GETTING TO NET ZERO

U.S. REPORT

PATHWAYS TOWARD CARBON NEUTRALITY

A REVIEW OF RECENT MID-CENTURY DEEP DECARBONIZATION STUDIES FOR THE UNITED STATES

A report led by
California-China Climate Institute (CCCI)

in collaboration with
Energy and Environmental Economics (E3)

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SERIES OVERVIEW

This series explores ways in which the United States and China can coordinate their near-term and mid-term efforts to achieve carbon neutrality by around the middle of this century, based on a review of deep decarbonization pathways studies in both countries. The series includes three reports: a synthesis report that develops a framework and proposes milestones for U.S.-China coordination on carbon neutrality, and two supporting reports that review and analyze recent deep decarbonization studies in the United States and China, respectively. This report contains the U.S. deep decarbonization studies review.

ABOUT THE CALIFORNIA-CHINA CLIMATE INSTITUTE

The California-China Climate Institute was launched in September 2019 and is a University of California-wide initiative housed jointly at UC Berkeley's School of Law (through its Center for Law, Energy, and the Environment) and the Rausser College of Natural Resources. It is Chaired by Jerry Brown, former Governor of the State of California, and Vice-Chaired by the former Chair of the California Air Resources Board Mary Nichols. The Institute also works closely with other University of California campuses, departments, and leaders. Through joint research, training, and dialogue in and between California and China, this Institute aims to inform policymakers, foster cooperation and partnership and drive climate solutions at all levels.

ACKNOWLEDGMENTS

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EXECUTIVE SUMMARY

In the first four months of 2021, the Biden administration announced two climate goals: first, in January, a goal of achieving carbon neutrality, or net-zero greenhouse gas (GHG) emissions economy-wide, by no later than 2050;[1] second, in April, a goal of reducing economy-wide GHG emissions by 50 to 52 percent, relative to 2005 levels, by 2030.[2] The Biden administration's announcements followed mid-century carbon neutrality commitments in eleven states, beginning with California in 2018. Other states are considering similar commitments, and 20 states and the District of Columbia have adopted economy-wide greenhouse gas reductions goals calling for at least an 80 percent reduction in greenhouse gas emissions by 2050.

What will it take to achieve these goals? This report aims to shed light on the energy system transformations and policies required to achieve a mid-century carbon neutrality goal in the United States, based on a review of recent (2014-2021) deep decarbonization studies, including five national studies and two state-level studies.

All of the studies included in our review emphasize that achieving carbon neutrality will require a decades-long transformation of the way energy is produced and consumed. The decade ahead, between now and 2030, will be critical if the United States (U.S.) is to establish the technology deployment, market transformations, and investment trends necessary to put the country on a realistic path toward carbon neutrality by mid-century.

Table 1 | Near-Term Priorities For Achieving Carbon Neutrality In The U.S. By Mid-Century

"PILLAR" of DECARBONIZATION	NEAR-TERM PRIORITIES
Electrification and efficiency	Rapid adoption of electric and hybrid-electric heat pumps in buildings, electric vehicles, and other electrified end-use technologies; increased investments in energy efficiency in buildings, industry, and transportation
Clean electricity	Rapid deployment of wind, solar, and battery storage, along with investments in grid reliability and zero-carbon firm capacity
Low-carbon fuels	Market development and continued research, development, and deployment (RD&D) for advanced, sustainable biofuels, hydrogen, and other advanced low-carbon fuels
Non-carbon dioxide (CO_2), non-combustion reductions	Reduction in methane leakage from oil and natural gas systems, shift to climate-friendly refrigerants and hydrofluorocarbon (HFC) replacements
Carbon capture, usage, and storage and enhanced land sinks	Increased investment in deployment of carbon-sequestering agriculture and forestry practices and RD&D in carbon capture utilization and storage (CCUS)

[1] The White House, "Executive Order on Tackling the Climate Crisis at Home and Abroad," January 2021, https://www.whitehouse.gov/briefing-room/presidential-actions/2021/01/27/executive-order-on-tackling-the-climate-crisis-at-home-and-abroad/.

[2] The White House, "FACT SHEET: President Biden Sets 2030 Greenhouse Gas Pollution Reduction Target Aimed at Creating Good-Paying Union Jobs and Securing U.S. Leadership on Clean Energy Technologies," April 2021, https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/22/fact-sheet-president-biden-sets-2030-greenhouse-gas-pollution-reduction-target-aimed-at-creating-good-paying-union-jobs-and-securing-u-s-leadership-on-clean-energy-technologies/

The studies reviewed in this report examine a broad range of future scenarios, yet there are areas of agreement pointing to nearer-term "no-regrets" strategies across five pillars of deep decarbonization. Table 1 characterizes priorities for the next decade that emerge from this literature review. Given the long lifetimes of buildings, building equipment, vehicles, and industrial and manufacturing equipment, the United States faces a wide turning radius in making the transition to clean energy technologies. Near-term action will be critical to scale up and deploy clean energy technologies over the next three decades.

Implementing nearer-term, no-regrets strategies will require tackling challenging institutional obstacles. For instance, results from two studies suggest that supporting the rapid expansion of solar and wind generation would imply an approximately three-fold expansion of the U.S. interstate electric transmission system by 2050. However, regional transmission investment has lagged in recent decades and would likely require a combination of stronger federal policy support and more streamlined permitting processes. Multiple studies also suggest that pathways consistent with carbon neutrality goals imply retirement of all U.S. coal generation by 2030, which may require strategies to address regulated utilities' investment incentives and stranded costs.

In the building and passenger transport sectors, a no-regrets shift toward greater reliance on electricity has important implications for the reliability and resilience of the electric grid, particularly in the context of increasing frequency of extreme weather events, due to climate change, and cybersecurity risks. The question of how to manage the reliability of the grid, while transitioning away from fossil fuels, as digitization and electrification makes electric reliability ever more essential, has started to receive more attention recently in the wake of major outages following wildfires and storms. Going forward, electric reliability and resilience should be core areas of focus for policy, regulation, research, development, and deployment (RD&D), and updated engineering and planning standards over the next decade.

Beyond these common no-regrets strategies, there is significant uncertainty in the technology pathways for decarbonizing industry and some segments of the transportation sector, and the "last mile" of decarbonization in the electricity sector. This uncertainty is reflected in the wide range of scenarios and assumptions within and across studies. Although all studies suggest that achieving carbon neutrality in the United States would be feasible with existing technologies at reasonable cost, uncertainty in technology pathways underscores the need for continued RD&D and commercialization of emerging technologies. Key areas of focus for RD&D include zero-carbon firm sources of generation, advanced low-carbon fuels, and zero emission technologies for off-road transportation and industry.

The scale of energy system transformations required over the next decade to meet a mid-century carbon neutrality goal far exceeds current levels of U.S. federal policy ambition. Some states and cities have filled the policy gap left by the federal government, and regional initiatives, such as regional cap-and-trade systems or coordinated zero emission vehicle (ZEV) goals, have facilitated some degree of interstate cooperation. However, even among leading states, levels of policy ambition do not yet match what would be needed to move the United States onto a trajectory to meet a 2050 carbon neutrality goal.

Current federal and state momentum for climate action presents a window of opportunity to develop a common vision of future energy, industrial, agricultural, and forestry systems, and to translate long-term carbon neutrality goals into near-term changes in policy and regulation that are consistent with trajectories that meet those goals.

Implementing this carbon neutrality vision will require near-term strategies that address challenges in four areas:

1. **First, the economics must be aligned for consumers and companies to adopt clean energy technologies at scale.** This will require capital investments to bring down the upfront costs of new technologies, through direct incentives, tax credits, and RD&D. It will also require aligning fuel prices around carbon reduction goals, most critically for gasoline, diesel,

natural gas and electricity. This alignment could occur through carbon pricing or other pricing policies, such as an advanced low carbon fuel standard. Overall, low-carbon technologies and decarbonized energy supplies must be affordable for consumers and businesses if this transition is to gain widespread momentum. Energy affordability must be considered in a holistic sense, including household, business, and transportation sector energy consumption.

2. **Second, broad changes in institutions and governance will be needed to encourage clean energy development, and to ensure rigorous GHG monitoring and accounting.** These changes span policy, regulatory, and institutional reforms across multiple sectors. They include changes in energy sector regulation, such as changes to electric and natural gas rate designs by public utility commissions and institutional changes to facilitate development of new interstate transmission and renewable energy siting. An additional core area for institutions and governance reforms will be in improving federal and state agencies' capabilities to monitor and track emission reductions by sector and fuels, and in particular, for CCUS and land use-related GHG emissions sources and sinks.

3. **Third, public engagement and education are needed** to encourage higher levels of clean energy technology adoption, to make climate policies more inclusive, and to avoid regressive policy impacts. Net-zero scenarios depend on high levels of adoption of zero-emissions vehicles, energy efficient equipment, and electric heating appliances in buildings. These choices all involve diffuse customer decision-making, which is not currently aligned with longer-term emissions goals. Public engagement and education, including targeted educational resources and decision-making tools, are essential strategies for aligning policy and adoption. Likewise, building trust and partnerships with a wide range of audiences and communities can help to ensure that federal and state policies are inclusive and foster equitable outcomes.

4. **Fourth, economic development assistance and workforce training and support are needed to enable a transition away from fossil fuels.** At a macro level, transition assistance includes federal development aid for states with large fossil fuel economies. At a more micro level, workforce training and support can help to address both the need for workers that have expertise in emerging technologies and the need to help transition existing fossil fuel jobs to new sectors. For instance, scaling up building energy efficiency and electrification in buildings will require skilled contractors, including electricians, heating, ventilation, and air conditioning (HVAC) specialists, plumbers, and general contractors, but the United States is currently in short supply of contractors who are proficient with building electrification and energy efficiency technologies. In addition, targeted, long-term strategies will be needed to transition workers out of the fossil fuel industry, and the coal industry in particular. A proactive approach to economic and labor transition is important to remove opposition to shifting away from fossil fuels, and to achieve the political consensus and momentum necessary to support the other strategies described throughout this report.

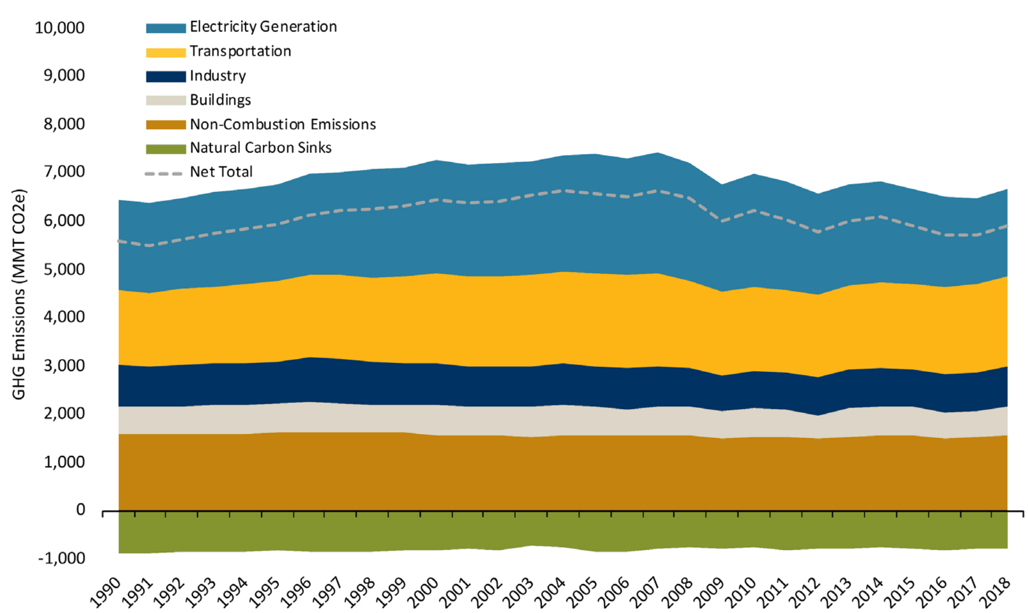
CHAPTER ONE
INTRODUCTION

As global average temperatures continue to rise and the present and future impacts of climate change become more apparent, there is growing scientific consensus and political support for the need to act urgently to reduce greenhouse gas (GHG) emissions. The Intergovernmental Panel on Climate Change's (IPCC's) 2019 Special Report, Global Warming of 1.5°C, found that limiting global average temperature increases to 1.5 degrees Celsius above preindustrial levels would be needed to avert the most damaging impacts from climate change, and that achieving this temperature target would require global net carbon dioxide (CO_2) emissions to be reduced to zero, along with steep reductions in non-CO_2 GHG emissions, by mid-century.[3]

The United States appears likely to formally adopt a GHG emissions target of carbon-neutrality by 2050 in the coming months. The Biden administration has already adopted an Executive Order establishing a net-zero GHG emissions target by 2050. Formally adopting a mid-century carbon-neutrality target would align with recent commitments from the European Union, China, and many U.S. state governments.

U.S. GHG emissions consist mostly (~80%) of CO2 released from the combustion of fossil fuels. The remainder of emissions (~20%) include methane, nitrous oxide and fluorinated gases, emanating from agriculture, industrial processes, and waste. Figure 1 below displays historical GHG emissions for the United States over the past three decades, showing CO2 emissions by sector, along with non-combustion emissions and natural carbon sinks.

Figure 1 | U.S. greenhouse gas emissions and sinks by sector



Source: EPA, 2020

[3] IPCC (2019).

While the COVID-19 pandemic led to an estimated 13% drop in GHGs in 2020, largely due to reduced travel- and transportation-related emissions, this effect is not expected to be lasting at this scale as the economy recovers and travel resumes.[4] Although net GHG emissions have decreased 11% from their peak in 2007, the United States is not currently on track to achieve carbon neutrality by 2050, nor is it on pace to achieve its 2025 Paris Agreement target of 26-28% below 2005 levels.[5]

Due to the absence of strong federal climate action thus far, a growing number of municipalities, states, electric utilities, academic institutions, and corporations across the United States have adopted net-zero GHG emissions targets. These net-zero emissions targets are generally defined to include both gross sources of greenhouse gas emissions (including CO_2, methane, certain fluorinated gases, and nitrogen oxides), as well as carbon sinks in natural and working lands.

Achieving a net-zero GHG target in the United States will require an unprecedented transition from an economy based on fossil fuels to one based on clean energy and non-emitting resources. A number of recent deep decarbonization studies have modeled the energy system transitions necessary to achieving carbon-neutrality by mid-century. In this report, we review several of these studies to determine where there is broad agreement about technology pathways, where there is less agreement, and what this means for near-term policy priorities.

Table 2 lists the major, economy-wide U.S. and state-level decarbonization studies included in this review. In addition to the more recent net-zero studies, we also include two landmark deep decarbonization studies. Including these studies allows us to recognize the "no-regrets" near-term strategies that are present in even less ambitious decarbonization pathways and highlight the sectors with difficult to abate emissions that must be addressed in a net-zero transition. While all of these studies evaluate technology changes between 2020 and 2030 on the path to 2050, the studies were not designed to achieve a specific 2030 GHG emissions constraint. As a result, the near-term, "no regrets" strategies discussed below, and the U.S. milestones identified in the synthesis report, should be understood as guidelines for a minimum viable pathway to achieving U.S. mid-century GHG goals, rather than as an approach towards achieving a specific 2030 emissions target.

Table 2 | Economy-wide deep decarbonization studies reviewed for this report

Study	Scenarios	Jurisdiction	GHG Emissions Target
Williams et al., 2014	Mixed	United States	80% by 2050
White House, 2016	MCS Benchmark	United States	80% by 2050
Energy Innovation, 2020	Policy Scenario	United States	Net-Zero by 2050 (CO2)
Williams et al., 2021	Central, Delayed Electrification	United States	Net-Zero by 2050 (CO2)
Larson et al., 2020	E+ (High Electrification), E- (Less High Electrification)	United States	Net-Zero by 2050
E3, 2020a	Balanced	California	Net-Zero by 2045
E3, 2020b	High Technology Availability	New York	Net-Zero by 2050

[4] Tollefson, Jeff. (January 15, 2021). COVID curbed carbon emissions in 2020 — but not by much. Nature. https://www.nature.com/articles/d41586-021-00090-3

[5] Larsen & Pitt (2021).

While this list is not exhaustive, it provides a useful range of studies that were developed for research purposes, as well as studies developed specifically to inform state-level policy developments. Many of these studies include a wide range of sensitivity scenarios, but we have chosen to compare quantitative results from the “core” decarbonization scenarios whenever possible for consistency and note whenever results of a sensitivity scenario are reported.

This report is organized into three sections. The first section reviews and describes the decarbonization strategies used in different studies for achieving carbon-neutrality across five “pillars.” The second section briefly summarizes federal, state, and regional decarbonization policies that have been adopted or proposed to date and provides a high-level assessment of their adequacy relative to the technology pathways identified in deep decarbonization studies. The third and final section summarizes the strategy and policy reviews and provides concluding thoughts.

CHAPTER TWO
DECARBONIZATION STRATEGIES

Many deep decarbonization studies have used the pillars framing to describe a set of broad strategies that support decarbonization and are common across a broad range of future scenarios. While the exact number and scope of the pillars varies by study, this report includes five:[6]

1. Electrification and efficiency
2. Clean electricity
3. Low-carbon fuels
4. Non-energy CO_2 and Non-CO_2 reductions
5. CO_2 capture, usage, and sequestration (CCUS) and enhanced natural land sinks

Using the pillars framework, this report compares the results of recent national and state-level deep decarbonization studies to determine where mitigation strategies are common across all studies and where they diverge. In addition, mitigation strategies are grouped into the following categories based on the near-term priorities for each:

1. **Deployment** – Need to achieve massive deployment at scale quickly. Technologies are already commercialized, and the main challenges are in widespread adoption.
2. **Market Transformation** – Need to bring down cost and bring new products to market at scale. Technologies are near-commercial or commercial but at limited scale and need further advancements and cost declines.
3. **Innovation** – Need to invest in RD&D to identify and commercialize new technologies.

2.1 Electrification and Efficiency

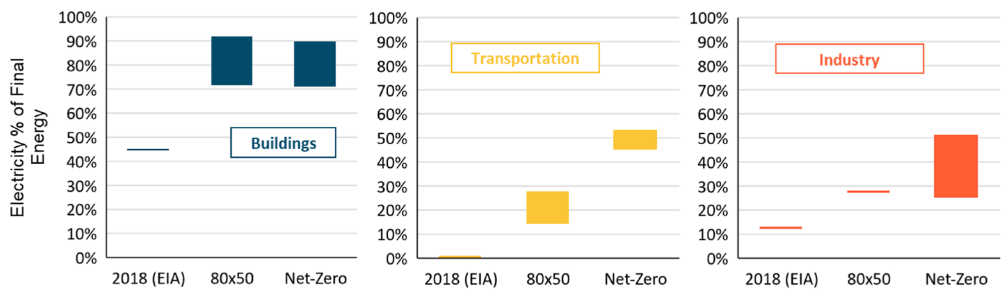
Both end-use electrification, where fossil fuel consuming devices are replaced with electrically-powered devices, and traditional energy efficiency measures are critical to emissions reductions in virtually all long-term decarbonization studies. Figure 2 shows the electricity share of final energy demand by sector in 2050 across the reviewed studies. For both transportation and industry, electrification rates increase in the carbon neutrality studies, relative to the 80x50 studies.

High electrification in buildings and on-road transportation is common across deep decarbonization studies, although there is little to no electrification for off-road transportation applications like aviation and shipping. Electrification for buildings and on-road transportation includes an efficiency benefit in addition to reducing emissions, as electric heat pumps and electric vehicles (EVs) are much more efficient than conventional gas furnaces and internal combustion engine vehicles (ICEVs). In addition, electric heat pumps and passenger electric

[6] This report collapses electrification and efficiency into a single pillar, for a total of five pillars, whereas the report, Getting to Net Zero: U.S.-China Framework and Milestones for Carbon Neutrality separates the two and has six pillars.

vehicles are already commercialized and are anticipated to be a lower cost alternative to other decarbonized fuel options across most of the studies reviewed.

Figure 2 | Electricity share of final energy demand by sector in 2050 from reviewed studies with historical comparison



Note: Values are from all studies except for Energy Innovation, 2020, where final electricity demand outputs were not readily available. The single value for industry in the 80x50 studies is from Williams et al., 2014, as the 2016 White House MCS study only reports values for manufacturing industries.

Because of the long lifetimes for devices like home heaters and vehicles, sales of electric devices need to ramp up dramatically in the 2020 to 2030 timeframe and dominate market share by 2040 in order to hit the high saturation levels required by mid-century in most carbon-neutrality studies. Figure 3 shows an example of this dynamic from Williams et al. (2021): EVs reach sales share parity with ICEVs by 2030 and make up virtually all new sales by 2040 in the Central scenario.

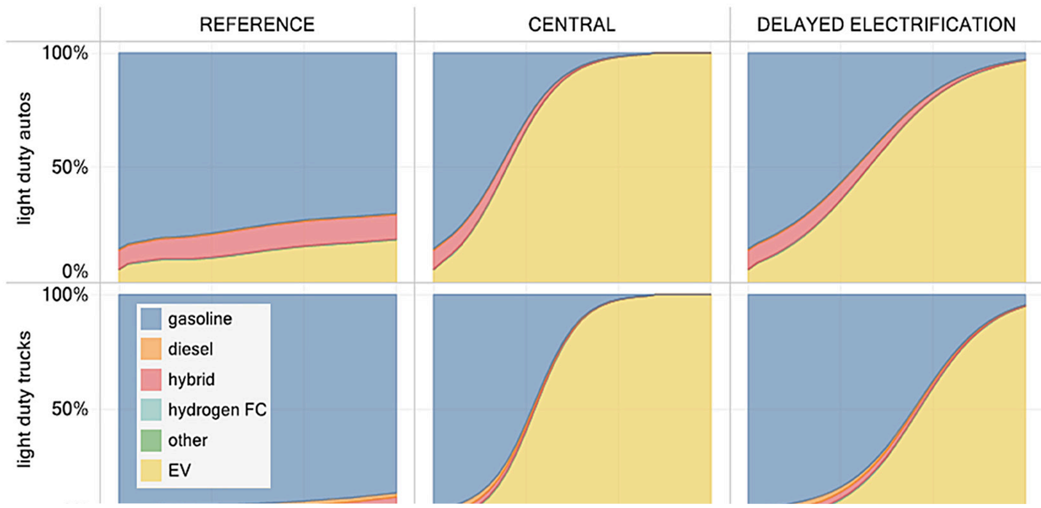
One important consideration in the deployment of electric air source heat pumps (ASHPs) is the need for a backup source of supplemental heat. The maximum heat output of an ASHP declines as outdoor temperatures fall, and because ASHPs are generally sized to meet a building's heat demand for most hours of the year, they may require supplemental heat in the very coldest hours. Supplemental heat can be provided by electric resistance backup or onsite fuel combustion, often called a "dual-fuel system" or "hybrid heat pump."

In regions of the United States with particularly cold climates such as New England and the Upper Midwest, the shift to electric space heating could have a significant impact on system peak load, and hybrid heat pumps could help reduce system peak relative to ASHPs with electric resistance backup. While the optimal distribution of supplemental heat sources has not been examined in the deep decarbonization studies reviewed here, recent studies for New York and New England have assumed an equal split between ASHPs with electric resistance backup and hybrid heat pumps in in recognition of this dynamic.[7] The expected shift to electricity as a heating fuel also requires an increased focus on maintaining electricity system reliability, as a greater portion of Americans will rely on the grid to provide this essential service.

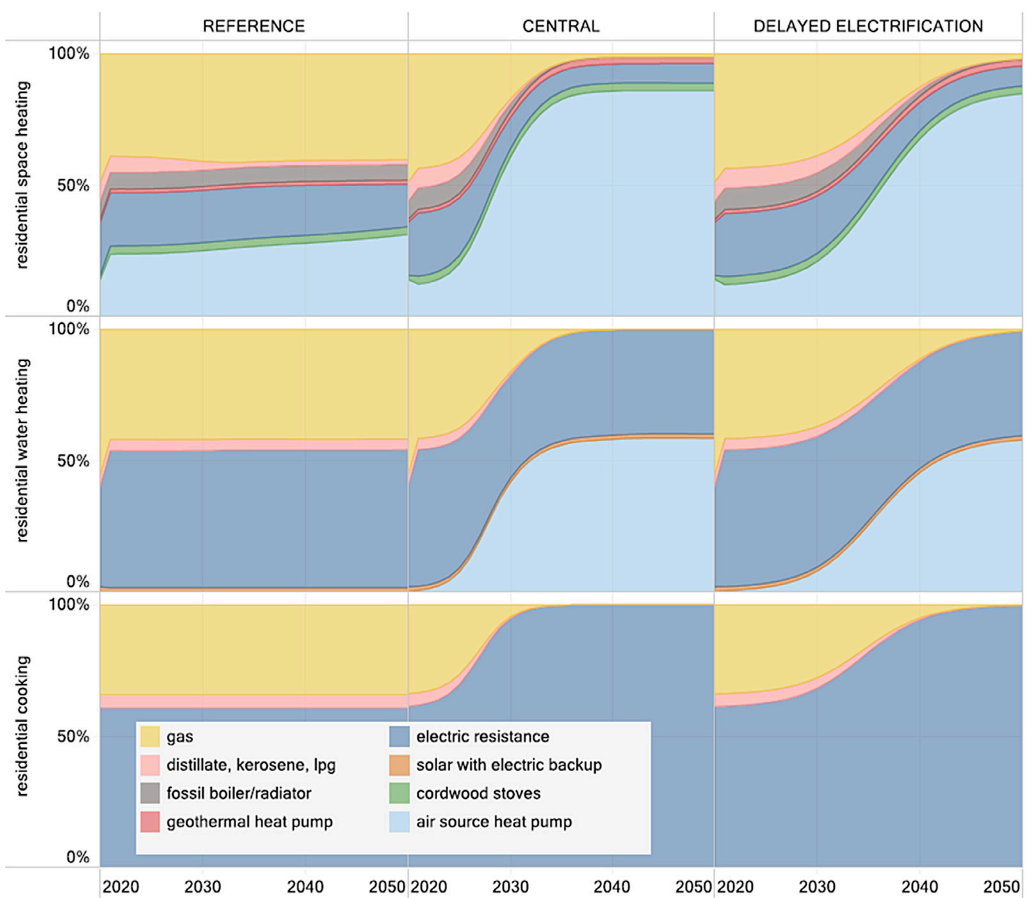
[7] See E3 & Energy Futures Initiative, Net-Zero New England: Ensuring Electric Reliability in a Low-Carbon Future (2020) and E3, Pathways to Deep Decarbonization in New York State (2020)

Figure 3 | Passenger vehicle sales and key residential equipment sales shares

TRANSPORTATION SALES



KEY RESIDENTIAL SUBSECTOR SALES



Source: Williams, et al. 2021

In contrast, electrification tends to play a smaller role in hard to decarbonize sectors like industry, marine shipping, and aviation across studies. While some incremental electrification in industry is generally included, industrial end-uses are heterogenous and less well-represented in deep decarbonization models than those of other demand sectors, and separate decarbonization analyses for many major industrial subsectors (e.g., cement, iron and steel, bulk chemicals) have found barriers to electrification that suggest other decarbonization strategies may be lower cost and easier to implement.[8] There are some industrial applications where electrification may be the most cost-effective strategy like infrared heating for drying or industrial heat pumps for food processing, but further research and development is needed to identify potential strategies and drive down costs.[9]

Traditional energy efficiency measures focused on replacing technologies with newer models of the same energy type are important, both in terms of reducing demand for electricity (e.g., light emitting diodes (LEDs)) and for remaining liquid or gaseous fuels in hard to decarbonize sectors (e.g., industry and aviation). All deep decarbonization studies reviewed include measures where all new end-use appliances are high efficiency models by 2050, in addition to assuming energy efficiency improvements for industry and aviation. While energy efficiency in all sectors is essential to reducing the overall cost of achieving net-zero goals, efficiency improvements in the hard to decarbonize sectors like industry and off-road transportation are crucial to minimizing costs for zero carbon fuels or negative emissions technologies (NETs) needed to reach net-zero emissions.

The combination of traditional energy efficiency and the efficiency benefits of electrification mean that deep decarbonization scenarios lead to a significant reduction in final energy demand relative to a future business-as-usual scenario, ranging from 23% (E- Scenario from Larson et al., 2020) to 41% (E3, 2020b) lower in 2050.[10] On a sectoral level, reductions in final energy demand are largest in transportation due to the large efficiency benefits of moving from internal combustion engines to electric drivetrains in vehicles.

Table 3 | Priority Focus Areas for Electrification and Energy Efficiency

Priority Focus	Technologies / Strategies
Deployment	Heat pump space and water heaters Light-duty EVs Higher efficiency building shells Plug load efficiency and management LED lighting and lighting management
Market Transformation	Medium and heavy-duty EVs Commercial building electric HVAC and water heating solutions, particularly in retrofits Industrial boiler electrification
Innovation	Off-road transportation electrification Industrial process heat electrification

Table 3 provides a summary of priority focus areas for the electrification and energy efficiency pillar. As described above, many of the technologies and strategies in this pillar are either at a deployment or market transformation stage, while off-road and industrial electrification require additional RD&D.

8 Friedmann, Fan, & Tang (2019).

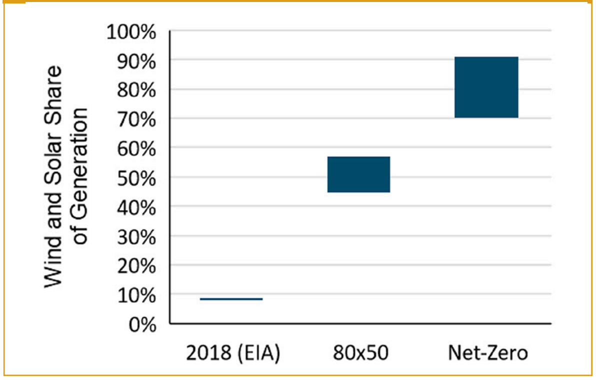
9 Mai, et al. (2018).

10 The low end of this range comes from the E- scenario in Larson et al. (2020), while the high end of the range comes from E3, Pathways to Deep Decarbonization in New York State (2020).

2.2 Clean Electricity

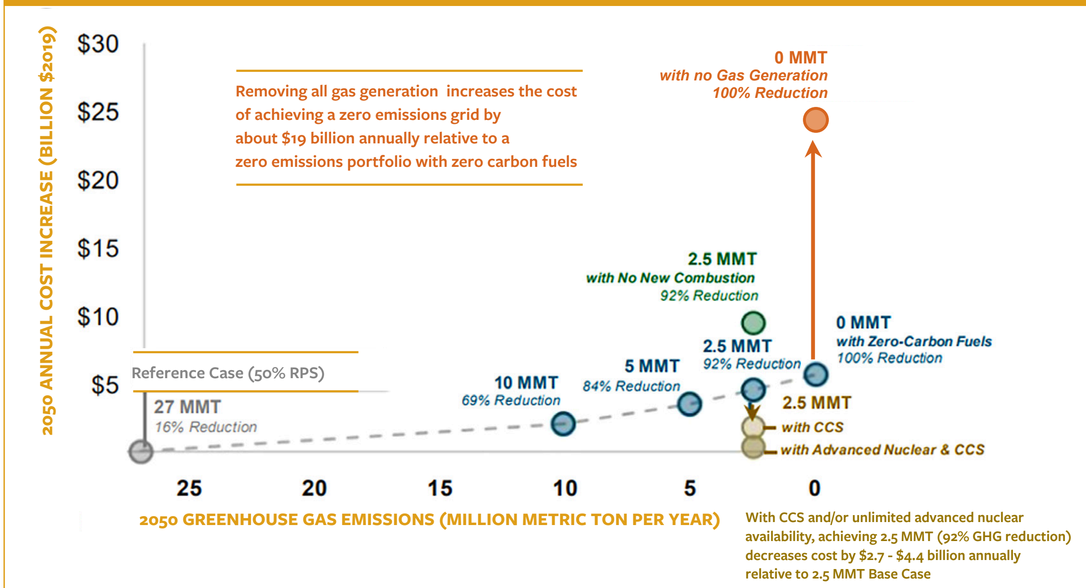
Deep decarbonization of the power sector is universally required across the reviewed studies to reach net-zero CO_2 emissions. In all net-zero scenarios where annual generation is reported, coal is phased out by 2030, accompanied by a dramatic increase in wind and solar capacity and generation. The increase in wind and solar generation is accompanied by the deployment of 4-hour and 8-hour battery storage capacity in order to avoid curtailment and help balance loads with generation on the grid. Installed grid battery capacity ranges from around 140 gigawatts (GW) to 180 GW in 2050 in the E- and E+ scenarios in Larson et al. (2020). Additional multi-day or seasonal energy storage may also become necessary as the grid approaches zero-carbon depending on what other forms of zero-carbon dispatchable capacity are available in the 2040 to 2050 timeframe.

Figure 4 | Wind and solar combined share of electricity generation in 2050 from reviewed studies with historical comparison (results are net curtailment)



Despite the declining costs of variable renewable energy (VRE) and short-duration battery storage, multiple studies have concluded that some amount of firm energy and capacity will be necessary to reliably meet load and maintain stable grid operations in a deeply decarbonized power system.[11] In studies

Figure 5 | Increase in electricity system modeled costs relative to reference scenario in 2050 under a range of emissions and resource constraints



Note: Values are from all studies except for Energy Innovation, 2020, where final electricity demand outputs were not readily available. The single value for industry in the 80x50 studies is from Williams et al., 2014, as the 2016 White House MCS study only reports values for manufacturing industries.

Source: E3 & Energy Futures Initiative, 2020 ($ values are in $2019)

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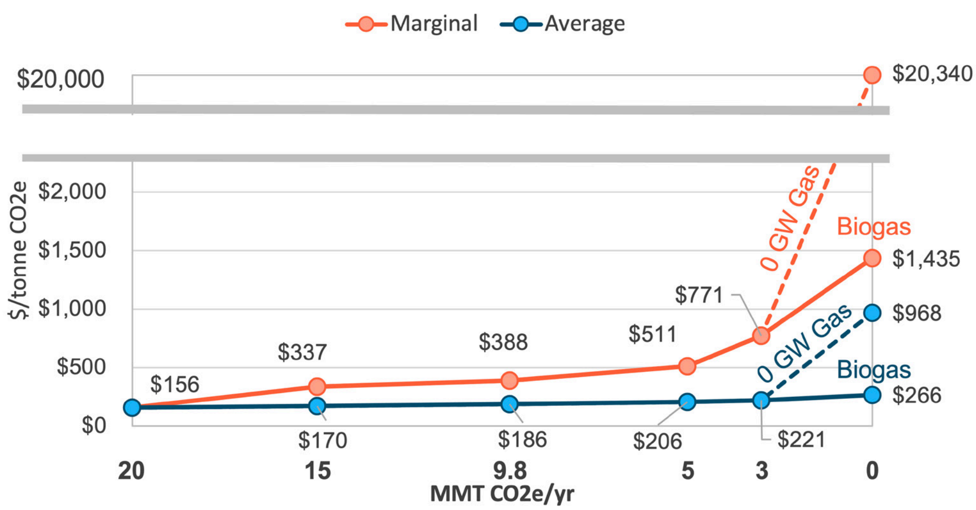
[11] See Sepulveda, Jenkins, de Sisternes, & Lester (2018), Ming et al. (2019), and E3 & Energy Futures Initiative, Net-Zero New England: Ensuring Electric Reliability in a Low-Carbon Future (2020)

where a small amount of gross emissions are allowed in the power sector, firm energy needs are typically met with natural gas combustion turbines. When a zero emissions constraint is applied, firm capacity needs are met with technologies that are not yet commercial at a large scale today if available in the model. These include advanced nuclear, natural gas with carbon capture and sequestration (CCS), combustion turbines fueled with renewable natural gas or hydrogen, and multi-day, or seasonal energy storage resources.

Figure 6 | Carbon abatement cost of zero emissions electricity system in California in 2050



Source: E3 & Energy Futures Initiative, 2020 ($ values are in $2019)

Although a zero-emission power system comprised of only existing commercial technologies is technically feasible, it would require a dramatic overbuild of renewables and short-duration battery storage to reliably operate. As shown in Figure 5 and Figure 6, recent modeling of deeply decarbonized regional power grids in New England and California by E3 found that zero emission systems with no gas combustion were exorbitantly expensive when compared with systems where combustion of biogas or hydrogen was allowed.

Table 4 | Priority Focus Areas for Clean Electricity

Priority Focus	Technologies / Strategies
Deployment	Renewable energy Short-duration storage Transmission expansion and distribution upgrades DERs, flexible loads integration
Market Transformation	DERs, flexible loads integration
Innovation	Clean firm generating resources (hydrogen, advanced nuclear, CCS and/or multi-day or seasonal energy storage)

Priority focus areas for the clean electricity pillar include rapid deployment of renewable generation, short-duration storage, an expansion of the transmission system, and upgrades to distribution systems (Table 4). Market transformation of DERs could provide additional flexibility to the electricity systems. Clean firm generation resources are the primary R&D need.

2.3 Advanced Low-Carbon Fuels

Although widespread electrification is a critical component of net-zero pathways, advanced low-carbon fuels are expected to complement decarbonized electricity for applications where electrification is not cost-effective. These include off-road transportation sectors like aviation and marine shipping, some portion of long-haul on-road freight transportation, and process heating for many industrial applications. At least some of the energy demand in these sectors is met with advanced low-carbon fuels across studies. In addition, the rapid customer adoption of electrified technologies needed to reach electrification levels assumed in many scenarios is highly uncertain, and advanced low-carbon fuels may be needed for these end-uses as well under a net-zero emissions constraint. Most studies reviewed for this report included three categories of advanced low-carbon fuels:

- Advanced biofuels used as a drop-in replacement for liquid and gaseous fossil fuels. These advanced biofuels would be produced using advanced techniques from biomass wastes and residues to produce a fuel that is identical to gasoline, diesel, or jet fuel today. This stands in contrast to biodiesel, which is today largely produced from waste oils and fats, and ethanol, which is generally produced from food crops such as corn, sugar cane, or soy.
- Hydrogen made from either electrolysis powered by clean electricity, biomass gasification with or without CCS, or natural gas reformation with CCS.
- Synthetic hydrocarbon fuels made from hydrogen and a climate-neutral source of CO_2 (such as from biomass or from captured CO_2).

The use of advanced biofuels and biomass-derived hydrogen is limited by the sustainable supply of biomass feedstocks, which most studies assume is the economically recoverable supply in the United States. Given that other countries will also need to achieve carbon neutrality and may reserve their own supplies of biomass for these purposes, imported biomass and biofuels are generally excluded from these estimates. In its 2016 Billion-Ton Report, the U.S. Department of Energy estimated that around 800 million dry tons of domestic biomass could be available by 2040, although half of this amount comes from energy crops grown on lands converted from food production.

Due to sustainability concerns around dedicated energy crops and competing priorities with food production, most net-zero scenarios assume that a sustainable supply of biomass is limited to forest and agricultural residues and waste resources, although some studies also consider the repurposing of land from corn ethanol production to high-yield energy crop production. The use of purpose-grown forests for biomass has received recent attention, given the widespread use of this option in Europe, but there are concerns about its sustainability and some researchers have estimated that the use of forest products can cause a near-term net increase in CO_2 emissions due to the time needed for replacement forest to mature on harvested land.[12]

There is significant variation in how biomass resources are used across the studies. In previous deep decarbonization studies where bioenergy with carbon capture and sequestration (BECCS) was included, it was primarily used with biomass combustion for electricity generation. More recently, Williams et al. (2021) and Larson et al. (2020) find that one of the most valuable uses for biomass is for hydrogen production via gasification with the CO_2 byproduct from gasification being captured and sequestered. This pathway is advantageous from a modeling perspective because it provides both a low-carbon fuel and negative emissions, although it is a relatively new process that has not yet been deployed.

Apart from BECCS, biomass feedstocks are often allocated towards advanced renewable fuels that can be used as drop-in replacements for liquid fuels in the transportation sector, since the relatively high cost of petroleum fuels like gasoline, diesel, and jet fuel make them more cost-effective to replace with biofuels than natural gas. Biomass combustion for electricity consumption usually plays a small role by 2050 in net-zero scenarios, if it is present at all. In Larson et al. (2020), biomass combustion

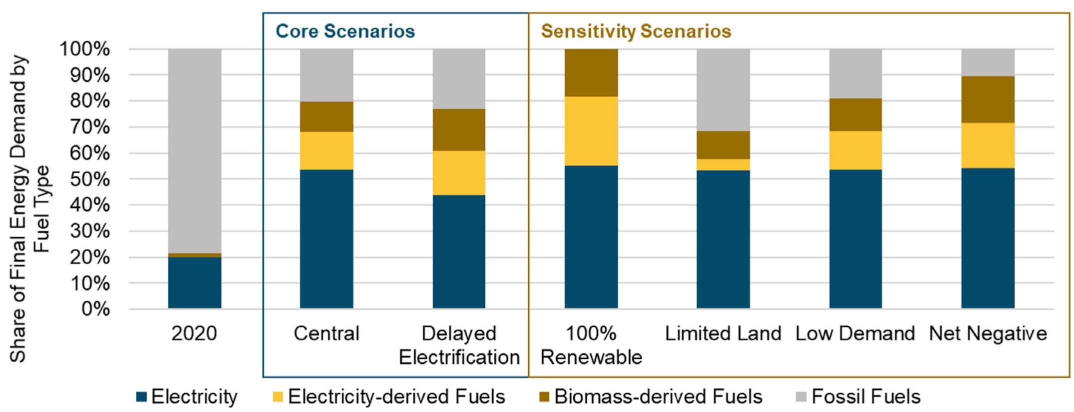
12 Sterman, Siegel, & Rooney-Varga (2018).

accounts for less than 1% of annual electricity generation in the Central and Delayed Electrification scenarios, while in Williams et al. (2021) it no longer plays any meaningful role in the power sector.

Recent and projected cost declines for hydrogen production have led to increased interest in its role as a low-carbon fuel. Hydrogen can be used as a feedstock for synthetic fuels, a transportation fuel for fuel cell vehicles, and a source of heat that can replace natural gas combustion in many applications. Due to the superior economics of electrification for most space heating and light-duty transportation applications, however, most net-zero studies see hydrogen as a final demand fuel in heavy-duty transportation and industrial heating. Combustion turbines burning hydrogen can also provide clean firm energy and capacity to the electric grid.

Finally, while synthetic fuels made from green hydrogen and CO_2 captured from the atmosphere have the advantage of being compatible with existing energy infrastructure, they are the most expensive low-carbon fuel option and are usually reserved for liquid fuel use in the hardest to decarbonize sectors like aviation if they are used at all in net-zero scenarios, due to the high prices of conventional fossil liquid fuels and the lack of other cost-effective decarbonization options for these sectors. Figure 7 shows the share of final energy by fuel type in 2050 across six scenarios from the Williams et al. (2021) study. While low-carbon fuel use varies widely in the sensitivity scenarios due to scenario design choices and constraints, it accounts for roughly 25-30% of final energy demand in the core net-zero scenarios.

Figure 7 | Share of final energy demand by fuel type in 2050 across scenarios



Source: Williams, et al. 2021

Table 5 | Priority Focus Areas for Advanced Low Carbon Fuels

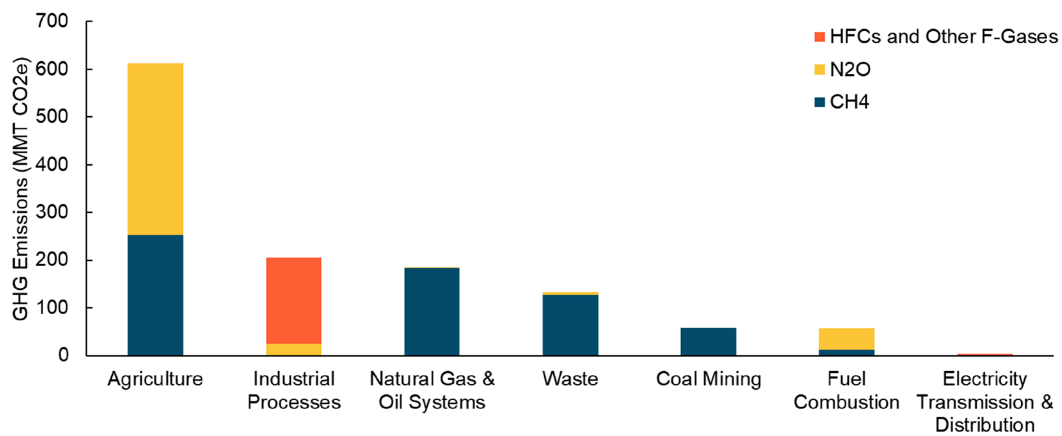
Priority Focus	Technologies / Strategies
Deployment	Biomethane from waste
Market Transformation	Hydrogen electrolysis
Innovation	Biogenic hydrogen production Advanced biofuels production Synthetic fuels production

Unlike the electrification and energy efficiency and clean electricity pillars, the advanced low-carbon fuels pillar has limited options for near-term deployment (Table 5). Instead, the priority focus is on market transformation of hydrogen via electrolysis and R&D for biogenic hydrogen, advanced biofuels, and synthetic fuels.

2.4 Non-CO_2, Non-Combustion Emission Reductions

Emissions of non-CO_2 gases like methane (CH_4), nitrous oxide (N_2O), and fluorinated gases (HFCs, SF_6, others) accounted for almost 20% of gross U.S. emissions in 2018 and mostly come from the agriculture, industrial processes, natural gas and oil systems, and waste sectors (Figure 8). Reducing emissions from these sources is an important component of net-zero pathways in all reviewed studies, but these reductions are typically more difficult to achieve than combustion CO_2 emissions from the energy sector due to a lack of low-cost or feasible control technologies or replacements for many processes or products.

Figure 8 | U.S. non-CO2 emissions in 2018 by source and gas



Source: EPA, 2020

While some CH_4 emissions can be captured and re-purposed as fuel (landfills, wastewater treatment plants, and natural gas pipeline leaks), many sources of CH_4 emissions are dispersed and capture is not practical. In these cases, the only mitigation options are to reduce the emissions-generating activity or offset these emissions elsewhere. Agricultural CH_4 and N_2O generally have relatively low mitigation potential, although studies have shown some reductions in methane emissions from enteric fermentation in livestock are achievable through changes in animal diet.[13] Some oil and gas CH_4 emissions can be prevented with improved industrial practices and technology, but emissions are also expected to decline with declining extraction in net-zero scenarios. For non-CO_2 gases besides methane, mitigation options are generally limited to activity reduction or offsets (e.g., reducing nitrogen fertilizer application to reduce N_2O emissions from soils). HFC replacements with low global warming potential (GWP) alternatives address the largest sector of industrial process emissions at a reasonable cost, with estimates that 73% of HFC emissions can be mitigated by 2050 at a cost of less than $100/metric ton of carbon dioxide equivalent (tCO_2e).[14]

The IPCC's Global Warming of 1.5°C report indicates that while non-CO_2 greenhouse gasses do not need to reach net-zero globally in order to achieve a 1.5 degree temperature target, these gases must be reduced relative to 2010 levels. Global scenarios consistent with a 1.5 degree future include approximately a 50% reduction from methane and black carbon by mid-century, relative to 2010 levels.[15] If lower levels of GHG mitigation among non-CO_2 GHG emissions are achieved, then greater levels of CO_2 removal would be needed to limit global average temperature increases to 1.5°Celsius. The Environmental Protection Agency (EPA) estimates that around 440 million metric tons of carbon dioxide equivalent (MMT CO_2e) of non-CO_2 emissions could be abated by 2050 at a cost of

13 Min, et al. (2020).

14 EPA (2019).

15 IPCC (2019).

less than \$100/tCO_2e, relative to a business-as-usual forecast.[16] This would result in a 25% reduction in non-CO_2 emissions relative to 2018 levels. The EPA found maximum abatement regardless of cost to be 500 MMT CO_2e below business as usual by 2050, a 30% reduction relative to 2018 levels.

Some CO_2 is also emitted as a byproduct of certain industrial processes like iron and steel manufacturing, cement manufacturing, and oil and gas extraction and processing, and there are also CO_2 emissions from fossil fuels used as feedstocks for industrial products or other non-energy uses, although these tend to be much smaller than the emissions that would occur from combustion. Collectively, these non-combustion CO_2 emissions accounted for around 6% of U.S. gross emissions in 2018. Decarbonization strategies for CO_2 released through industrial processes include a shift towards cleaner production methods (e.g., electric arc furnaces and direct reduced iron for iron and steel) or CCS (e.g., cement). For CO_2 emissions from fossil fuels as feedstocks or for other non-energy uses, these fuels can technically be replaced with biogenic or synthetic replacements, but this option was only chosen in highly restrictive scenarios where no fossil fuel use of any kind was allowed in Larson et al. (2020) and Williams et al. (2021)

Priority focus areas for non-CO_2 GHGs that are deployment-ready include technologies that limit methane leakage from oil and gas systems, landfills, wastewater, and dairies, as well as HFC replacements (Table 6). High value R&D areas focus on difficult to reduce emissions in the agricultural sector.

Table 6 | Priority Focus Areas for Advanced Low Carbon Fuels

Priority Focus	Technologies / Strategies
Deployment	Leak detection and repair (LDAR) for oil and gas Low global warming potential gas HFC replacements Methane capture from landfill gas, wastewater treatment and dairy manure methane Methane leakage standards for gas end uses
Market Transformation	Compressed CO2 refrigerants for HFC replacement
Innovation	Reductions in methane emissions from enteric fermentation Reductions in agricultural nitrogen oxide emissions

2.5 CO_2 Capture, Usage, and Sequestration (CCUS) and Enhanced Natural Land Sinks

CCUS technologies are deployed in a wide variety of applications across the studies reviewed in two main categories:

1. CCUS for fossil fuel combustion emissions, essentially netting out greenhouse gases that would have been emitted to the atmosphere. Examples include:
    a. Natural gas combined-cycle power plants with CCS
    b. Industrial CCS for large point source facilities like cement or iron and steel factories
    c. Hydrogen production from natural gas reformation with CCS

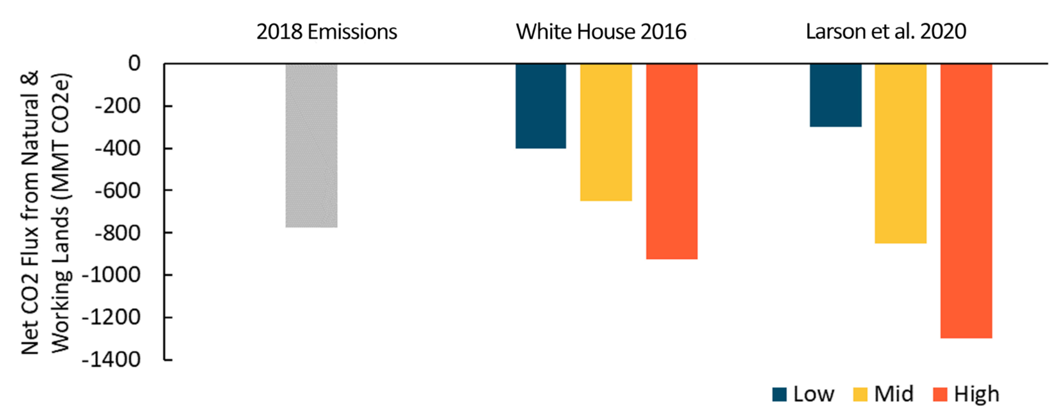
[16] EPA (2019).

2. Negative emissions technologies (NETs), which sequester non-fossil CO_2 and reduce the concentration of CO_2 in the atmosphere. Examples include:
    a. Biopower electricity generation with CCS (BECCS)
    b. Advanced biofuels or biogenic hydrogen production with CCS (BECCS)
    c. Hydrogen production from natural gas reformation with CCS
    d. Direct air capture (DAC) with CCS

CO_2 captured and sequestered through BECCS and DAC is treated as negative for the purposes of emissions accounting, and these technologies play a critical role in offsetting residual emissions from the rest of the economy in most net-zero scenarios despite not yet being commercially-available today. In the core scenarios of the studies reviewed, 85-90% of the reductions needed to hit net-zero come from reductions in gross emissions from fossil fuel combustion and other human activities, while the remaining 10-15% come from offsets, which include both NETs and an expansion of the natural land sink.

Estimates of the size of the terrestrial land sink in 2050 in the reviewed studies range from 300 to 1,300 million metric tons CO_2 (Figure 9). Key drivers of uncertainty include future land-use changes and forest management practices, maturation of forest regrowth, and an increase in climate-related natural disturbances like wildfires. While the terrestrial ecosystems of the U.S. currently act as a net sink of CO_2, the size of this sink is expected to decline by 2050 in a business-as-usual future without significant changes to land use and management strategies.[17] Natural land sinks are critical for net-zero scenarios, because they help offset residual emissions from the rest of the economy and avoid the most expensive abatement measures.

Figure 9 | Net CO2 flux from natural and working lands in 2050 in reviewed studies with historical comparison



Source: EPA, 2020, White House, 2016 and Larson et al., 2020

Changes in agricultural and forestry practices can maintain and enhance natural land sinks, but their exact impacts are uncertain and there are practical constraints to their widespread adoption.[18] Most net-zero studies that include net CO_2 flux from natural and working lands assume that some improvement in natural land sinks is possible, but they also examine the emission reduction implications for the rest of the economy if the land sink is constant of declining.

[17] Tian, Sohngen, Baker, Ohrel, & Fawcett (2018)

[18] World Resources Institute (2018)

Priority focus areas for CCUS and natural carbon sinks include deployment of new agricultural and forestry practices, market transformation to support CCS in electricity generation and industrial processes, and R&D for BECCS and DAC (Table 7).

Table 7 | Priority Focus Areas for CCUS and Natural Carbon Sinks

Priority Focus	Technologies / Strategies
Deployment	Improved agricultural and forestry practices for carbon sequestration and management
Market Transformation	CCCS for electricity generation and industrial processes
Innovation	BECCS DAC

CHAPTER THREE
DECARBONIZATION POLICY

3.1 Overview of Energy and Climate Policy in the United States

Due to the nature of U.S. federalism, jurisdiction over energy and climate policy is shared across federal, state, and local levels of government (Table 8). The federal government has broad

Table 8 | Jurisdiction for Common Decarbonization Policies by Sector

Sector	Policies/Regulations	Federal	State	Local
Buildings	Building codes		Can be Primary (state-specific)	Can be Primary (state-specific)
	Zoning, permitting			Primary
	Appliance standards	Primary	Limited	
	Efficiency & Electrification Incentives	Tax credits	State and utility incentive programs	Municipal utility incentive programs
Transportation	Vehicle standards	Primary	Limited	
	Domestic aviation & shipping	Primary		
	Urban planning & public transit		Limited	Primary
	Incentives	Tax credits	State and utility incentive programs	Municipal utility incentive programs
Industrial	Permitting & siting			Primary
	Environmental regulation	Primary	Secondary	
	Efficiency Incentives	Tax credits	State and utility incentive programs	Municipal utility incentive programs
Electricity	Procurement & regulation	Limited	Primary	Limited
	Transmission	Limited (expanded role is possible)	Secondary	Primary
Fuels	Emissions regulation	Primary	Limited	
Non-CO_2, Non-Combustion	Methane regulations/ HFC regulations	Primary	Secondary	Limited
Carbon Capture & Sequestration and Carbon Removal	Tax credits (e.g., 45Q)	Primary		

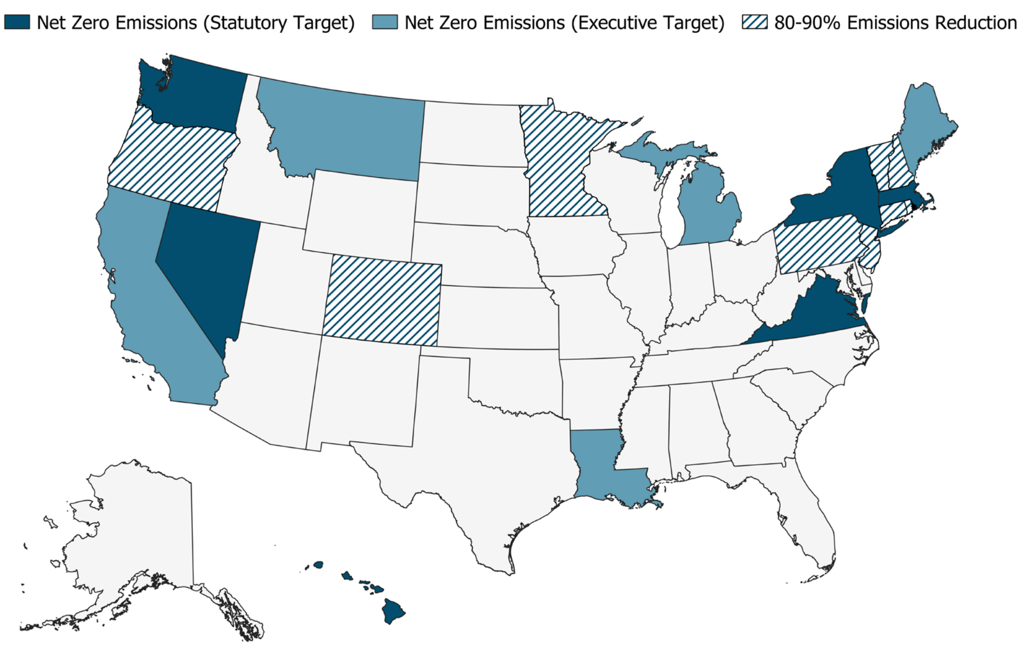
Note: Primary jurisdiction here means that the branch of government has authority over most regulatory and policy decisions that would impact energy consumption for a certain sector of the economy. Secondary jurisdiction means that the branch of government has authority that can be overruled by another branch, while limited jurisdiction means authority over a narrower set of regulations.

authority to regulate activities that have an impact on interstate commerce and explicit authority where jurisdiction has been legislatively delegated to the federal government (e.g., creating and enforcing vehicle fuel economy standards). State governments retain the authority to regulate activities that do not interference with federal jurisdiction over interstate commerce and/or where jurisdiction has not been delegated to the federal government. Finally, local governments also retain authority over certain aspects of energy and climate policy, mainly through jurisdiction over permitting and siting of infrastructure. As a result, achieving the milestones laid out in the previous section will require coordinated, ambitious action at every level of government.

3.2 State Policies

A growing number of states, municipalities, electric utilities, academic institutions, and corporations have adopted, and continue to adopt net-zero emissions targets. In the span of just over two years, beginning in late 2018, 11 state governments have established mid-century net-zero goals, either through legislative statute or executive order (Figure 10). Several other states are currently studying commitments.

Figure 10 | Map of U.S. states with announced net-zero GHG emissions targets



Source: C2ES State Climate Policy Maps

In addition to economy-wide net-zero targets, states and utilities have defined a growing number of electric sector targets consistent with deep decarbonization. As of October 2020, states and utilities with legislation or commitments for achieving renewable portfolio standard (RPS) and clean energy standard (CES) targets of greater than 80% by 2050 (with most at 100%) accounted for 53% of U.S. electricity sales and 57% of existing CO_2 emissions from the electric sector.[19]

A few states have established comprehensive planning and policymaking processes to align sector-specific policies and emissions regulations with long-term goals. The box below briefly describes the target setting and planning processes in California, sector-specific policies that aim to align with long-term goals, and current gaps. It also emphasizes the importance of state-specific planning and policymaking, since state-level challenges will be different due to differences in economic activity, geography, and climate.

19 Clean Air Task Force (2020)

Case Study: Overview of California policy goals and gaps to 2030 and 2045

A longtime leader in state-level energy and climate policy, California's official target of carbon neutrality by 2045 was set in 2018 through an executive order by Governor Brown. This mid-century executive target is in addition to an earlier legislative emissions reduction target of 40% below 1990 levels by 2030, which was set in 2015 through SB 32. In both cases, the target setting process was informed by deep decarbonization pathways studies showing deep emissions reductions are achievable, and a slate of polices were enacted to help guide the state towards its goals. From an economy-wide policy perspective, the most notable of these is California's cap and trade program, which runs through 2030. California also has set several sector-specific decarbonization policies as well. These include:

Electrification and Efficiency

- Manufacturer zero emissions vehicles (ZEV) sales requirements for light-duty vehicles (LDVs) and medium- and heavy-duty vehicles (MHDVs) through CARB's ZEV and Advanced Clean Trucks programs, respectively, which will be updated to align with Governor Newsom's recent executive order targeting 100% ZEV sales by 2035 for LDVs and 2045 for MHDVs
- SB 1477, passed in 2018, directed the California Public Utilities Commission (CPUC) to develop two pilot programs for building decarbonization, the BUILD and TECH programs
- AB 3232, also passed in 2018, requires the California Energy Commission (CEC) to assess the potential for the state to reduce building sector emissions 40% by 2030
- SB 350, passed in 2015, mandates a doubling of statewide energy efficiency savings for electricity and natural gas end uses by 2030, subject to cost-effectiveness

Clean Electricity

- SB 100, passed in 2018, mandates a 60% renewable portfolio standard by 2030 and 100% zero-carbon electricity by 2045

Zero Carbon Fuels

- CARB's Low Carbon Fuel Standard regulation targets a 20% reduction in the carbon intensity of transportation fuels by 2030

Non-CO2 Reductions

- SB 1383, passed in 2016, directed CARB to develop a strategy to achieve a 40% reduction in methane and HFC emissions and 50% reduction in anthropogenic black carbon emissions by 2030 relative to 2013 levels

While these policies have led to significant emissions reductions in California, economy-wide modeling from E3 and Energy Innovation indicates that additional action is likely necessary for the state to achieve its 2030 and 2045 targets.[1] Although the existing cap and trade system is one potential tool that could be used to close the emissions gap, the program only runs through 2030, and it is unclear if allowance prices would be allowed to increase to the level necessary to reach the state's emissions targets.

The challenges facing individual states with net-zero emissions targets vary due to geography, climate, and predominant economic activity. For example, states in the Upper Midwest and New England face particular challenges decarbonizing building heating due to their colder climates, while states with large oil and gas extraction like Colorado and New Mexico must manage economic impacts to industries that provide crucial jobs and tax revenues.

1 See Busch & Orvis (2020) and Mahone et al. (2020)

3.3 Regional Initiatives

In addition to state initiatives, two kinds of regional initiatives merit discussion: regional CO_2 cap and trade programs, and memoranda of understanding (MOU) between states for zero-emission vehicle targets. These regional initiatives provide mechanisms to facilitate interstate cooperation, either to fill the gap left by an absence of federal policy or to enable regionally coordinated regulation and markets.

Cap and Trade Programs

There are two regional cap and trade programs operating in North America: the Regional Greenhouse Gas Initiative (RGGI), which prices carbon emissions from the power sector in eleven Northeastern U.S. states, and the Western Climate Initiative (WCI), which prices emissions across approximately 80% of economy-wide greenhouse gas emissions in California and the Canadian Provinces of Quebec and Nova Scotia. Both of these programs operate with carbon price floors, and soft caps on the upper bound of carbon prices, and in both programs carbon prices have historically traded near the price floor. Given the relatively low carbon prices experienced in the market to date, the primary benefit of these cap and trade programs has been to raise revenue for clean energy programs and to send a stable carbon price signal to the power sector (in the case of RGGI) or the broader energy sector (in the case of WCI).

RGGI is an electricity sector-only cap and trade program, and the first such market-based program developed in the United States. It covers eleven states in the Northeastern U.S.: Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, Vermont, and Virginia. Market prices currently trade between \$7-\$8 per ton CO_2.[20] There is a price floor in 2021 of \$6/ton and a price ceiling of \$13/ton in 2021, with both increasing by 7% per year. These price containment mechanisms provide some market price certainty around future carbon prices, and also mean that the carbon price, in practice, operates similarly to a carbon tax.

The WCI is a regional organization designed to support the implementation of economy-wide cap and trade programs in WCI member jurisdictions, including in the State of California and the Provinces of Quebec and Nova Scotia. While the carbon markets in California and Quebec are linked through carbon trading, the market in Nova Scotia is not linked to the other two regions. California and Quebec carbon market prices are also governed by a price floor, and a soft cap on the upper end of carbon prices. Like in the RGGI system, WCI prices have remained close to the price floor, and are currently trading around \$18/ton.[21]

Zero Emission Vehicles Memoranda of Understanding (MOU)

In 2013, the governors of nine states collectively representing 27% of the US light-duty vehicle (LDV) market signed an MOU to create and implement state zero emissions vehicles (ZEV) programs and to collaborate on a multi-state ZEV Program Implementation Task Force. The signatory states agreed to a collective target of at least 3.3 million zero emission LDVs on the road by 2025. Furthermore, in 2020, 15 states and the District of Columbia signed an MOU committing to ZEV targets for medium- and heavy-duty vehicles (MHDV). The targets identified in the MOU are a 30% market share for zero emission MHDVs by 2030 and a long-term goal of all MHDV sales being zero emissions vehicles by 2050.

In addition to the MOUs, a group of ten states have formally adopted California's ZEV regulations. The current ZEV program, administered by the California Air Resources Board (CARB), sets a ZEV sales requirement for manufacturers using a credit-based system that increases in stringency through 2025. Recently, California's Governor directed CARB to develop new regulations requiring

[20] The Regional Greenhouse Gas Initiative (2020)

[21] California Air Resources Board (2021)

ZEV sales to increase to 100% of new vehicles sold in the state by 2035 for LDVs and 2045 for MHDVs. While it is unclear if the other states following CARB's ZEV program will continue to do so with updated requirements, one state, Massachusetts, has already issued its own mandate requiring 100% ZEV sales for LDVs by 2035.

3.4 Proposed Federal Policies

In 2020, the U.S. federal government put forward two notable comprehensive energy and climate policy proposals: The Congressional Action Plan from the House Select Committee on the Climate Crisis and the Biden Campaign Climate Plan. While the range of issues addressed by both plans extends beyond the scope of most deep decarbonization studies into important areas like environmental justice, racial and economic equity, and climate resilience, there are specific proposals from these plans that can be compared to key measures from deep decarbonization studies.

- **Economy-wide Emissions:** Both plans set an economy-wide target of net-zero greenhouse gas emissions for the United States by no later than 2050.
- **Electrification and Efficiency:** Both plans call for standards to increase the share of electric vehicles on the road. The Congressional Action Plan sets a target of 100% ZEV sales for LDVs by 2035 and MHDVs by 2040, while the Biden plan includes new fuel economy standards "aimed at ensuring 100% of new sales for light- and medium-duty vehicles will be electrified and annual improvements for heavy duty vehicles," although a target year is not specified. The Biden plan also includes the installation of 500,000 EV charging stations nationwide by 2030. Both plans discuss the need to reduce emissions in the building sector through a combination of updated appliance standards, weatherization, and electrification but recognize that the federal government will need to work with state and local governments who have greater authority over building codes and standards in their respective jurisdictions.
- **Clean Electricity:** Both plans set an emissions target specifically for the electric power sector. In the Congressional Action Plan, this means achieving "net-zero emissions the electricity sector by 2040," while the Biden Plan targets achieving "a carbon pollution-free power sector by 2035."
- **Advanced Low-Carbon Fuels:** Both plans highlight the need for advanced low-carbon fuels like advanced biofuels and hydrogen to achieve net-zero emissions. The Congressional Action Plan proposes that Congress establish a Low Carbon Fuel Standard to reduce emissions from remaining gasoline-powered vehicles and transportation sectors where electrification may not be a viable option.
- **Non-CO_2 Reductions:** Ratification of the Kigali Amendment, which targets HFCs, is a key component of both plans. President Biden has already initiated the process of ratifying the Kigali Amendment since taking office. The Congressional Action Plan also proposes a national methane pollution reduction goal for the oil and gas sector of 65-70% by 2025 and 90% by 2030 relative to 2012 levels.
- **CCUS and Enhanced Land Sinks:** Both plans recognize the critical importance of natural carbon sinks and call for a national goal of protecting at least 30% of all U.S. lands, waters, and oceans by 2030. Neither plan includes a specific target for CCUS deployment.

Beyond standards and targets that are easily comparable to measures modeled in deep decarbonization studies, both the Biden and Congressional Action Plans include calls for greater investment in both technology deployment and RD&D by the federal government. The comprehensive and aggressive actions proposed in both plans would better position the United States to achieve net-zero emissions by mid-century if enacted.

CHAPTER FOUR
CONCLUSIONS

The deep decarbonization studies reviewed in this report suggest that any pathway to carbon-neutrality in the United States will rest on transformative and near-term progress in technology deployment, market transformation and investment across five key pillars of decarbonization:

1. Electrification and efficiency
2. Clean electricity
3. Low-carbon fuels
4. Non-CO_2, non-combustion reductions
5. CO_2 capture, usage, and sequestration (CCUS) and enhanced natural land sinks

Electrification is expected to be the dominant decarbonization strategy for space and water heating in buildings and on-road vehicles. Because many electric technologies for these end-uses are already commercially available today, ramping up sales of these technologies over the next decade is critical to achieving high penetration by mid-century. While a handful of states have joined California in targeting sales of electric vehicles, ramping up sales for both electric vehicles and electric heat pumps should be a major near-term priority for the entire United States.

At the same time, as electrification leads to increased demand for electricity, rapid decarbonization of electricity generation is needed to achieve deep emissions reductions. This is largely driven by the deployment of wind and solar resources that are expected to make up a majority of electricity supply by mid-century, with some firm zero-carbon resources needed to maintain grid reliability and keep costs affordable. The need for firm resources on a zero-carbon grid is likely to be met with resources that are not yet commercial today, such as natural gas with CCS, advanced nuclear, or hydrogen use in combustion turbines. Additional innovation and R&D is needed to identify and commercialize the clean firm resources of future electricity systems.

For applications where electrification is not cost-effective or has not reached high penetration, low-carbon fuels will likely be needed to replace fossil fuels. This is particularly true for hard-to-decarbonize sectors like industry and off-road transportation. Low-carbon fuel options include direct hydrogen combustion, advanced biofuels, and synthetic fuels made from hydrogen and climate-neutral carbon sources. Low-carbon fuels production will likely need to be ramped up significantly by mid-century in any carbon-neutral future, although the pace and depth of electrification will largely drive the amount of remaining liquid and gaseous fuels. Additional policy support will be critical in the coming decades to bring down the cost of low-carbon fuel production and create markets for low-carbon fuels.

Non-CO_2 emissions represent a much smaller share of total GHG emissions in the United States than CO_2 emissions from fossil fuel combustion, but their mitigation is still crucial to meeting the Paris Agreement's temperature goals. Shifting to low-GWP HFC replacements in line with the Kigali Amendment and reducing methane leaks from the natural gas and oil sectors are critical near-term priorities.

CO_2 sequestration plays an important role in reaching carbon-neutrality in all of the studies reviewed for this report. In most cases, negative emissions technologies like DAC and BECCS help offset a small amount of remaining emissions from hard-to-decarbonize sources by mid-century, but these technologies are by no means a replacement for aggressive mitigation measures throughout the entire economy. Increased CO_2 sequestration from natural land sinks is also crucial to cost-effectively achieving carbon-neutrality, as any reduction in the size of the current land sink will mean additional mitigation measures needed elsewhere.

The United States is currently tackling climate change in a politically and geographically heterogeneous way, with differing policies and levels of ambition across state and local levels. The United States has a long history of learning from different state and local actions, lauding states as a laboratory for innovation where ideas are tested, and lessons can be learned to inform federal action.

While considerable progress has been made at the state level on clean electricity deployment and to a smaller extent in passenger vehicle electrification, the scale of the energy system changes required to achieve carbon-neutrality far exceed existing state and federal policies. Recent policy proposals from the Biden administration and Congress include many of the strategies identified in the deep decarbonization studies reviewed in this paper.

In the near term, initiating the transition from fossil fuel to predominantly non-fossil fuel energy systems will require strategies that address challenges in four areas, summarized in Figure 11.

1) Aligning economics for consumers and companies to adopt clean energy technologies, by bringing down upfront costs and ensuring affordability and equitable cost burdens.
2) Changes in institutions and governance that improve public sector processes and capabilities, focused on reducing policy, regulatory, and institutional barriers to clean energy deployment, and improving government capabilities in monitoring and tracking GHG emission reductions.
3) Public engagement and education, aimed at shifting purchasing patterns, fostering inclusion, and building trust with a wide range of audiences and communities.
4) Economic assistance and workforce training and support, supporting economic and workforce transitions to a non-fossil fuel energy system.

Figure 11 | Public Policies to Support Carbon Neutrality in the United States

1. **Aligning economics** for customers and companies to adopt clean energy
   - Direct **incentives** and **tax credits** to reduce upfront costs
   - **Research and development** to bring capital costs down and create optionality
   - Policies to ensure **affordability and equity**

2. **Changes in institutions and governance** that enable transition
   - Aligning **policy and institutions** to remove barriers to technology deployment
   - Institutional support for **monitoring and tracking** progress

3. **Public engagement and education** to encourage adoption and build trust
   - **Shifts in purchasing patterns**, especially in vehicles and building appliances
   - **Tools and resources** for consumer and business action
   - **Trust and partnerships** with a wide range of audiences and communities

4. **Economic transition and workforce training and support**
   - **Development assistance** for fossil fuel-reliant states
   - **Workforce development** in emerging industries (e.g., building electrification)
   - **Transition plans and support** for transitions out of fossil fuel jobs

The challenge will be to turn GHG emission reduction goals into legislatively-mandated action that spurs near-term deployment of the clean energy technologies commercially available now and identifies and invests in the technologies needed in the coming decades to achieve carbon-neutrality.

CHAPTER SIX
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