of electricity and buildout of generation to power an electricity-based economy. This requires the following:
- Double total generation compared to the current level, to 8000 TWh per year.
- Reduce the carbon intensity of electricity to more than 95% below its current level by 2050.
- Complete the buildout of wind and solar generation in order reach 16 times current renewable capacity (~2500 GW) by 2050.
- Continue expanding the transmission system to at least double current inter-regional transmission capacity (greater than 100 GW new capacity).
- Continue to allow new natural gas power plants to be built to replace retiring plants, maintaining current capacity for reliability.
- Replace current generation nuclear with new technologies.

Fuels. Complete the commercial development of biofuels and electric fuels, and link carbon capture to fuel production process to achieve net zero and net negative fuels.
- Deploy circular carbon economy based on electrolysis and carbon capture to produce synthetic fuels and balance renewable generation.
- Complete large-scale buildout of electrolysis capacity for producing hydrogen, reaching 100 GW by 2050.
- Complete commercial-scale production capacity for biofuels, reaching 2 MBCD (million barrels per calendar day) by 2050.
- Fully deploy biofuel production with carbon capture

Transportation. Continue the large-scale electrification of the vehicle fleet in all vehicle classes.
- Complete electrification of light duty vehicle stock by 2050
- Continue electrification of medium and heavy duty vehicles
**Buildings.** Complete electrification of fossil fuel end uses in buildings, replacing oil and natural gas with electricity.

- **Complete electrification of space and water heating** in residential buildings by 2050.
- **Complete electrification of space and water heating** in commercial buildings by 2050.

**Industry**
- **Increase carbon capture** in industrial facilities including fuel production to ~ 500 million tons of CO$_2$ per year by 2050.
- **Complete deployment at scale of negative emissions technologies** (direct air capture and bio-energy with carbon capture)
- **Complete deployment of carbon-neutral feedstocks** by 2050
Considerations for Effective Decarbonization Policy

Lessons learned from developing deep decarbonization policy at all levels of government forms the basis for the recommendations below. Like most “best practices,” these require customization and judicious application. A key lesson learned is that energy decision-making is widely distributed and context-specific, and policy has to fit the context in order to succeed. This section offers general suggestions, while subsequent sections discuss specific policy tools, settings, and challenges.

Recommendations:

1. Start with a long-term plan
2. Focus early on long-lived assets
3. Bet on market transformation to succeed
4. Identify no regrets strategies
5. Assume we act collectively
6. Keep policy nimble
7. Establish the right arenas for competition
8. Develop strategies that can be made universal

1. Start with a long-term plan

Too often a long-term plan is developed only after short- and mid-term targets and policies are already set. A better approach begins with backcasting, meaning to start from the end goal and work backwards to understand what needs to be done in the shorter term (Figure 14). It is critical to understand the physical end goal, for both emissions outcomes (like carbon neutrality) and the decarbonized infrastructure needed to produce that outcome.

Determining what a policy needs to accomplish – a step that should precede designing policy mechanisms, writing draft bills, and political bargaining – is grounded in understanding the physical transition all the way to the end state. This does not mean making policies that will span decades unaltered, but rather having a clear road map to follow, with the understanding that there will be twists and turns along the way.

Creating a long-term plan emphasizing the physical transformation also has narrative power for enlisting the support of stakeholders and the public, in addition to its practical value in making energy decisions. This is supported by social science research showing that a long-term move toward renewable energy is popular across the U.S. political spectrum and state boundaries, in contrast to policy mechanisms like carbon pricing, which are unpopular even in localities that have adopted aggressive climate policies.
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Figure 14. Back-casting from where you want to arrive (for example, carbon neutrality in 2050) is a key step in determining how to move forward.

2. Focus first on long-lived assets

Long-lived infrastructure should be an early focus to avoid carbon lock-in or stranded assets. The path to carbon neutrality is a sustained transition to efficient and low-carbon equipment and infrastructure. The more this can be done by replacing existing equipment at the end of its economic lifetime, the lower the cost of the transition.

However, the economic lifetime of energy supply and end-use equipment and infrastructure is long, with at most a handful of replacement opportunities between now and mid-century (Figure 15). For many of the most important types of infrastructure – buildings, electric power plants, heavy duty vehicles, industrial boilers – there may be only one replacement opportunity before 2050.

Therefore, when replacement time arrives, the emissions characteristics of the new infrastructure selected must be consistent with reaching carbon neutrality. Failure to replace retiring long-lived assets with efficient and low-carbon successors will lead either to failure to achieve the carbon target by mid-century, or to early retirement of the replacement infrastructure in order to meet the target.
Figure 15 (L) Typical lifetimes of energy supply and end-use equipment (R) Emissions trajectories that reach decarbonization targets or stop half-way to targets

3. Bet on market transformation to succeed

Market transformation – policies that lead to the rapid development of large markets for new technologies, raising production volumes and steeply reducing consumer prices – has a great track record in many industries, including energy. If designed and executed well, assuming such policies will succeed is a better bet than that they will fail.

There are numerous successful examples of national or subnational policies kick-starting new industries that are now essential strategies in deep decarbonization. California policy incentives in the 1980s launched the modern wind industry. Germany’s feed-in tariffs in the 2000s began the chain of events that led to today’s low-cost solar PV around the world (Figure 16).

One benefit of framing policies as market transformation is that this de-emphasizes the marginal cost of carbon abatement, which is not an appropriate metric for policies that need to play a larger role: transforming markets, sending clear signals to businesses, and catalyzing the emergence of a new normal.
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Figure 16. Germany’s solar feed-in tariff was the launching pad for global solar takeoff

Figure 17. Least-cost electricity generation mix across a wide range of carbon neutral pathways

4. Identify no regret strategies

Prioritize strategies that are robust across a wide range of uncertainties before entering more uncertain terrain. An example is the electricity generation mix, which modeling shows consists primarily of wind and solar across all carbon neutral scenarios (Figure 17) because these are the least-cost option under most circumstances. Rapid adoption of policies to accelerate deployment of wind and solar generation should be at the top of the priority list. In contrast, low carbon fuel pathways are contingent on many factors, some of them very uncertain at present. Policy in this case would be better advised to focus on encouraging technology development, supporting commercial scale pilots, and fostering competition among fuels options.
5. Assume we act collectively

Boundary conditions - assumptions about “what the neighbors are doing” – can have a strong impact on decarbonization strategies and economic analyses. While states and cities may have an admirable aspiration to reach carbon neutrality on their own if need be, this will be difficult to accomplish in most cases if neighboring states, or the state a city is part of, do not follow this course or work at cross purposes. A jurisdiction will be hard pressed to eliminate its GHG emissions if neighboring jurisdictions continue with business as usual.

The main reason for this is that energy systems are complex, interconnected, and slow to change, and take sustained, concerted effort to transform. Policy that assumes a ‘go it alone’ approach can have distorting effects or lead to bad policy. Comments such as these have been heard in policy discussions:

- “We don’t want to consider fuel cell trucks because we don’t think they will be able to fill-up once they leave our state.”
- “We are a wealthy state and it’s relatively inexpensive for us to buy wood pellets on the international market, so we will use that to decarbonize.”
- “When we have too much solar, we will export it to our neighbor…”

It is better both from the policy and analytical perspectives to make the assumption that neighboring jurisdictions will sooner or later act in concert. Planning with this in mind will make the reality easier to achieve.

Figure 18. U.S. regions
6. Keep policy nimble

Good policy acknowledges uncertainty and allows change based on new information. In the last 10 years alone we’ve seen dramatic evidence that technology evolves, relative costs change, science uncovers new evidence, models and understanding of the climate and energy systems improve. All 30 year forecasts will undoubtedly be wrong in some important aspects.

Yet action is urgent, and it is necessary to make decisions today. It is possible to both aggressively pursue actions we know with confidence are required, while also creating nimble policies that respond to emerging understanding in the future. A key element is planning, not as a one-time situation but an ongoing commitment. As demonstrated in many industries, such as electric power, this requires a substantial ongoing investment in process, analysis, and data.

7. Establish the right arenas for competition

Establish markets to compete within each pillar of decarbonization, but not between them. Competition among technologies is an important way to drive innovation and reduce costs, but it is important to design policies that create the right arenas for competition. In general, policies that lead to competition across the pillars of decarbonization are not productive. For example, policies that allow energy efficiency to substitute for low carbon generation, as the Clean Power Plan does, can be counterproductive.

Figure 19. Effective policies emphasize competition within the pillars of decarbonization, not across them.

8. Develop strategies that can be made universal
A characteristic of successful decarbonization strategies is that they are exportable. There is significant value in demonstrating successful actions that can be replicated elsewhere. Successful strategies tend to be attractive to other jurisdictions, and tend to become more cost-effective the more widely they are adopted. If a strategy is not scalable or if no one else is also trying to do it, this is a sign it may not be a great strategy.
The Policy Toolkit

The first step in developing policy for deep decarbonization is setting an explicit emissions target and timetable, for example reaching carbon neutrality by 2050. This provides clarity about the end point and purpose of action, and gives coherence to policies. Without this explicit goal it is difficult to marshal resources and inspire support.

The second step is pathways modeling, backcasting from the target to determine the sequence of actions required to get there. For the pathways analysis described in this report, these actions are spelled out by sector and decade in the previous section.

Pathways modeling keeps the long-term transformation goals visible and illuminates choices.

Having arrived at what policy needs to accomplish, the question becomes what policies are needed to accomplish it. Broadly speaking, there are five tools in the policy toolbox:

1. Research and development (R&D) support
2. Public-private collaboration
3. Direct subsidies
4. Technology standards
5. Carbon pricing

Determining which of these tools to apply involves asking a series of questions about the market status of a technology or suite of technologies that are required to reach carbon neutrality:

- Does the technology already exist in commercial form?
- Is it already cost effective?
- Is it already being adopted?
- Are there informational or other private sector barriers?
- Are there alternatives for achieving the same outcome?
- Are buyers sensitive to up-front costs?
- Are buyers sensitive to operational costs?

The different uses and permutations of each tool, and the factors determining the circumstances in which the tool is best applied, are discussed in more detail below, and illustrated in Figure 20.
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Figure 20. Determining the most suitable policy tool for the task.

Does the technology or approach exist?

\[ \text{No} \rightarrow \text{R&D Support} \]

\[ \text{Yes} \rightarrow \text{Is it cost effective?} \]

Is it cost effective?

\[ \text{Yes} \rightarrow \text{Is it already being adopted?} \]

\[ \text{No} \rightarrow \text{Are there informational or other private sector barriers?} \]

Are there informational or other private sector barriers?

\[ \text{Yes} \rightarrow \text{Public-Private Collaboration} \]

\[ \text{No} \rightarrow \text{Are there alternatives for decarbonization?} \]

Are there alternatives for decarbonization?

\[ \text{Yes} \rightarrow \text{Are buyers sensitive to up-front cost?} \]

\[ \text{No} \rightarrow \text{Direct Subsidies} \]

Are buyers sensitive to up-front cost?

\[ \text{Yes} \rightarrow \text{Carbon Pricing} \]

\[ \text{No} \rightarrow \text{Are buyers sensitive to operational cost?} \]

Are buyers sensitive to operational cost?

\[ \text{Yes} \rightarrow \text{Technology Standards} \]

\[ \text{No} \rightarrow \text{No Policy Needed} \]

---

1. R&D Support

Research and development policy is called for when technologies and decarbonization approaches have been identified as critical for reaching decarbonization goals but are not ready for commercial scale up. R&D support is a traditional government role in areas where there is a potential public benefit from developing a technology, but the cost or risk is seen as too high for individual companies in the private sector to pursue. This includes R&D conducted directly by federal agencies and national laboratories, and that
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conducted by universities and businesses with federal funding or cost-sharing. Some large states, like California and New York, also have substantial R&D portfolios.

It is important to distinguish between situations in which the technology is commercially ready but lacks scale, calling for market transformation policies, from those that are at an earlier stage in the development cycle, calling for R&D. Two candidates for R&D support identified in the “key actions” section above are direct air capture and large-scale synthetic fuel production, which are not yet ready for deployment at scale now but will be increasingly needed in the 2030s and beyond.

2. Public-Private Collaboration

Public-private collaboration is an appropriate strategy when technologies and
decarbonization approaches are mature and cost-effective, but there are informational or other private sector non-cost barriers that are limiting their adoption at the required scale, and preventing least-cost decarbonization outcomes for society. This is often a collective action problem, in which the cost or risk of overcoming these barriers is seen as too high for individual companies to pursue, even though it may benefit the industry as a whole and society at large. Public-private collaborations include a range of policy interventions in which government shares some of the cost and risk, or undertakes complementary actions.

This may take the form of what is traditionally described as public-private partnerships, such as loan guarantees for new technology deployment. It may also entail activities that aren’t usually thought of as partnerships but nonetheless require close collaboration. One example is providing consumer information, such as EPA’s Energy Star product labeling program. Another is creating or changing market designs and rules. In a carbon-neutral transition, collaboration of this kind will be needed for wholesale electricity markets, in order to enable participation by large-scale flexible loads, or to allow thermal generators needed for reliability but with low capacity factors to recover their investments.

Another key public-private collaboration needed in the 2020s is for government to lay the groundwork for construction of new high-voltage transmission capacity by private contractors. Expanded transmission will play a critical role in a deeply decarbonized energy system, enabling renewables-rich regions of the county to export to regions with resource constraints, and providing load-resource balancing. However, history suggests that favorable economics alone is often insufficient bring transmission projects to fruition. Policy can play a decisive role in enabling construction of new transmission, including cost allocations that produce the least-cost outcome for society.

3. Direct Subsidies

Subsidies are a strategy for dramatically increasing market penetration in cases where the primary barrier is capital cost, even when total lifecycle cost is lower for a low-carbon technology compared to a high-carbon incumbent. Subsidies can come in the form of purchase incentives such as rebates that reduce up-front costs, and investment incentives
such as investment and/or production tax credits, and these can be directed toward either producers or consumers. Some subsidies are ultimately paid for by taxpayers, while rebate programs administered by utilities are paid for by ratepayers. For energy efficiency programs, utility incentives are not necessarily subsidies, because in many cases the programs are cost-effective and produce net economic benefits for ratepayers.

A potential candidate for consumer incentives to accelerate market transformation is electric light-duty vehicles, which currently constitute less than 3% of US market share but need to reach 100% by 2030. Since the main barrier to consumer adoption is purchase price, an appropriate incentive design could be a “cash on the hood” that is large enough to drive a major change in consumer behavior, then phased out over time to encourage competition and reduce subsidy costs. Other candidates are residential building electrification as a whole, in concert with building energy codes, for new buildings, and heat pumps for residential space and water heating for retrofits.

4. Technology Standards

Technology standards are an appropriate strategy for market transformation when there is no substitute for a given technology or approach if emissions targets are to be reached. Standards can be used to address market failures or when incumbent technologies are preferred on cost grounds, and come in many forms. They can be emissions standards that preclude a technology on the grounds of being too high emitting, or an outright ban on technologies as has recently occurred in some European countries in plans to phase out internal combustion passenger vehicles. They can be codes that prescribe performance levels, as in the case of building energy codes and appliance efficiency standards, or portfolio standards that allow flexibility within the context of overall fleet compliance, as with motor vehicle fuel economy.

A potential candidate for standards in the 2020s is electric power generation. To reach the levels of low carbon generation required by the end of the decade, renewable portfolio standards or clean energy standards are likely required. An advantage of such standards is that they set explicit overall guidelines for the generation fleet, while also encouraging competition among alternative technologies, which provides flexibility and cost control.

5. Carbon Pricing

Carbon pricing is an appropriate strategy for market transformation when buyers are sensitive to operating costs. It is a vehicle for addressing the market failure in which incumbent technologies are preferred on cost grounds because externalities are not priced. Carbon prices increase the price of higher emitting technologies, and make lower emitting technologies more attractive. Carbon pricing can come in different forms: directly set prices in the case of a carbon tax, and indirectly set prices in the case of cap and trade, where limits on total emissions establish a market value for carbon.
Carbon pricing can be especially effective in changing the behavior of commercial and industrial firms who are both highly sensitive to operating costs and well-informed about alternatives. A potential candidate for carbon pricing is industrial electrification, for example the adoption of electric or dual-fuel boilers, by sending a price signal that moves industrial consumers away from lower-cost, higher-carbon fuels like coal. Carbon pricing could also be an effective policy for moving commercial fleet vehicles toward lower carbon options. Another area in which a carbon price could be effective is moving industries toward a redesign of their production processes and materials.

It is sometimes thought that a carbon price is the only policy tool required to motivate deep decarbonization, but this is not likely to be true for a number of reasons, both theoretical and practical.

- Carbon prices are consistent with a “low-hanging fruit” policy that procure 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 parallel with those with lower MACs.

- Carbon prices are likely to be capped, for political reasons, at levels too low to catalyze the transformations required for deep decarbonization. Prices greater than these expected values are often assumed to imply negative economic impacts, even though MACs are a poor indicator of the impact on energy system costs.

- Carbon prices penalize sunk investments, for example vehicles already purchased. Those who can’t afford to replace their equipment may be stuck indefinitely paying higher prices for fuel, which can be a serious equity problem.

- Price signals are very imperfectly refracted through fragmented energy markets, many segments of which are inelastic with regard to price. This can also impact low-income consumers without producing emission reductions.

- Carbon prices are a poor price signal for driving large-scale, long-term capital investment in many sectors. 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, cost uncertainty about siting and permitting, etc. These uncertainties impose high risks on investors, and will be reflected in a high premium on the cost of capital.
Achieving Carbon Neutrality in the United States

Carbon Neutrality Involves Multiple Transitions

The low carbon transition actually involves multiple transitions occurring in parallel, in infrastructure, energy economy, land use, jobs, and policy. Key findings in each of these areas are summarized below.

Infrastructure transition
- Carbon neutrality is achieved through a large-scale buildout of efficient, low carbon infrastructure to replace existing infrastructure.
- The infrastructure transition is based on four pillars: (1) energy efficiency, (2) electrification of end uses, (3) electricity decarbonization, and (4) carbon capture.
- This buildout needs to begin immediately and ramp up rapidly. Delay in going “all-in” adds costs, limits options, and intensifies future conflicts.
- A carbon-neutral energy system is organized around taking maximum advantage of low cost wind and solar electricity, even in cases with higher nuclear or fossil CCS.
- A renewables-based energy system is reliable and technically feasible. It calls for some improvement in electricity planning, operations, and regulation.
- The main uncertainties affecting future technology choices in energy are less a function of cost or engineering than of land use, biomass use, consumer adoption rates, jobs, public acceptance, and other social and environmental tradeoffs.

Energy economy transition
- Carbon neutrality in energy and industry by 2050 is achievable at a net cost of less than 1% of GDP across a wide range of scenarios and sensitivities.
- In the least cost case modeled, the net cost was about $130B in 2050, or 0.4% of GDP in that year, with a net present value from 2020 to 2050 of less than $2 trillion.
- Energy spending as a share of total U.S. GDP in carbon neutral scenarios is about 5% in 2050, higher than BAU but still on the low end of historical range since 1950.
- Changes in gross economic flows are large, with about $1T per year less spent on fossil fuels, and about $1T per year more spent on technology.
- Capital investment requirements would increase but remain a small share of overall investment in the U.S.
- The changes in gross revenue flows in the energy economy means that there are winners and losers among industries, businesses, workers, and communities.

Jobs transition
- A carbon neutral transition will provide jobs over multiple decades and across many sectors and regions.
- Phasing out fossil fuels will result in job losses in many industries, occupations, and regions. Rural communities dependent on extraction will be most affected.
- Planning, policies, and institutional support for an equitable labor transition is needed to overcome political economy constraints on rapid decarbonization.

Land use transition
Achieving Carbon Neutrality in the United States

- Carbon neutrality requires land for three purposes: (1) siting of energy infrastructure, (2) biomass feedstocks, and (3) the land CO₂ sink.

- Land requirements for wind, solar, and transmission siting are large and can be a bottleneck for rapid decarbonization if not handled with prudent anticipation.

- Sequential planning and environmental approval processes, along with go-it-alone state planning that ignores regional neighbors, are recipes for increased delay and cost.

- Integrated land-energy-climate planning can identify development options that provide economic opportunities while avoiding land use conflicts.

- Regional coordination enables low-cost, low-impact renewable energy and transmission development if undertaken early and proactively.

Policy transition

- The infrastructure changes required over the next 10 years are well-understood and consistent across pathways.

- These provide a robust analytical basis for setting targets and developing policies for implementation now.

- The political economy challenge of managing distributional effects is essential to the political success of a low carbon transition.

- Tradeoffs among technology choices, land use, and jobs call for both better planning and increased stakeholder engagement.

- We need policy processes that do not currently exist, especially where planning and coordination across time, sectors, geographies, and jurisdictional levels is required.

Pathways modeling in planning and decision-making

Pathways modeling is a way of developing physically and economically feasible strategies for deep decarbonization. It plays a number of valuable roles, both narrative and technical. Done well it tells an internally consistent story that can capture people’s imaginations and motivate action. It provides a technical foundation for setting policy targets and timelines. It identifies both no-regrets strategies that can be pursued, and infeasible or dead-end strategies that can be eliminated. Critical for planning, it allows future decision points and tradeoffs to be anticipated and planned for.

Pathways modeling also has limitations. Pathways are what-if scenarios, not forecasts. The future may turn out differently than our modeling results suggest. They illustrate technical transitions but largely ignore human and institutional constraints that are hard to quantify. They do not represent the full range of options or capture all uncertainties. Both data inputs and model structure can bias inputs in ways that aren’t always clear.

Nevertheless, decisions are made in the face of uncertainty and pathways modeling provides a common, concrete set of actionable information. If pathways modeling educates decision makers and stakeholders about choices, and provides directionally correct results, it is very valuable. By making assumptions and causal relationships explicit, pathways modeling can be updated to reflect new information from the realms of climate science, domestic and world affairs, and technological innovation.