WORLD RESOURCES INSTITUTE

WORKING PAPER

BUILDING BLOCKS FOR A LOW-CARBON ECONOMY: CATALYTIC POLICY AND INFRASTRUCTURE FOR DECARBONIZING THE UNITED STATES BY 2050

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EXECUTIVE SUMMARY

Highlights

- This working paper identifies key climate policies and investments and estimates their emissions-reduction potential and associated costs, which can enable the United States to reduce economy-wide greenhouse gas (GHG) emissions by 50–52 percent compared to 2005 levels by 2030 and reach net-zero GHG emissions by midcentury, the goals set by the Biden administration.
- Tax credits for existing and new low-carbon technologies, in combination with federal investment in climate-smart infrastructure, significantly improve the adoption of new technologies but are not enough by themselves to enable the country to reach its 2050 goal.
- Performance standards, such as a clean electricity standard, zero-emissions vehicle standard, low-carbon fuel standard, and appliance energy efficiency standards, are necessary to attain economy-wide net-zero emissions by 2050, especially in the absence of economy-wide carbon pricing.
- Remaining emissions in hard-to-mitigate sectors will need to be offset by enhanced natural and working land sinks and negative emissions technologies.
- Despite the falling costs of electric vehicles, the life expectancies of internal combustion engine vehicles greatly limit the pace of decarbonization in the transportation sector.

CONTENTS

Working Papers contain preliminary research, analysis, findings, and recommendations. They are circulated to stimulate timely discussion and critical feedback, and to influence ongoing debate on emerging issues. Working Papers may eventually be published in another form and their content may be revised.

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- Decarbonizing the U.S. economy is economically feasible. With reference oil prices, net costs are $40 billion (0.2 percent of U.S. gross domestic product [GDP]) higher in 2030 than in the Reference Scenario (RS). By 2050, net costs are $113 billion less than in the reference case, meaning there is a net savings of 0.3 percent of U.S. GDP. Net costs vary with fuel price assumptions but are affordable in all cases.

Context

Decarbonizing the U.S. economy to achieve a 50–52 percent reduction in GHG emissions by 2030 and net-zero emissions by midcentury will require the accelerated deployment of existing low-carbon technologies as well as new technologies that are not yet commercially available. Recent studies have identified key technologies for achieving a net-zero emissions economy—including clean electricity; energy efficiency and electrification; low-carbon fuels; carbon capture, usage, and storage (CCUS); and enhanced natural land sinks—and have performed scenario modeling of these various technology pathways to understand what it will take to meet U.S. decarbonization targets in a cost-effective manner.

Even as low-carbon technologies continue to become more cost-competitive, their pace of deployment needs to increase rapidly. Federal policies and investments are needed to spur clean manufacturing, drive technology deployment and market transformation, change consumer behavior, and encourage investment in infrastructure and key technologies needed for a net-zero economy.

About This Working Paper

This working paper identifies near-term policies and federal investments that can catalyze emissions reductions over the coming decade (from now to 2030) and set up the economy for deeper emissions reductions in later decades. Our analysis focuses on the role played by tax incentives, infrastructure investments, targeted spending, and performance standards, which form the building blocks for a successful decarbonization strategy. We explore how different combinations of policies at different ambition levels can spur technology deployment at the necessary pace. The modeling was done for WRI by Energy + Environmental Economics, Inc. (E3). Although carbon pricing would be an additional cost-effective tool, it is not modeled here, given that it has been extensively analyzed in other studies.

Specifically, the paper attempts to answer the following questions:

- What is the current emissions path as dictated by existing policies, technologies, and economic trends?
- What technologies and policies are needed in each sector to achieve at least a 50 percent reduction in emissions by 2030 and net-zero emissions by 2050?
- To what extent can specific combinations of policies contribute to emissions reductions across sectors both in the near term (by 2030) and over the longer term (by 2050), including tax incentives, infrastructure investments, targeted spending, and performance standards?
- How do policies work together to accelerate emissions reductions by 2050, particularly in terms of sequencing and relative impact?

To answer these questions, our analysis compares the relative progress toward a net-zero goal offered by different policy packages that overlap and build on one another. The analysis includes one reference scenario and three policy and investment scenarios (Figure ES-1):

- The **Reference Scenario (RS)** includes current federal policies in effect and extensions expected through federal legislation, as well as legally binding state climate and clean energy policies.
- **Scenario 1 (S1)** extends current tax incentives, including for renewable energy and electric passenger vehicles and increases spending programs that target infrastructure, such as for electric vehicle charging and transmission and distribution, to help drive early adoption of clean energy and energy-efficient technology required to kick-start broader sector transformation.
- **Scenario 2 (S2)** includes the tax credit extensions from S1 as well as new tax credits for other low-carbon technologies, in addition to federal spending and investment, to drive broader adoption of key technologies.
- **Scenario 3 (S3)** layers on sector-specific performance standards and economy-wide net-zero emissions cap to enable the United States to achieve net-zero emissions by 2050 across the economy.

Figure ES-1 | **Description of Mitigation Scenarios and Building Blocks Underlying Each Scenario**

	Reference Scenario	SCENARIO 1: Extended Tax Credits and Infrastructure Spending	SCENARIO 2: Advanced Tax Credits and Infrastructure Spending	SCENARIO 3: Comprehensive Policies to Reach Net Zero
GOAL	Reflects existing federal policies, as well as binding state-level policies to estimate emissions reduction in a business-as-usual scenario.	Reflects extension of existing tax credits and increase in federal spending on low-carbon infrastructure, with the goal of driving early adoption required to kick-start broader sector transformation.	Reflects extension of existing tax credits and federal spending on infrastructure from S1 and layers in new tax credits for technologies for which tax credits do not currently apply. Goal is to drive broader adoption of technologies.	Layers on sector-specific performance standards and economy-wide net zero emissions cap to demonstrate policy-driven, sector-level transformation required to achieve "net zero."
POLICY LEVERS	**Existing federal policies,** including tax credits for renewable power and ZEVs, CAFE standards, and NSPS methane regulations.	**Low-carbon infrastructure spending,** including for building sector energy efficiency, weatherization, and electrification programs, deployment of electric vehicle charging station infrastructure and grid modernization and transmission. (Scenarios 1–3)		
	Existing state-level policies, including state-level RPS and ZEV targets.	**Extended tax credits**, including extending existing incentives for LDV ZEVs and renewable power. (Scenarios 1–3)		
			Advanced tax credits, including new tax credits for LDV and MHDV ZEVs, electric heat pumps, renewables, and firm zero-carbon resources. (Scenarios 2–3)	
				Sector-specific performance standards, including a CES, and **economy-wide net-zero emissions cap**.

Notes: CAFE = Corporate Average Fuel Economy; CES = clean electricity standard; LDV = light-duty vehicle; MHDV = medium- and heavy-duty vehicle; NSPS = New Source Performance Standards; RPS = Renewable Portfolio Standard; ZEV = zero-emissions vehicle. Please see Table 1 and Technical Appendices B–C for more details about individual policies included under each scenario.

Source: WRI authors and E3.

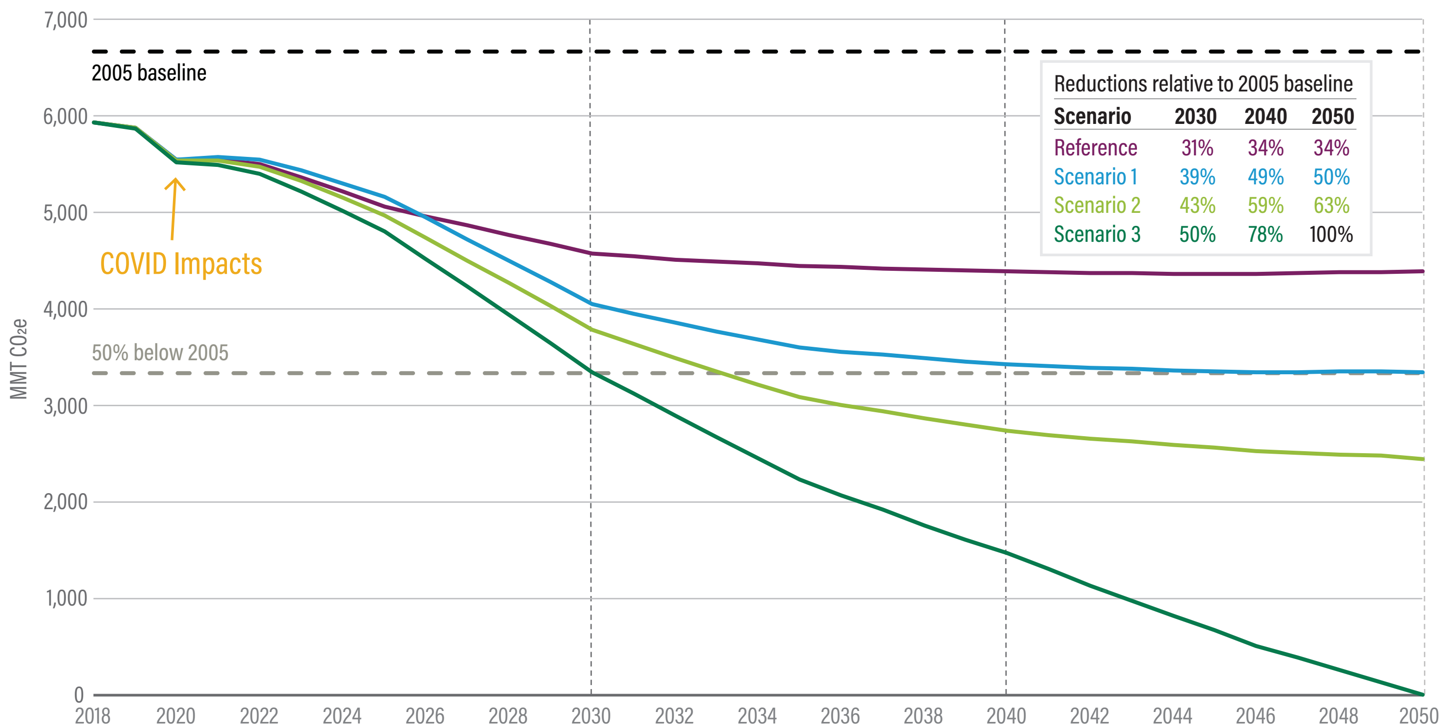
While this paper offers an evaluation of policy and investment packages and net incremental costs associated with these scenarios to reach 2030 and 2050 climate goals, a forthcoming WRI working paper will more fully explore the economic benefits accruing from the three policy and investment scenarios, including a discussion of equity considerations in the design of policies.

Findings and Recommendations

Several key insights emerge from the modeling analysis:

- Extending and expanding tax credits, and increasing federal spending and investment in infrastructure, along with falling technology costs, achieve significant GHG reductions through 2030 (see S1 and S2 results in Figure ES-2) but on their own are insufficient to achieve 2050 climate goals.
- Sector-specific performance standards, especially in the absence of an economy-wide carbon pricing mechanism, are needed to achieve deep decarbonization by 2050 and to position the United States to reach a 50–52 percent emissions reduction by 2030.
- Remaining emissions in hard-to-mitigate sectors such as industry must be offset by enhanced natural and working land sinks and negative emissions technologies.
- Despite the falling costs of electric vehicles, the life expectancies of internal combustion engine cars and trucks greatly limit the pace of decarbonization in the transportation sector.
- Although getting to a net-zero economy will require significant investments, avoided spending on fossil

Figure ES-2 | **Net Annual Greenhouse Gas Emissions across the U.S. Economy by Scenario through 2050**



Source: WRI authors and E3.

fuels will bring substantial savings, resulting in costs that are small relative to the size of the economy. Assuming reference oil prices, net costs are $40 billion (0.2 percent of U.S. GDP) higher in 2030 than in the RS. By 2050, net costs are $113 billion less than in the reference case, meaning there is a net savings of 0.3 percent of U.S. GDP. For the high oil price scenario, the savings are even higher, while for the low oil price scenario net costs are incurred in the 2030 time frame.

Policy intervention over the next 10 years is crucial to reduce emissions in this decade and set up the economy to eliminate remaining net emissions by 2050. Furthermore, reaching economy-wide net-zero emissions by 2050 will require a combination of different policy tools, including advanced tax credits, increased spending on climate-smart infrastructure and programs, and sector-based performance standards that can together reduce GHG emissions. Table ES-1 highlights key policy priorities for each sector.

Table ES-1 | **Decarbonization Policy Priorities by Sector**

Power ▪ Extend current tax credits for zero-carbon electricity generation and include a direct pay option to maximize their impact. ▪ Expand tax credits to include stand-alone energy storage technologies. ▪ Expand tax credits to include electricity transmission investments. ▪ Implement a clean energy standard mandating or incentivizing 80% clean electricity by 2030 and 100% by 2035. ▪ Make significant investments in modernizing the electricity grid.	**Transportation** ▪ Extend and expand tax credits for zero-emissions vehicles (ZEVs) in all vehicle segments to make them more cost-competitive. ▪ Implement scrappage incentives or early internal combustion engine vehicle retirement programs to help consumers cover the cost of switching to ZEVs. ▪ Implement 100% zero tailpipe emissions standards by 2035 to ensure that ZEVs can attain 100% sales share by 2035. ▪ Make significant investments in charging infrastructure to support growth in electric vehicle adoption. ▪ Implement tighter Corporate Average Fuel Economy (CAFE) standards and provide incentives for reducing vehicle miles traveled to support emissions reductions before ZEVs make up most of the vehicle fleet.
Buildings ▪ Expand residential and commercial tax credits for building electrification. ▪ Mandate or incentivize net-zero energy use by all new buildings and homes by 2030. ▪ Invest in energy efficiency upgrades, especially providing support to low- and middle-income households. ▪ Provide technical and financial support to states and cities for engaging in consumer education and outreach, contractor training, and building code development and enforcement, among others.	**Industry** ▪ Reform and expand the 45Q tax credit for carbon capture and storage and direct air capture. Raise incentive levels for both technologies and extend the eligibility period. ▪ Incentivize the production of clean hydrogen by implementing a hydrogen production tax credit. ▪ Place an emissions cap on industrial sectors or implement a low-carbon product standard on emissions-intensive products. ▪ Increase funding for research and development programs for low-carbon manufacturing technologies and products. ▪ Increase funding for demonstration and pilot projects focused on industrial low-carbon hydrogen production and use.
Agriculture and Natural and Working Lands ▪ Expand federal and state cost-share, grant, and payment programs to incentivize climate-friendly agriculture and forestry practices on private land, including practices that sequester carbon and decrease emissions. ▪ Increase funding for reforestation and forest restocking programs on public and private land. ▪ Increase funding for research on climate-friendly agricultural technologies such as biochar and carbon-sequestering crop phenotypes. ▪ Enhance federal and state protection of carbon-storing lands and ecosystems, including through increased funding for wildfire risk mitigation.	**Carbon Removal** ▪ Reform and expand the 45Q tax credit for carbon capture and storage and direct air capture. Raise incentive levels for both technologies and extend the eligibility period. ▪ Implement an economy-wide emissions cap or price on carbon and/or a low-carbon fuel standard. ▪ Increase funding and programs for carbon removal demonstration and pilot projects focusing on capture technologies, transport, and storage. ▪ Provide funding for hydrogen projects demonstrating production from sustainable biomass utilizing carbon capture and storage.

1. INTRODUCTION

The latest report by the Intergovernmental Panel on Climate Change makes clear that the world must reduce net greenhouse gas (GHG) emissions to zero by 2050 to limit global temperature rise to 1.5° Celsius and avoid the worst impacts of climate change (Masson-Demotte et al. 2021). As one of the world's largest emitters, the United States needs to play a leading role in decarbonizing the global economy.

Building on efforts by U.S. states and local governments, the Biden administration has set new emissions targets for the United States: to reduce economy-wide GHG emissions by 50–52 percent by 2030 relative to 2005 levels and to achieve economy-wide net-zero GHG emissions by midcentury. Achieving these goals will require action across all sectors of the economy, the deployment of existing and emerging or new low-carbon technologies at scale, and action by governments at all levels, the private sector, and civil society (Kennedy et al. 2021).

COVID-19 is estimated to have led to a decline in U.S. GHG emissions in 2020 of more than 10 percent, largely driven by reduced travel demand (Larsen et al. 2021). This decline, however, is expected to be temporary, with emissions increasing once again as the economy recovers (Tollefson 2021).

Even though U.S. GHG emissions were estimated to be 21 percent below 2005 levels in 2020 (Larsen et al. 2021), the country is not on a path to achieve either its 2030 or 2050 decarbonization target unless more ambitious strategies and policies are adopted.

A number of studies have shown that there are cost-effective technology pathways across all sectors to achieve the country's decarbonization targets (Mahajan et al. 2020; Larson et al. 2020; Williams et al. 2021). These studies point to seven key pillars of decarbonization and evaluate different pathways by which the United States can achieve emissions reduction in keeping with 2050 climate goals (Loken et al. 2021):

- **Rapid deployment of clean electricity and energy storage**, combined with power grid investments, including expanding high-voltage transmission lines
- **Electrifying and optimizing efficiency** of buildings, manufacturing, and vehicles
- **Low-carbon fuels**, including clean hydrogen, sustainable biofuels, and other synthetic fuels
- **Carbon capture, usage, and storage (CCS/CCUS)** in combined cycle gas power plants and energy-intensive manufacturing processes, such as the production of cement, steel, and chemicals
- **Negative emissions technologies**, such as bioenergy with carbon capture and storage (BECCS) and direct air capture (DAC), which pull CO_2 from the atmosphere
- **Enhanced natural land carbon sinks** accompanied by climate-friendly agricultural and forestry practices
- **Non-CO_2 emissions reductions**, including methane, nitrous oxide, and hydrofluorocarbons (HFCs), which primarily come from agriculture, industry, natural gas and oil systems, use in refrigeration and air conditioning equipment, and waste sectors

However, the natural deployment of low-carbon technologies that are becoming more cost-competitive with their fossil counterparts alone will not enable the United States to achieve its decarbonization goals. We need a step change in the pace of adoption of low-carbon technologies. Federal, state, and local policies will be needed to spur technology deployment, market transformations, and investments in this decade in order to position the United States to achieve net-zero GHG emissions by 2050.

Reducing GHG emissions 50–52 percent below 2005 levels by 2030 requires immediate mobilization of low-carbon technologies that are commercially available or close to commercial deployment. While some low-carbon technologies are already cost-competitive, the upfront cost of other technologies, such as heat pumps and electric vehicles (EVs) in the light-duty vehicle (LDV) and medium- and heavy-duty vehicle (MHDV) segments, needs to decline further so that more of them become affordable for consumers and businesses, underscoring the critical role of enabling policies such as direct incentives and tax credits. Achieving net-zero GHG emissions by 2050 requires additional technological solutions, many of which are not commercially available today, to address decarbonization in harder-to-abate sectors, including heavy-duty transport such as trucking, aviation, and shipping and energy-intensive industry such as cement, steel, and chemicals. This will require federal spending on research, development, demonstration, and deployment of new technologies.

Furthermore, despite low-carbon technologies continuing to become cost-competitive with their fossil fuel counterparts, the pace and scale of deployment required for deep decarbonization needs to be much greater than what would result from normal investment cycles and infrastructure replacement. Policies that impose performance standards to eliminate GHG emissions can play an important role in increasing the penetration of these technologies and more rapidly shifting the market away from incumbent technologies.

This working paper identifies key climate policies and investments and estimates their emissions-reduction potential and associated costs. In contrast to other decarbonization studies that evaluate different technology pathways to reach net-zero emissions by midcentury, our analysis takes a "building blocks" approach to explore what combinations of policies are needed this decade to put the United States on the path to a net-zero economy by 2050. To do that, modeling by Energy + Environmental Economics, Inc. (E3) estimated reductions in GHG emissions over the next 10 and 30 years under different policy and federal spending scenarios.

2. STUDY DESIGN AND METHODOLOGY

This study developed three mitigation scenarios to assess the potential of different policies and investments to contribute to GHG emissions reductions by 2030 and 2050. These scenarios were modeled, and the results were compared to a reference scenario that estimates the emissions trajectory of the United States under existing policies and economic and technology trends.

The Reference Scenario (RS) was structured to generally align with the reference case in the Annual Energy Outlook (AEO) 2020 published by the U.S. Energy Information Administration (EIA)[1] and to account for existing federal policies, such as the production tax credit and investment tax credit in the power sector and tax credits for plug-in electric vehicles in the transportation sector. The RS includes current sunset provisions for these policies. This scenario also incorporated binding state-level actions such as Renewable Portfolio Standard (RPS) targets and announced zero-emissions vehicle (ZEV) targets as of September 2020. Finally, the RS accounts for federal policies such as Corporate Average Fuel Economy (CAFE) standards for light-duty vehicles and the Obama administration's amended New Source Performance Standards methane regulations.

Scenarios 1–3 built on the RS by incorporating additional measures directed toward scaling up deployment of existing cost-effective technologies over the next decade and encouraging innovation of emerging clean energy technologies needed in later decades. Further details about the selection and combination of policy measures across the three policy scenarios and the RS are discussed in Section 3; underlying assumptions and data sources used to develop these scenarios are presented in the Technical Appendices.

The evolution of U.S. energy demand and supply and emissions reductions under these scenarios from 2018 through 2050 were assessed using E3's PATHWAYS and RESOLVE models (Figure 1). These models utilize inputs such as projections of fuel prices, cost and performance-related characteristics of energy infrastructure, and equipment sales to forecast annual energy demand, emissions by fuel type, stocks and sales of energy-consuming devices, and electricity supply infrastructure for each simulated year.

Further details on PATHWAYS and RESOLVE, modeling assumptions, inputs, and outputs are provided in the Technical Appendices.

3. OVERVIEW OF POLICY CONTEXT AND SCENARIO DESIGN

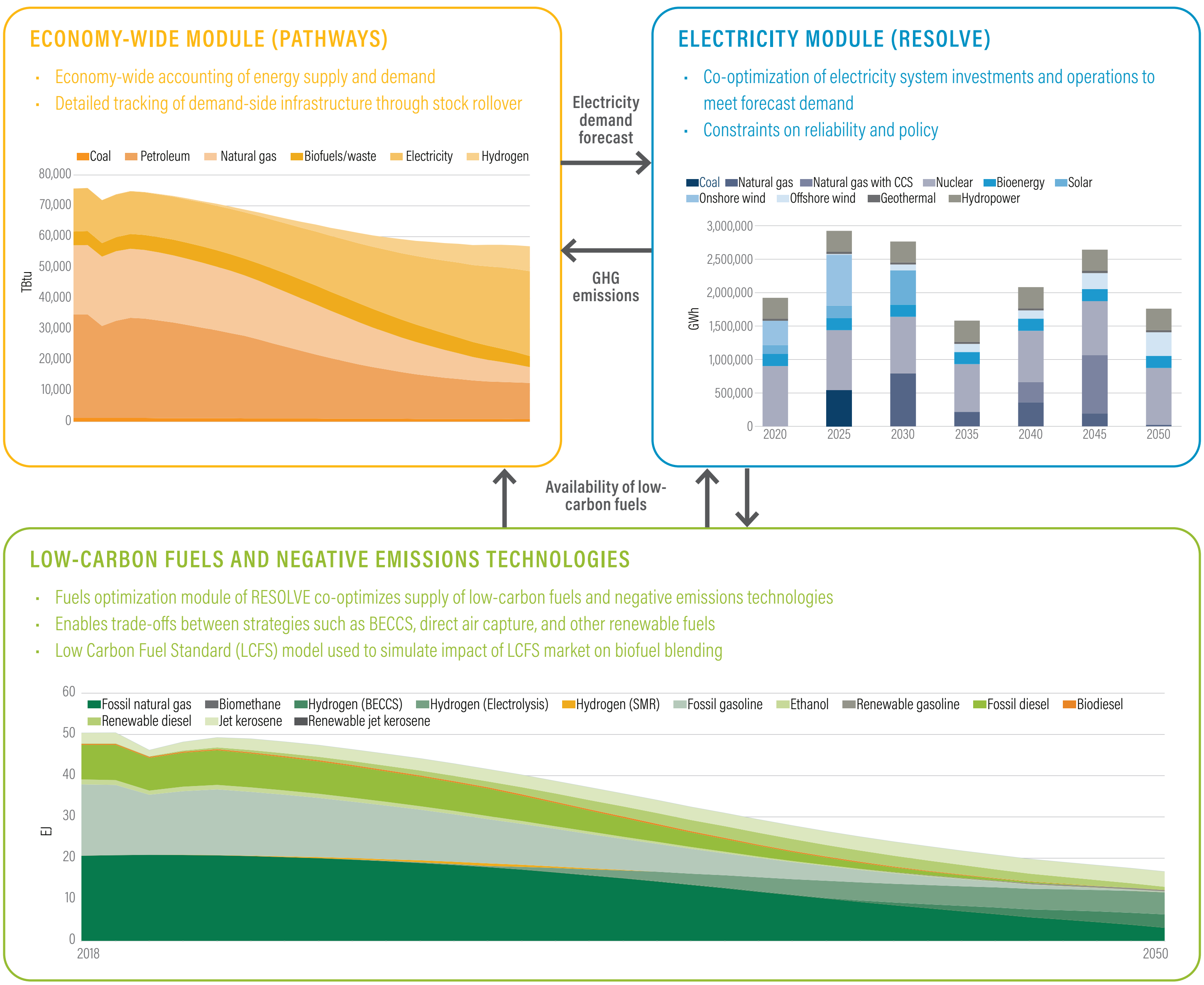
This paper presents modeling results corresponding to three scenarios that estimate the impact of various policy sets on GHG emissions. Underlying each scenario is a different policy context, emphasizing the role of different policy tools at the disposal of the federal government, with each successive scenario becoming more ambitious and comprehensive in the deployment of policy tools.

3.1 Building Blocks for Decarbonization

Among the many tools available to the federal government for decarbonization are tax credits, investment in climate-smart programs and infrastructure, and performance standards. The specific challenges of decarbonizing each sector of the U.S. economy require distinct combinations of these policy tools.

Tax credits play a valuable role in enabling the deployment of both early-stage technologies that are seeking entry into the market and more mature technologies that have not yet reached widespread deployment. They do this by acting as a supply push policy that brings technologies further down the cost curve and helps overcome real or perceived risks in deploying less-established technologies. Tax credits like the federal production tax credit and the investment tax credit have driven down the cost of wind and solar energy, enabling their faster deployment, while the plug-in electric vehicle tax credit has supported consumer adoption of electric vehicles. Tax credits can also support a virtuous cycle of technological advancement (Hart and Noll 2019), and they can be particularly effective if certain considerations are incorporated into their design and implementation (Saha et al. 2021a). In general,

Figure 1 | **Overview of E3's PATHWAYS and RESOLVE Models**



Note: BECCS = bioenergy with carbon capture and storage; EJ = exajoules; GHG = greenhouse gas; GWh = gigawatt-hours; TBtu = trillion British thermal units.
Source: E3.

they should be technology-neutral, performance-based rather than investment-based, refundable, equitable—that is, accessible to low- and middle-income Americans—and contain clear phaseout criteria based on achieving market penetration or emissions-reduction goals.

Infrastructure investments promote economic growth by creating jobs and spurring economic activity and are necessary for a transition to a cleaner economy. For example, the buildout of renewable energy capacity will require simultaneous development of high-voltage transmission lines and storage capacity. According to one study, transmission capacity needs to increase 40 percent by 2030 to be on a path to achieve net-zero emissions by 2050 (National Academies of Sciences, Engineering, and Medicine 2021). Decarbonizing transportation will also require improvements to the electrical grid to support the buildout of charging infrastructure needed for the massive increase in the number of EVs on the road that will accompany the transition away from fossil fuel vehicles. While the private sector will be an important player in filling the gap, new federal investments will be crucial to expedite the low-carbon transition, prioritize investments in communities and regions facing the greatest need, and unleash greater private sector investment.

In addition to tax incentives and investments, performance standards must also be considered as a key building block for decarbonizing the U.S. economy. These include, but are not limited to, clean electricity standards, renewable portfolio standards, vehicle emissions standards, low-carbon fuel standards, and building performance standards. Performance standards set a benchmark—either in terms of percentage of clean electricity, emissions per mile of vehicle travel, or percentage of zero-emissions vehicles for new car sales—and require producers to meet or exceed that benchmark. Over time, the benchmark can be made more stringent, spurring a continuous cycle of performance improvement. When a performance standard requires firms to pay when they exceed an established benchmark and credit firms when they reduce emissions below the benchmark, they can serve as a de facto carbon price.[2] Performance standards have generally commanded popular and political support. For example, state RPSs, which require that a certain share of electricity come from renewable or other clean sources, have played an important role in U.S. renewable energy growth and have resulted in significant emissions reductions in the power sector (Barbose 2018, 2021).

Finally, a well-designed carbon pricing mechanism can be a powerful and economically efficient way to reduce emissions. By incorporating climate change costs into economic decision-making, a carbon price makes clean technologies more financially attractive compared to their dirtier counterparts (Dasgupta and Lashof 2021). Carbon pricing has been extensively studied, with a recent analysis reiterating that pricing carbon pollution, along with a clean energy tax incentive package and a clean electricity standard (similar to goals included in the proposed Clean Electricity Performance Program in the Build Back Better Act), can be more effective in reducing emissions than any individual policy or combination of policies that does not include carbon pricing (Hafstead et al. 2021). Despite the attractiveness of carbon pricing as the most direct tool to address climate change, support for it has not been consistent at either the federal or state level.[3] Concerns related to carbon pricing have included determining the "right" price on carbon and the environmental justice and equity implications of the system (Patnaik and Kennedy 2021).

Given the extensive literature on economy-wide carbon pricing mechanisms, our analysis does not include carbon pricing in the mitigation scenarios. Instead we focus on whether tax credits, federal investment and spending programs, and sector-specific performance standards together can provide a path for the United States to meet a net-zero emissions goal by 2050. The window of what is politically possible in climate policy can change, and we believe that economy-wide carbon pricing should remain on the table as part of the climate agenda.[4]

3.2 Description of Modeling Scenarios

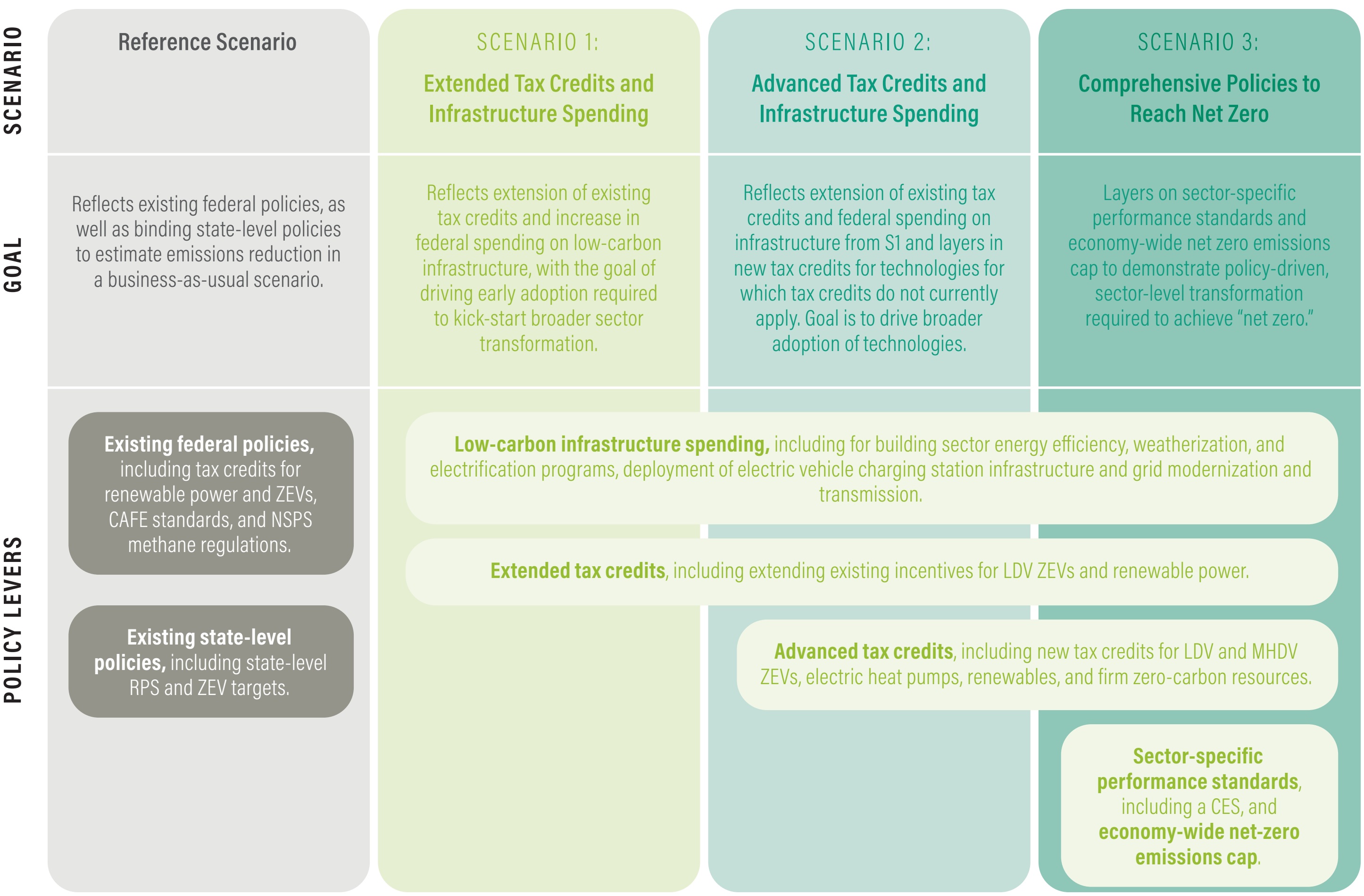
Our analysis compares the relative progress toward a net-zero goal offered by different policy packages that overlap and build on one another. We include one reference scenario and three policy and investment scenarios.

- The **Reference Scenario (RS)** includes current federal policies in effect, with some modest extensions expected through federal legislation. It also includes current legally binding state climate and clean energy policies.
- **Scenario 1 (S1)** includes the extension of current tax incentives, along with increases in spending programs that target infrastructure, to help drive early adoption of clean energy and energy efficient technology required to kick-start broader sector transformation. Key measures include extending tax incentives for renewable energy and EVs in the light-duty vehicle segment.

- **Scenario 2 (S2)** includes the addition of advanced tax credits for low-carbon technologies such as heat pumps and EVs in the medium- and heavy-duty vehicle segment to drive broader adoption of various clean technologies. S2 includes S1 policies.
- **Scenario 3 (S3)** builds on S2 to include the addition of stringent sector-specific performance standards and an economy-wide net-zero emissions cap, required to achieve net-zero emissions by 2050 across the economy.

Figure 2 summarizes the overlap of policy sets between the three policy scenarios, while Table 1 summarizes the policy assumptions for each type of policy. The Technical Appendices detail the federal and state policy assumptions across all scenarios and reference case, in addition to describing how each assumption was modeled.

Figure 2 | **Description of Mitigation Scenarios and Building Blocks Underlying Each Scenario**



Notes: CAFE = Corporate Average Fuel Economy; CES = clean electricity standard; LDV = light-duty vehicle; MHDV = medium- and heavy-duty vehicle; NSPS = New Source Performance Standards; RPS = Renewable Portfolio Standard; ZEV = zero-emissions vehicle. Please see Table 1 and Technical Appendices B–C for more details about individual policies included under each scenario.

Source: WRI authors and E3.

Table 1 | **Key Federal Policies Assumptions across the Scenarios**

EXISTING TAX CREDITS (MODELED IN S1, S2, S3)
▪ **Section 45 Production Tax Credit** for zero-carbon electricity generation, including nuclear, extended through 2035 and made refundable.
▪ **Section 48 Investment Tax Credit (ITC)** for zero-carbon electricity development extended through 2035 and lowered through 2050. Made refundable and expanded to include storage technology.
▪ **Section 45Q Credit for Carbon Oxide Storage** for carbon capture and storage (CCS) and enhanced oil recovery.
▪ **25D Residential Energy Efficient Property Credit** extended through 2030 for installing renewable energy technologies.
▪ **+25C Non-business Energy Property Tax Credit** extended through 2030 for energy efficiency appliance and building envelope upgrades.
▪ **179D Commercial Buildings Energy Efficiency Tax Deduction** extended through 2030 energy efficiency appliance and building envelope upgrades in commercial buildings.
▪ **30D Plug-In Electric Vehicle (EV) Credit** extended through 2035, with the manufacturer cap removed and made refundable.
▪ **30C Alternative Fuel Vehicle Refueling Property Credit** extended to 2035 to support EV charging infrastructure.
▪ **30B Fuel Cell Vehicle Credit** extended through 2035 for light-, medium-, and heavy-duty fuel cell vehicles.
SPENDING AND INFRASTRUCTURE (MODELED IN S1, S2, S3)
▪ **Internal Combustion Engine (ICE) Vehicle Scrappage Program** for the early retirement and scrappage of ICE vehicles, combined with the plug-in EV tax benefit, through 2050.
▪ **Federal Infrastructure Investment** for EV charging and grid transmission and distribution.
▪ **State Energy Efficiency and Insulation Rebate Program** funded at $8 billion spent over 10 years.
▪ **Weatherization Assistance Program** funded at $5 billion annually over 10 years.
▪ **Building Energy Code Incentives and Technical Assistance** to help states, tribal areas, and territories accelerate review and adoption of the latest building energy codes, 2018 IECC and ASHRAE 90.1.
▪ **U.S. Department of Agriculture Cost Share, Grant, and Payment Programs** to provide landowners financial incentives to adopt practices that sequester carbon and reduce emissions to increase the land sink by 180–360 million metric tons carbon dioxide equivalent by 2030.
▪ **Federal Investment in Agricultural Research** to develop carbon-sequestering crop phenotypes and identify best practices for soil carbon management and non-CO_2 emission, with the goal of reducing agricultural emissions by 32% by 2030.
ADVANCED TAX CREDITS (MODELED IN S2 AND S3)
▪ **Advanced ITC** of 40% for advanced nuclear power, CCS, and flow battery investments through 2050.
▪ **Grid ITC** of 30% for transmission and distribution grid investments through 2050.
▪ **Used EV Tax Credit** of 30% for the purchase of a used EV.
▪ **Battery EV Tax Credit** at $7,250 for medium-duty and $13,750 for heavy-duty through 2050.
▪ **Fuel Cell Electric Vehicle Tax Credit** at $20,000 for medium-duty vehicles through 2050 and $31,000–$40,000 for heavy-duty vehicles through 2050.
▪ **Residential Building Electrification Tax Credit** through 2050 for electric heat pumps at $5,000 per household, fully refundable.
▪ **Commercial System Electrification Tax Credit** through 2030 at $100 per ton of cooling capacity installed.

Table 1 | **Key Federal Policies Assumptions across the Scenarios (Cont'd)**

PERFORMANCE STANDARDS (MODELED IN S3)
▪ **Clean Electricity Standard** of 80% by 2030 and 100% by 2035.
▪ **Zero GHG Emissions Vehicle Performance Standard** for new light-duty cars and trucks by 2035, and for new medium- and heavy-duty trucks by 2040 whereby all light-duty vehicle sales are battery electric vehicles (BEVs) from 2035 and all medium- and heavy-duty vehicle sales are BEVs or fuel cell electric vehicles from 2040.
▪ **Vehicle Fuel Economy Standard (Corporate Average Fuel Economy)** increase 5% annually from model year (MY) 2027 to MY 2031 and constant after.
▪ **National Low-Carbon Fuel Standard** to reduce carbon intensity in fuels.
▪ **Building Emissions Standard** to phase out the sale of fossil fuel equipment in both residential and commercial buildings between 2030 and 2040.
▪ **Updated Appliance Energy Efficiency Standards** setting minimum energy conservation standards for appliances and equipment, with the model assuming that all new appliances would be the most efficient option available by 2030–35.
▪ **Implementation of the Kigali Amendment** to phase down production and use of hydrofluorocarbons (HFCs).[a]
▪ **Enhanced Methane Standards** for oil and gas industry.
▪ **Economy-wide Net-Zero Emissions Cap** to get rid of all remaining emissions, except for the most difficult emissions to abate, which are assumed to be offset.

Notes: Policies included in the three scenarios were chosen based on authors' expert judgment and consultation with experts. We also included provisions from the Bipartisan Infrastructure Bill (H.R.3684) and the Build Back Better Act due to their political salience. Tax credit values for various low-carbon technologies and federal spending on infrastructure are based on previous research done by the authors and expert consultations (Saha et al. 2021a; Carlock 2020a, 2020b).

[a] In September 2021, the U.S. Environmental Protection Agency passed a rule requiring U.S. manufacturers to phase down HFC production and consumption by 85 percent in the next 15 years. The new regulation brings the United States into compliance with the Kigali Amendment. Even though this was modeled in S3, if the modeling were done today, this would be included in the Reference Scenario.

Source: WRI authors and E3.

4. ECONOMY-WIDE EMISSIONS RESULTS

Overall, the results reveal that tax credits for existing and new low-carbon technologies, in combination with federal investment in climate-smart infrastructure, significantly improve the adoption of new technologies but are not enough by themselves to enable the country to reach its 2050 goal. Performance standards, such as a clean electricity standard, zero-emissions vehicle standard, low-carbon fuel standard, and appliance energy efficiency standards, are necessary to attain economy-wide net-zero emissions by 2050. Figure 3 compares net annual emissions trajectories by scenario through 2050.

4.1 Emissions Reductions across Mitigation Scenarios

Reference Scenario

In the RS, the United States is heading toward 31 percent and 34 percent emissions reduction below 2005 levels, by 2030 and 2050, respectively. This implies that there is almost no reduction in GHG emissions in the 2030s and 2040s. Any emissions reduction is due to existing policies at federal and subnational levels and market trends driving adoption of low-carbon technologies, particularly in the power and transportation sectors. The power sector sees the greatest emissions reduction, especially by 2030, which is a very optimistic outcome. Given that the modeling is driven by cost-minimization on the supply side, it is not accounting for friction in the real world, which could slow down deployment without a vigorous policy push. Building emissions remain relatively flat, while industrial emissions increase from continued growth in output.

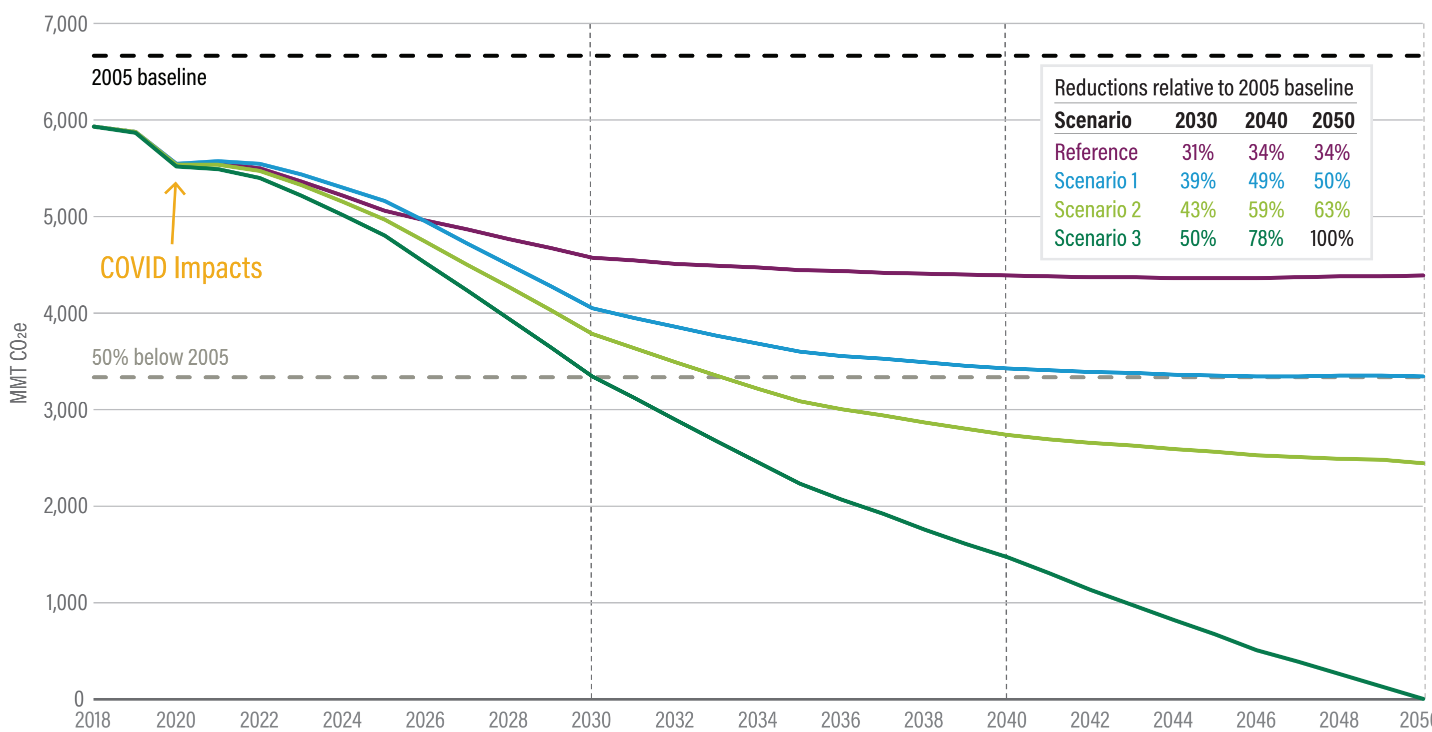
Emissions from sectors other than fossil fuel combustion also increase during the period, including greater emissions from agriculture and oil and gas systems and a shrinking of the emissions sink provided by natural and working lands.

Figure 4 shows annual gross GHG emissions by U.S. sector by different scenarios and annual net GHG emissions and removals by scenario through 2050.

Impact of Tax Credits and Federal Spending in S1 and S2

Our modeling assumes similar federal spending in S1 and S2, while S2 includes additional tax credits for low-carbon technologies. As a result, S2 provides evidence of the

Figure 3 | **Net Annual Greenhouse Gas Emissions across the U.S. Economy by Scenario through 2050**

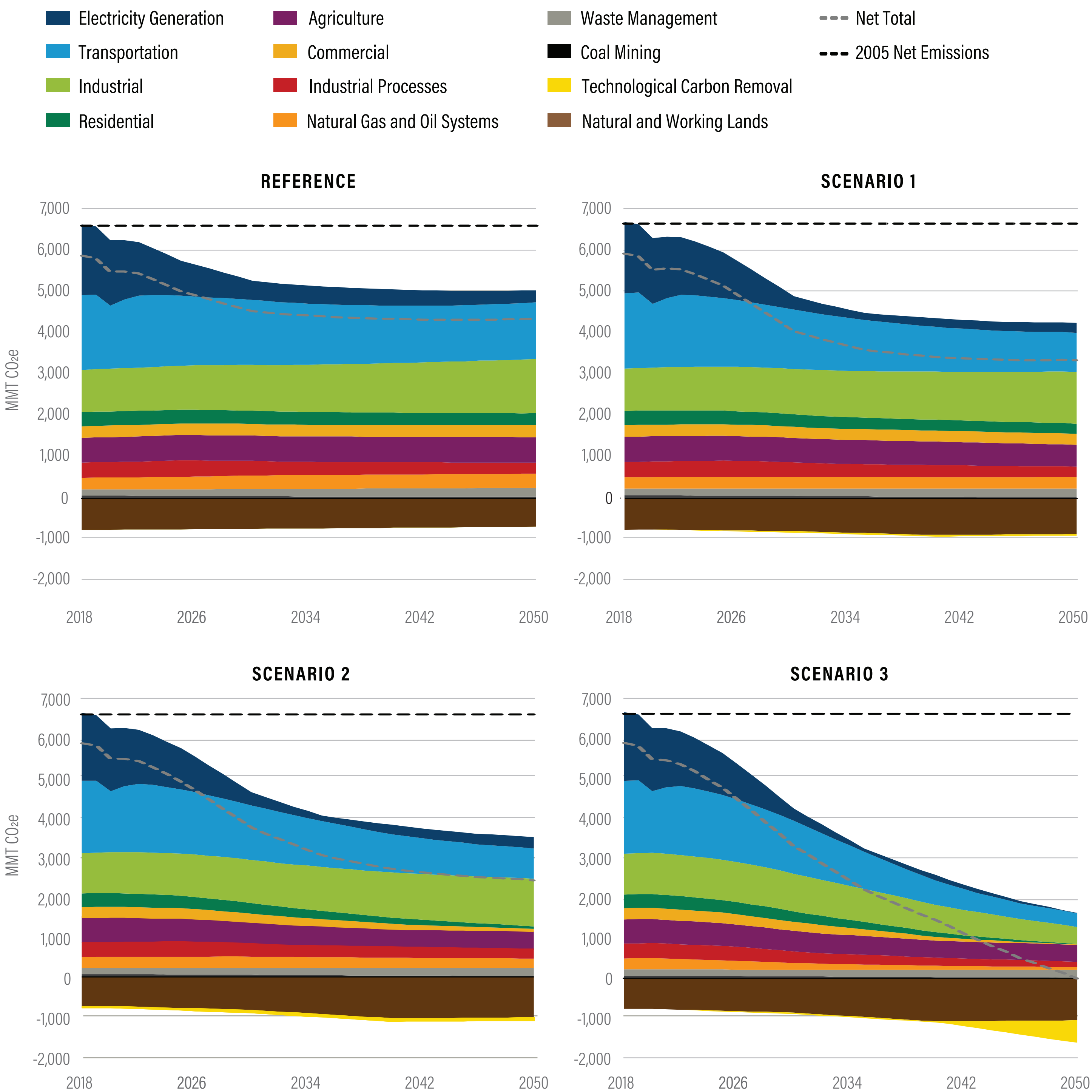


Reductions relative to 2005 baseline

Scenario	2030	2040	2050
Reference	31%	34%	34%
Scenario 1	39%	49%	50%
Scenario 2	43%	59%	63%
Scenario 3	50%	78%	100%

Source: WRI authors and E3.

Figure 4 | **Annual Gross Greenhouse Gas Emissions by U.S. Sector by Scenario and Net GHG Emissions and Removals by Scenario through 2050**



Source: WRI authors and E3.

impact of advanced tax credits compared to extending the current suite of clean energy tax credits in S1.

Tax incentives and federal spending on climate-smart infrastructure can play important roles in enabling the deployment of low-carbon technologies and reducing annual emissions rapidly up to 2030, by 39 percent and 43 percent in S1 and S2, respectively. Neither scenario hits the 2030 U.S. climate target, however. Furthermore, in both scenarios the pace of emissions reduction slows significantly between 2040 and 2050, and the combination of tax credits and federal spending is not sufficient to help the country reach net-zero emissions. High-carbon fuels continue to outcompete low-carbon and renewable alternatives in many industrial processes.

The impact of advanced tax credits plays out differently in different sectors. Advanced tax credits do not lend themselves to greater electricity-sector emissions reductions in either 2030 or 2050, in comparison to the impact of continuing with existing tax credits in S1 (Table 2). This is in part because market trends and the policies included in S1 already reduce power sector emissions 87 percent by 2030 in our model. In addition, there is no binding carbon constraint on the system. Because gas and renewables are still cheaper than emerging technologies (even with tax credits), the model chooses not to deploy the latter because it is minimizing cost. The model deploys gas where firm capacity is needed and continues to rely on renewables.

In contrast, advanced tax credits make a bigger difference to building and transportation sector emissions reduction in S2 (Table 2). Tax credits for residential and commercial building electrification in S2 lead to dramatic reduction in building emissions by 2050, compared to S1 tax credit outcome. Similarly, additional tax incentives for medium- and heavy-duty vehicles and for used EVs in S2, in combination with federal spending, lead to a bigger emissions reduction in transportation, compared with S1 results.

Table 2 | **Emissions and Removals across Scenarios by Sector for 2030 and 2050 (Percent Changes Relative to 2005 Levels)**

	GHG EMISSIONS/ REMOVALS IN 2005 (MMT CO_2E)	REFERENCE		SCENARIO 1		SCENARIO 2		SCENARIO 3	
		2030	2050	2030	2050	2030	2050	2030	2050
Electricity generation	2,459	467 (-81%)	298 (-88%)	318 (-87%)	243 (-90%)	331 (-87%)	288 (-88%)	304 (-88%)	9 (-100%)
Transportation	2,004	1,592 (-21%)	1,381 (-31%)	1,444 (-28%)	954 (-52%)	1,392 (-31%)	769 (-62%)	1,335 (-33%)	342 (-83%)
Industrial energy	855	1,120 (31%)	1,329 (55%)	1,102 (29%)	1,255 (47%)	1,093 (28%)	1,210 (42%)	952 (11%)	426 (-50%)
Residential buildings	371	323 (-13%)	282 (-24%)	302 (-19%)	245 (-34%)	267 (-28%)	64 (-83%)	263 (-29%)	14 (-96%)
Commercial buildings	251	286 (14%)	302 (21%)	274 (9%)	273 (9%)	232 (-7%)	72 (-71%)	229 (-9%)	9 (-96%)
Agriculture	578	619 (7%)	627 (9%)	594 (3%)	527 (-9%)	519 (-10%)	427 (-26%)	519 (-10%)	427 (-26%)
Industrial process emissions	397	353 (-11%)	267 (-33%)	340 (-14%)	253 (-36%)	340 (-14%)	253 (-36%)	293 (-26%)	135 (-66%)
Oil and gas systems	241	334 (39%)	348 (44%)	298 (24%)	278 (15%)	288 (20%)	230 (-5%)	166 (-31%)	65 (-73%)
Waste management	191	175 (-8%)	212 (11%)	175 (-8%)	212 (11%)	175 (-8%)	212 (11%)	166 (-13%)	198 (4%)
Coal mining	78	52 (-33%)	43 (-45%)	49 (-37%)	18 (-77%)	49 (-37%)	18 (-77%)	9 (-88%)	2 (-97%)
Natural and working lands[a]	-788	-744 (-6%)	-696 (-12%)	-804 (2%)	-876 (11%)	-864 (10%)	-1,056 (34%)	-864 (10%)	-1,056 (34%)
Technological carbon removal[b]	0	0 (--)	0 (--)	-39 (--)	-39 (--)	-39 (--)	-39 (--)	-32 (--)	-571 (--)
Total Gross Emissions	**7,423**	**5,321 (-28%)**	**5,089 (-31%)**	**4,896 (-34%)**	**4,258 (-43%)**	**4,686 (-37%)**	**3,543 (-52%)**	**4,236 (-43%)**	**1,627 (-78%)**
Total Net Emissions	**6,635**	**4,577 (-31%)**	**4,392 (-34%)**	**4,053 (-39%)**	**3,342 (-50%)**	**3,784 (-43%)**	**2,446 (-63%)**	**3,339 (-50%)**	**0 (-100%)**

Notes: [a]Natural and working lands values are negative, therefore a positive percent change denotes an increase in carbon stored relative to 2005. [b]The baseline for technological carbon removal is zero, thus a percentage change cannot be calculated.

Source: WRI authors and E3.

Industrial sector emissions, in contrast, increase with economic growth in both S1 and S2, highlighting the difficulty of decarbonizing this sector. While the Section 45Q tax credit does enable some reduction in GHG emissions from large industrial sources compared to the baseline, it is not enough to address this sector's emissions in its entirety.

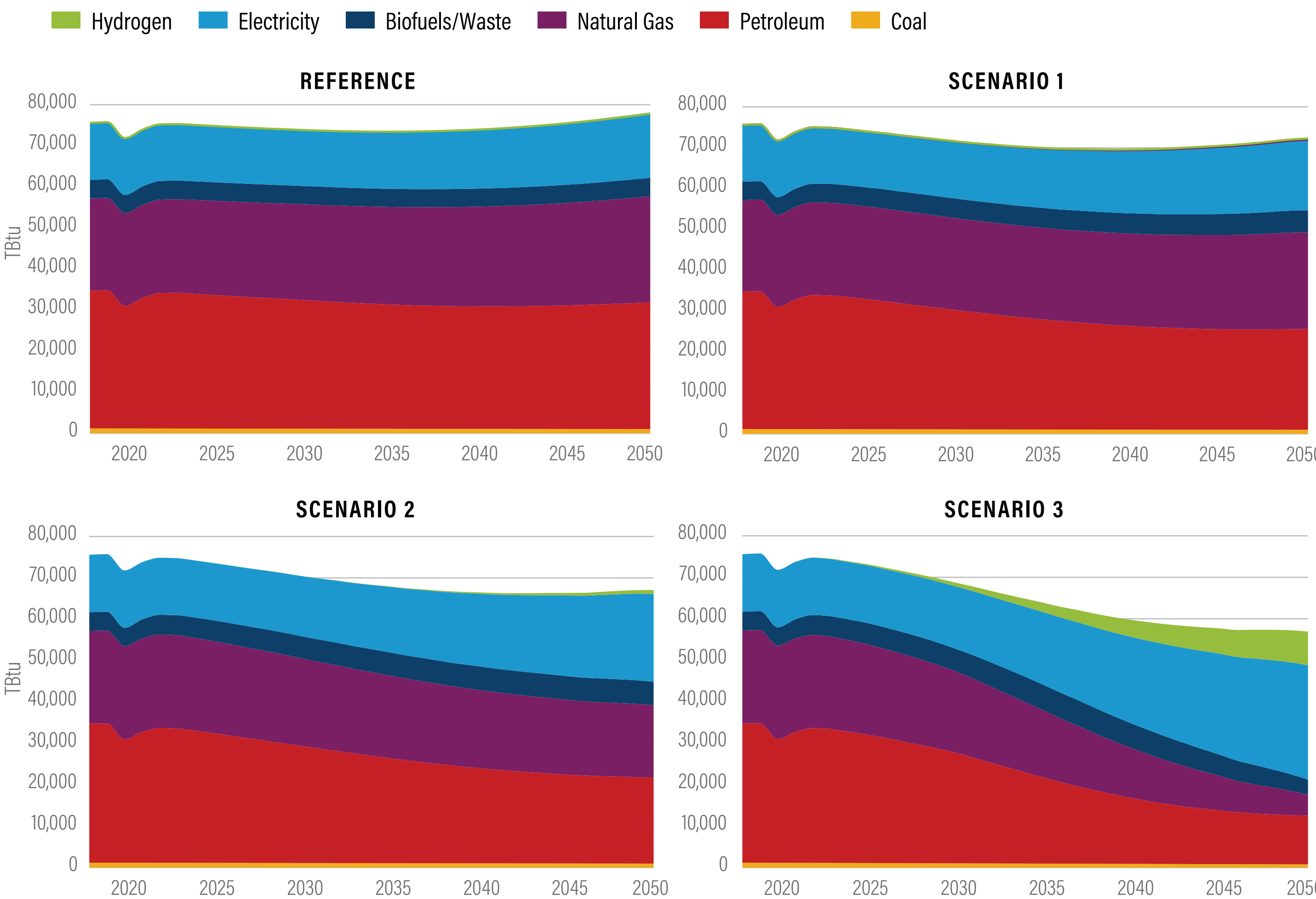
Impact of Performance Standards in S3

S3 highlights the critical role played by performance standards in significantly reducing carbon-intensive fuels and technology in the 2030–50 time frame, thereby enabling the United States to reach net-zero emissions by 2050. The adoption of a clean electricity standard in the power sector and a combination of performance standards in the transportation sector, including a zero-emissions vehicle standard for new light-duty cars and trucks by 2035 and for new medium- and heavy-duty trucks by 2040, along with aggressive vehicle fuel economy standards, help set the stage for the United States to reach a 50 percent economy-wide emissions reduction by 2030. The electricity sector is close to 100 percent decarbonized by 2035, in keeping with the Biden administration's goal of reaching 100 percent carbon-free electricity by 2035.

In addition to performance standards, negative emissions technologies (NETs) that remove and sequester CO_2 directly from the atmosphere are needed to reach net-zero emissions by 2050. NETs are expected to play an important role in tackling residual emissions from harder-to-abate nonelectric sectors such as heavy transport and industry.

Significant fossil fuel use remains in 2050 even after widespread electrification of on-road transportation and buildings in S3. For instance, petroleum demand declines by 65 percent but continues to fuel heavy transport and some

Figure 5 | **Final Energy Demand by Fuel Type across Scenarios**



Note: TBt = trillion British thermal units.
Source: WRI authors and E3.

industrial use. Fuel switching to hydrogen-based, synthetic, and/or bio-derived fuels in industry and off-road transportation is still needed in S3 (Figure 5).

Our analysis also shows that a modest reduction in agricultural emissions through improved management of enteric fermentation, manure, soil, and fertilizer, and a moderate expansion of the natural working lands sink can reduce emissions. Without significant action on fugitive emissions in the oil and gas sector, however, this does not result in net negative nonenergy emissions. S3 sees a 73 percent reduction in fugitive emissions from oil and gas activities, which together with agricultural emissions reduction and expansion of natural carbon sinks leads to net negative nonenergy emissions by 2050.

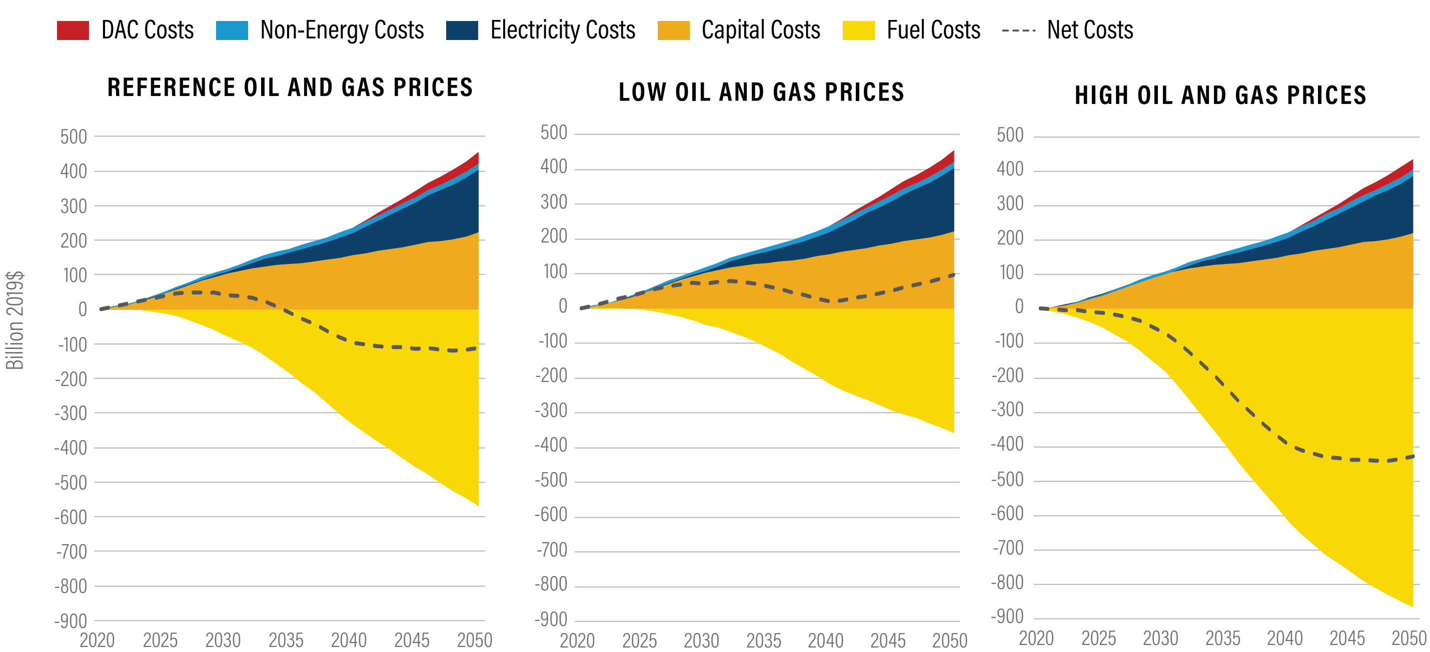
4.2 The Costs of Decarbonizing the U.S. Economy

While a fully decarbonized economy will require substantial investments for the deployment of clean technologies and supporting infrastructure, it can also enable cost savings through reduced energy bills and avoided expenditures on fossil fuels. The costs included in our modeling are shown in Table 3.

Though modeled costs are dependent on fossil fuel prices in all scenarios, this effect is most pronounced in S3 due to the scale of transformation in that scenario. With reference oil prices,[5] total net modeled costs in S3 are $40 billion higher than in the Reference Scenario (RS) in 2030, meaning that once modeled costs and savings are taken into account, S3 costs an additional $40 billion relative to the RS in 2030 (Figure 6). However, total modeled net costs in S3 are $113 billion less than in the RS by 2050, primarily as a result of significant fuel savings in transportation. Contrary to the perception that decarbonization will impose huge costs on the economy, our results show that the relative cost of decarbonization in S3 will amount to only 0.2 percent of U.S. GDP in 2030.[6] By 2050, there is a net savings of 0.3 percent of U.S. GDP.

In contrast, under a low oil price trajectory, net modeled costs in S3 are $70 billion in 2030 (0.3 percent of U.S. GDP) and $96 billion in 2050 (0.3 percent of U.S. GDP) compared to the RS.[7] Under a high oil price trajectory,[8] S3 results in net savings of $70 billion in 2030 (0.3 percent of U.S. GDP) and $428 billion in 2050 relative to the RS (1.2 percent of U.S. GDP). Fuel cost savings are higher under the high-price trajectory and reduced under the low-price trajectory. Table 3 shows net modeled costs for each of the three mitigation scenarios relative to the RS.

Figure 6 | **Net Modeled Costs for S3 Relative to Reference Scenario (in Billion 2019$) under Different Fuel Price Assumptions**



Note: DAC = direct air capture.
Source: WRI authors and E3.

Table 3 | **Net Modeled Costs in 2030 and 2050 Relative to the Reference Scenario (in Billion 2019$)**

SCENARIO	COST CATEGORY	REFERENCE OIL AND GAS PRICES		LOW OIL AND GAS PRICES		HIGH OIL AND GAS PRICES	
		2030	2050	2030	2050	2030	2050
Scenario 1	Residential capital costs	11	6	11	6	11	6
	Residential fuel costs	–3	–7	–3	–5	–4	–9
	Commercial capital costs	13	1	13	1	13	–1
	Commercial fuel costs	–1	–3	–1	–3	–1	–4
	Industrial capital costs	4	18	4	18	4	18
	Industrial fuel costs	–3	–13	–2	–9	–4	–19
	Transportation capital costs	25	–3	25	–3	25	–3
	Transportation fuel costs	–34	–146	–21	–82	–76	–263
	Power generation fixed costs	3	12	3	12	–4	0
	Power generation operating costs	–7	–4	–7	–4	–7	–1
	Nonenergy abatement costs	4	7	4	7	4	7
	Direct air capture (DAC) costs	0	0	0	0	0	0
	Net costs	**13**	**–133**	**27**	**–63**	**–37**	**–267**
Scenario 2	Residential capital costs	13	1	13	1	13	1
	Residential fuel costs	–9	–38	–8	–30	–12	–49
	Commercial capital costs	29	63	29	63	29	63
	Commercial fuel costs	–7	–44	–6	–35	–7	–57
	Industrial capital costs	7	29	7	29	7	29
	Industrial fuel costs	–4	–22	–3	–15	–6	–31
	Transportation capital costs	28	4	28	4	28	4
	Transportation fuel costs	–30	–192	–13	–103	–100	–360
	Power generation fixed costs	7	52	7	52	–1	42
	Power generation operating costs	–6	6	–6	6	–6	4
	Nonenergy abatement costs	6	12	6	12	6	12
	DAC costs	0	0	0	0	0	0
	Net Costs	**32**	**–128**	**52**	**–16**	**–51**	**–342**

Table 3 | **Net Modeled Costs in 2030 and 2050 Relative to the Reference Scenario (in Billion 2019$) (Cont'd)**

SCENARIO	COST CATEGORY	REFERENCE OIL AND GAS PRICES		LOW OIL AND GAS PRICES		HIGH OIL AND GAS PRICES	
		2030	2050	2030	2050	2030	2050
Scenario 3	Residential capital costs	13	–2	13	–2	13	–2
	Residential fuel costs	–9	–45	–7	–36	–14	–59
	Commercial capital costs	29	83	29	83	29	83
	Commercial fuel costs	–6	–54	–5	–43	–9	–71
	Industrial capital costs	28	125	28	125	28	125
	Industrial fuel costs	–11	–95	–6	–54	–28	–156
	Transportation capital costs	34	16	34	16	34	16
	Transportation fuel costs	–52	–374	–29	–224	–128	–580
	Power generation fixed costs	14	152	14	152	5	138
	Power generation operating costs	–8	30	–8	30	–7	27
	Nonenergy abatement costs	8	17	8	17	8	17
	DAC costs	0	33	0	33	0	33
	Net Costs	**40**	**–113**	**70**	**96**	**–70**	**–428**

Note: Net modeled costs here refers to total costs and savings in the three mitigation scenarios relative to the Reference Scenario.

Source: WRI authors and E3.

5. SECTOR-SPECIFIC RESULTS AND INSIGHTS

This section unpacks sector-level modeling results and policy insights, with a specific look at key milestones through 2030 and what is needed between 2030 and 2050 to help the United States reach a net-zero economy by 2050.

5.1 Electricity Generation

The U.S. power sector is moving away from fossil fuels and replacing them with clean sources like solar and wind. Between 2005 and 2020, energy-related CO_2 emissions from the power sector declined by 40 percent (EIA 2021a). However, there is still a long way to go to meet goals for the sector of 80 percent clean electricity by 2030 and 100 percent by 2035. In 2020, the United States obtained nearly 40 percent of its electricity from clean sources—20 percent each from nuclear and renewables (EIA 2021b). Considering the announced retirement of some nuclear power plants, the challenge of moving from 40 percent clean electricity to 100 percent in a matter of 15 years is substantial.[9]

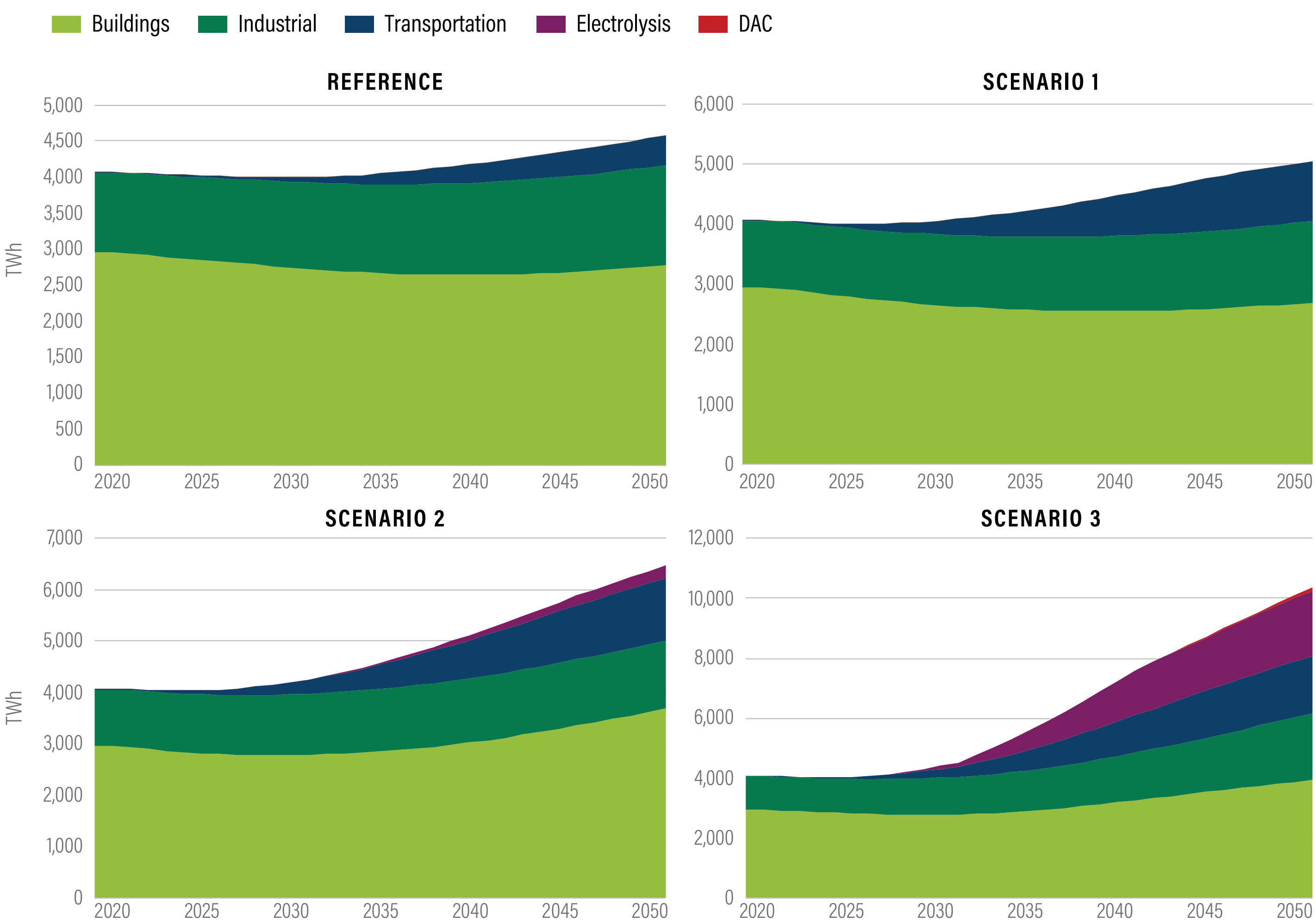
Key Results

The most important indicators for decarbonization of the power sector include an increase in the share of renewable and zero-emissions generation sources, the retirement of coal power plants, and reduced generation from gas power plants while retaining existing gas capacity to provide reliability in the near to medium term.[10] Our analysis yields the following key results:

- **Electrification of transportation, buildings, and low-carbon fuel production results in a massive increase in electric load through 2050.** In S2 and S3, electricity demand for industry, buildings, transportation, hydrogen electrolysis, and direct air capture (DAC) increases 59 percent and 154 percent, respectively, between 2018 and 2050 (Figure 7). Under S3, the electricity share used for hydrogen electrolysis and DAC increases to 22 percent by 2050.

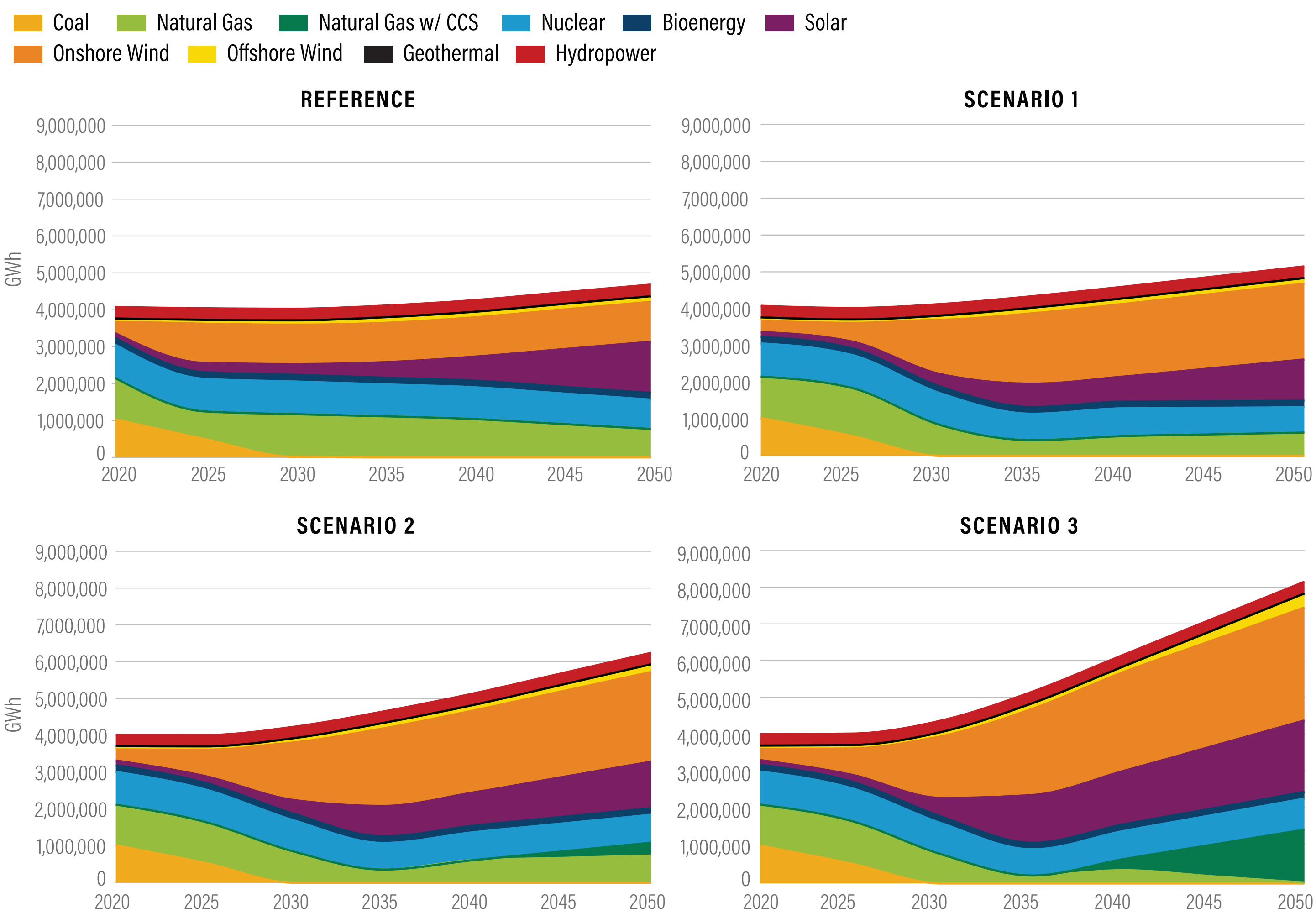
- **Coal power plant capacity and generation phase out almost entirely by 2030 in all mitigation scenarios.** This is largely driven by the relative cost-competitiveness of renewables and natural gas along with the older age of existing coal plants planned for retirement in that period (Figure 8). Even under a business-as-usual scenario, coal is under increasing pressure, with utilities closing an increasing number of uneconomical coal plants in the model. While this result makes sense in the context of a modeling framework that develops least-cost electricity generation portfolios, it may not reflect the real-world decision-making of utilities, including rural electric cooperatives and municipal utilities that are reliant on coal.[11] When market forces alone are not enough to retire assets that are uneconomical, additional policies targeting coal power plant retirement would be needed.
- **The installed capacity of renewable energy increases substantially through 2050 in all scenarios.** U.S. 2020 solar and wind capacity—178 gigawatts (GW) combined—increases to 1,100 GW under S1, 1,295 GW under S2, and 1,898 GW under S3

Figure 7 | **Electricity Demand by Sector across Scenarios**



Note: DAC = direct air capture.
Source: WRI authors and E3.

Figure 8 | **Annual Electricity Generation (GWh) from 2020 to 2050 by Policy Scenario**



Source: WRI authors and E3.

by 2050. Renewables' share of electricity generation reaches a high of 82 percent by 2035 under S3 (Figure 8). Deploying onshore wind and solar at this scale has the potential to generate conflicts over land use and siting, which will require policy solutions to address the land use impacts of renewable energy.

- **Lithium-ion battery storage plays an important role in decarbonizing electricity production by shifting renewable electricity to times of the day when it is most needed to power cars and buildings.** Installed capacity increases from 0.78 GW in 2020 to 342 GW (or 15 percent of total electricity generating capacity), 220 GW (9 percent), and 221 GW (6 percent) in 2050 under S1, S2, and S3, respectively. Solar deployment, in particular, is complemented by short-duration battery storage. There is significantly less battery deployment in S2 and S3, compared to S1, in our modeling. The period after 2045 in S2 and after 2040 in S3 sees an increase in gas, with CCS deployment substituting for batteries. In addition, the capacity value of storage declines over time, and, as S2 drives down the cost of clean, firm technologies, it becomes economical to swap some batteries with the new technology.

- **Firm energy sources[12] such as nuclear, natural gas, and natural gas with CCS play a vital role in the long run, despite growth in renewable energy**. As solar and wind become the primary sources of electricity generation and the economy becomes increasingly electrified, firm energy sources are required as an insurance policy to maintain sufficient system reliability during challenging periods (e.g., multiday periods of sustained low renewable output) (Sepulveda et al. 2018; Jenkins et al. 2018). Though the share of nuclear energy goes down in all scenarios through 2050, it continues to play an important role, with shares ranging between 14 and 17 percent of generation in 2035 and between 10 and 13 percent in 2050 under the three mitigation scenarios (Figure 8).[13] Furthermore, gas still constitutes between 8 and 10 percent of generation by 2035 and between 11 and 12 percent by 2050 in S1 and S2. The adoption of a clean electricity standard in S3 cuts natural gas (without CCS) use to 4 percent of generation in 2035 and completely eliminates it from the grid by 2050. However, gas with CCS plays an important role between 2040 and 2050, accounting for 15 percent of total generation in S3 and contributing to system reliability needs. Other emerging technologies may also be able to fill this need if they become commercialized and cost-competitive, including hydrogen combustion in converted natural gas generators or long-duration energy storage.

Key Building Blocks and Policy Insights

Decarbonizing the power sector is critical for enabling the decarbonization of other sectors of the economy through electrification of home heating and cooking, transportation, and industrial processes.

Clean energy tax credits emerge as an important near-term policy tool to drive clean energy deployment in the power sector, though on their own they are not enough to achieve 100 percent power sector decarbonization. In S1, the extension of the Section 45 production tax credit and Section 48 investment tax credit through 2035 encourages further development of zero-carbon electricity generation, including renewable energy and nuclear, displacing fossil fuel technologies. As a result, renewable energy reaches 74 percent of generation by 2035, compared to 52 percent in the reference case (Figure 8). In S2, the expansion of tax credits to support transmission investments and storage technology pushes renewable energy generation to 77 percent in 2035. By 2050, however, renewable energy's share of generation stays the same in S1 and drops to 70 percent in S2. Despite this drop, there is significant increase in renewable energy generation between 2020 and 2050 in S2 versus S1, implying that the difference in gigawatt hours between these scenarios is much larger than the difference in share of generation.

To ensure maximum impact from clean energy tax credits, Congress should improve their design, including ensuring long-term availability of credits, and incorporating refundability and direct pay provisions (Saha et al. 2021a). Allowing renewable energy developers—who currently either need to have tax liability or partner with an equity investor to benefit from the tax incentives—to receive the incentive as a fully refundable tax credit or through a direct pay mechanism can drive significantly more renewable deployment.

A clean electricity standard (CES), requiring utilities all across the country to reduce their emissions, is necessary to completely eliminate emissions from the grid. Our analysis indicates that clean energy tax credits, along with federal investment in modernizing the electricity grid, lead to an 87 percent reduction in the power sector by 2030, relative to 2005 (Table 2). A CES becomes important to eliminating residual power sector emissions by ensuring that increasing electricity demand due to widespread electrification is not served by natural gas without carbon capture and storage (CCS), given that gas remains the cheapest dispatchable form of generation.

Finally, power sector decarbonization requires massive investment in the electricity grid, including in replacing fossil fuels with clean sources of electricity, building new transmission capacity to move clean energy between different regions of the country, and modernizing the operation of the electricity grid through the adoption of various smart advanced grid technologies. While the private sector will continue to bear responsibility for much of this investment, federal investment in the nation's power grid through grants, loans, and loan guarantees will be crucial to mobilizing and leveraging private money. Additionally, it will be important to address permitting and regulatory challenges that can choke off the siting and building of projects.

5.2 Transportation

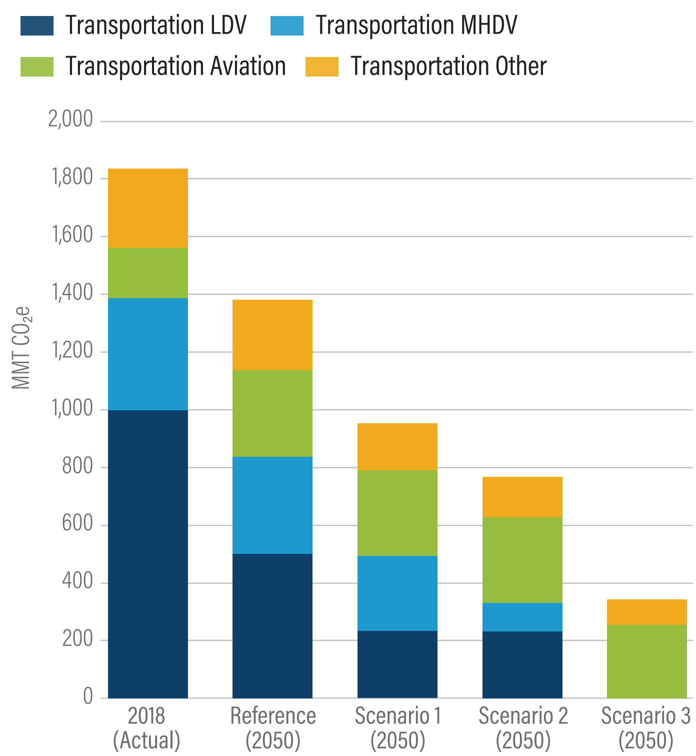
Transportation represented the largest share (36 percent) of total U.S. energy-related CO_2 emissions in 2020, with fossil fuels accounting for 90 percent of total energy use in the sector (EIA 2021a, 2021b). Achieving deep decarbonization of the sector by 2050 will require fully phasing out the sales of internal combustion engine (ICE) passenger vehicles between 2030 and 2040 and aggressive adoption of zero-emissions freight vehicles, including EVs and hydrogen fuel cell electric vehicles (FCEVs) (Larson et al. 2020). Decarbonizing shipping will require a mix of technologies, including batteries and zero-emissions fuels like liquefied green hydrogen for short-haul shipping and liquefied green ammonia for longer distances (IEA 2020), while sustainable aviation fuel (SAF) is gaining momentum as a decarbonization solution for aviation, with the Biden administration outlining a goal of producing 3 billion gallons of SAF annually by 2030 and reducing carbon emissions in the sector by 20 percent compared to business-as-usual levels (Duncan 2021).

Key Results

Important indicators for transportation decarbonization are an increase in the share of EVs and improvements in vehicle fuel efficiency. Our analysis yields the following key insights:

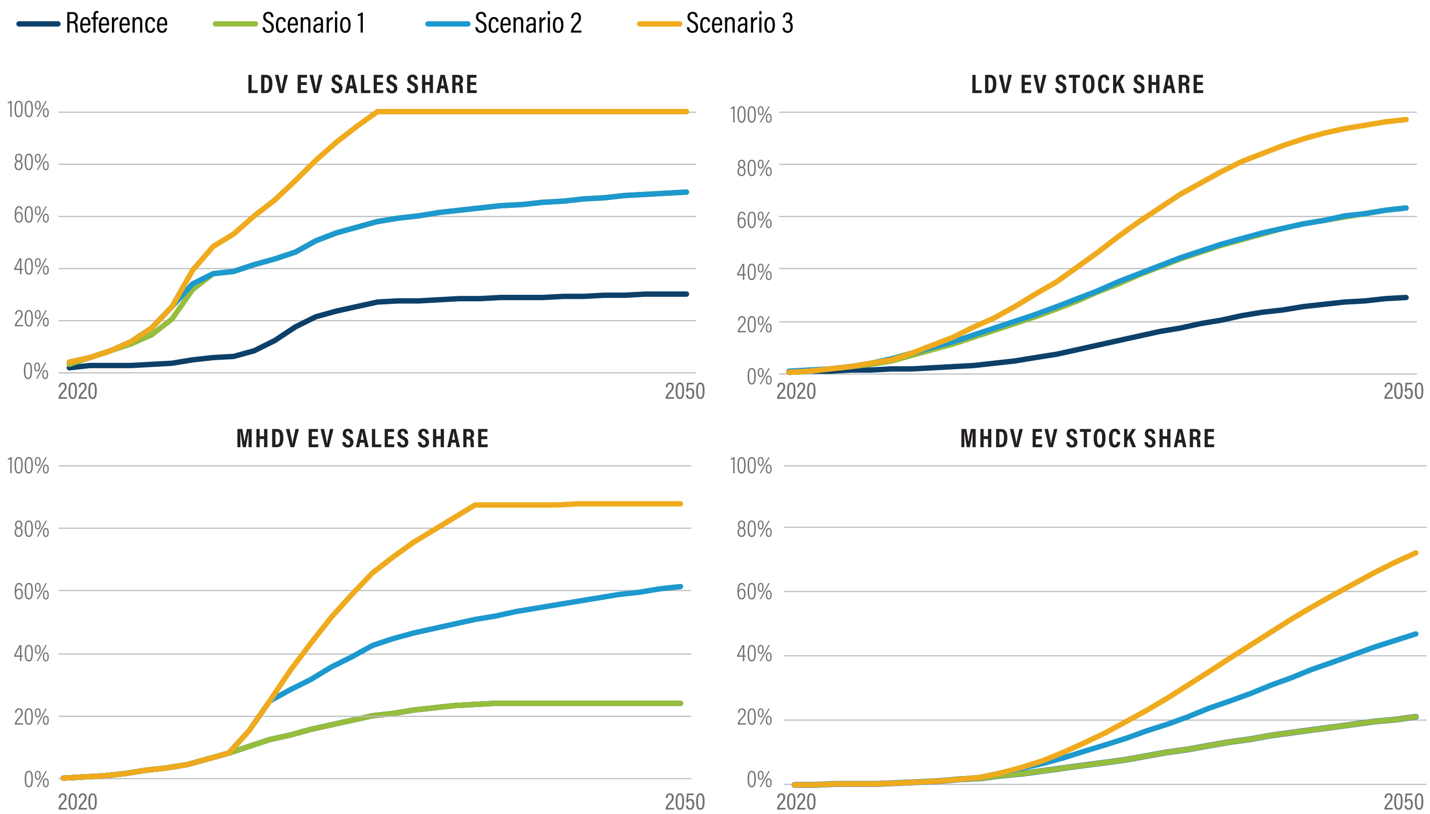
- **Electrification of the light-duty vehicle (LDV) segment is the main driver of reductions in transportation sector energy-related CO_2 emissions in S1.** Battery EVs represent 44 percent of LDV sales by 2030 and 69 percent by 2050 under S1 (compared to 13 percent and 30 percent by 2030 and 2050, respectively, under the Reference Scenario), which shows that the extended EV tax credit for LDVs encourages higher EV sales. For medium- and heavy-duty vehicles (MHDVs), the sales trajectory for battery EVs is identical under the RS and S1, with battery EVs representing 13 and 24 percent of MHDV sales by 2030 and 2050, respectively. Relative to 2018 levels, S1 achieves a 48 percent reduction in emissions by 2050 (Figure 9). LDV emissions decline by 77 percent in 2050, while emissions in the MHDV segment are 33 percent lower, compared to 2018 levels.
- **While the trajectory of EV adoption is identical between S1 and S2 for LDVs, increased electrification of MHDVs under S2 leads to greater reductions in emissions.** The sales share of LDV EVs remains at 44 percent and 69 percent by 2030 and 2050, respectively, under this scenario, but battery EVs account for 25 percent and 61 percent of MHDV sales by 2030 and 2050, respectively, with the availability of the MHDV tax credit enabling faster electrification in S2 (Figure 10). This scenario shows a 58 percent decrease in transportation emissions compared to 2018 levels, with MHDV emissions declining by 75 percent in 2050.
- **S3 achieves the greatest reduction in emissions from the sector as tailpipe emissions standards ensure 100 percent ZEV sales in the LDV and MHDV segments by 2035 and 2040, respectively.** Compared to 2018 levels, transportation emissions decline by 81 percent, with emissions from both LDVs and MHDVs decreasing by 100 percent. Hydrogen accounts for over 2,500 trillion British thermal units (TBtu) (17 percent) of final energy demand in the transportation sector in 2050 in S3, with heavy-duty vehicle (HDV) fuel cell vehicles making up 86 percent of all FCEVs in 2050.

Figure 9 | **Transportation Emissions by Subsector and across Scenarios, 2050**



Note: Only direct emissions shown; emissions associated with electricity consumption not included.
Source: WRI authors and E3.

Figure 10 | **EV Share of LDV and MHDV Sales and Stock, 2020–50**



Note: EV = (battery) electric vehicle; LDV = light-duty vehicle; MHDV = medium- and heavy-duty vehicle.
Source: WRI authors and E3.

- **For LDVs, EVs reach upfront cost parity with ICE vehicles by 2024, but despite declining costs slow vehicle turnover restricts the increase in share of EVs in the LDV stock.** Under S3, EVs achieve 100 percent sales of LDVs by 2035 but only represent 47 percent of the LDV stock by 2035 and 97 percent by 2050 (Figure 10). The share of EVs in the LDV vehicle stock reaches 64 percent by 2050 under S1 and S2 (compared to 29 percent in the Reference Scenario).
- **Sensitivity analysis results indicate that tightening CAFE regulations and reducing vehicle miles traveled (VMT) can result in lower emissions.** Layering in such changes in different scenarios achieves additional emissions reductions as discussed below.
- **Emissions from transportation subsectors like aviation, shipping, and off-road transportation remain hard to abate across all scenarios.** These subsectors remain hard to electrify, and tax credits and other policies modeled in this study do not heavily impact these subsectors. Energy-related CO_2 emissions from subsectors like shipping, off-road transportation, and rail decrease by 41–68 percent by 2050 relative to 2018 levels under S1–S3 compared to an 11 percent decline under the Reference Scenario. Emissions from aviation increase by 72 percent relative to 2018 levels in the RS, S1, and S2, while S3 shows a 46 percent increase.

Key Building Blocks and Policy Insights

Vehicle electrification plays a dominant role in driving emissions reductions in the transportation sector in our analysis. Our results suggest the following insights about the main policy building blocks for this sector:

Continuation and expansion of EV tax credits can increase EV adoption. However, tax credits

alone are not enough to completely eliminate ICE vehicle sales by 2050. S1 shows that availability of the EV tax credit with the manufacturer cap removed and other incentives in the form of the Section 30C to support EV charging infrastructure can drive up the EV sales share as discussed above. While continuation of such incentives stimulates EV adoption, results suggest that higher incentives have a marginal impact on EV sales. S2—which includes an LDEV incentive of up to $10,000 through 2035—shows cumulative EV sales between 2020 and 2030 reaching 46 million (compared to 44 million in S1). S1 and S2 require significant federal spending on consumer EV tax credits. Cumulative spending on EV tax credits between 2020 and 2030 reaches up to $327 billion and $342 billion in S1 and S2, respectively (compared to $73 billion under the RS). Due to modeling limitations, the $10,000 incentive in S2 was modeled as a reduction in upfront cost for EVs, but different studies have shown that scrappage incentives or early vehicle retirement programs could make EVs more affordable to lower-income groups and a broader section of the U.S. population (UCS 2021; Linn 2020).

S2 also indicates that the availability of tax credits increases the electrification of the MHDV segment. Under this scenario, the share of EVs in MHDV sales in 2050 is about 2.5 times higher compared to the RS and S1. Additionally, the availability of a $31,000 tax credit for HDV fuel cell vehicles (FCEVs) helps FCEVs reach 30 percent of HDV sales by 2050. S2 requires up to $5 billion of cumulative spending to attain these levels of EV and FCEV adoption.

Along with tax credits to reduce upfront vehicle costs, investments in required infrastructure development and manufacturing will be vital to accelerate the deployment and adoption trends expected. While this study did not directly assess the impacts of charging infrastructure availability on EV adoption, multiple studies highlight access to charging infrastructure as a key barrier to accelerating adoption even as EVs reach cost parity with ICE vehicles (Knittel et al. 2021). Spending should be prioritized in the next decade to support the levels of growth seen under S1–S3.

Performance standards are needed to accelerate EV adoption beyond 2030 and support deep decarbonization of the sector. As shown by S3, stronger CAFE standards (a 5 percent annual increase in LDV fuel economy from model year [MY] 2027 through MY 2031 after a 1.5 percent annual increase until MY 2026 as outlined under the Safer Affordable Fuel-Efficient [SAFE] vehicles rule) and tailpipe emissions standards that kick in as LDEVs reach price parity can push up EV adoption to 100 percent by 2035 and the share of EVs in LDV stock to 97 percent by 2050. Tailpipe emissions standards also accelerate ZEV adoption beyond 2030 for MHDVs, ensuring 100 percent ZEV sales in the MHDV segment by 2050 under S3.

Results also show that tighter fuel economy standards can enable further emissions reductions under the RS, S1, and S2. Adding a 5 percent annual increase in LDV fuel economy from MY 2027 through MY 2031 after the SAFE rule in the RS, S1, and S2 reduces transportation emissions in 2030 by an additional 0.9–1.2 percent and transportation emissions in 2050 by an additional 5.4–6.6 percent.[14] The U.S. Environmental Protection Agency (EPA) has outlined new GHG emissions standards that increase in stringency by 10 percent for MY 2022–23 and by 5 percent annually for MY 2024–26 to replace the SAFE rule (EPA 2021a). While this analysis did not model the EPA's proposal, the EPA estimates that its targets could reduce LDV CO_2 emissions by 174 million metric tons (MMT) by 2030, an additional 21 percent reduction from 2020 levels, compared to a business-as-usual scenario (EPA 2021a).

Reductions in LDV vehicle miles traveled can also achieve additional emissions reductions, especially in the near term through 2030, before the LDV fleet becomes primarily electric. Results show that layering in a 3 percent and 10 percent reduction in LDV VMT (compared to 2020 LDV VMT levels) by 2030 across the scenarios decreases transportation emissions in 2030 by an additional 1.3–4.5 percent and transportation emissions in 2050 by an additional 0.9–3.6 percent.[15] Incentives that encourage less driving and promote the use of resource-efficient travel options—including walking, bicycling, ridesharing, or public transit—as well as development of more compact and multimodal neighborhoods, can support emissions reduction goals in the transportation sector and offer additional socioeconomic benefits (Litman 2021). This study did not directly model different policy measures to achieve LDV VMT reductions and assumed a 3 percent and 10 percent reduction in LDV VMT by 2030 based on trends reported by the U.S. Federal Highway Administration (2020) and Chong (2020). However, studies highlight that policy tools such as tax credits for electric bicycles and investments to make public transit more frequent and reliable need to be considered, as they can offer congestion reductions, consumer savings, and social equity benefits through improved public health and safety and improved access to different mobility options for low-income households, along with emissions reductions (Litman 2021; Yudkin et al. 2021).

5.3 Buildings

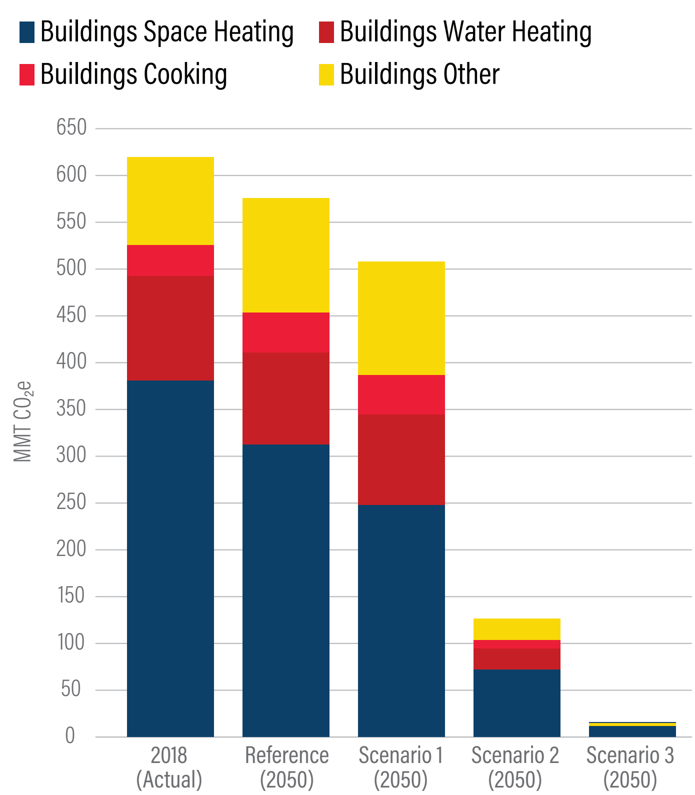
Decarbonizing the buildings sector will require widespread electrification of residential and commercial space and water heating, supported by energy efficiency measures to reduce energy use and costs. While building decarbonization requires reducing emissions that are both direct (from on-site use of fossil fuel for heating, cooking, and hot water) and indirect (from electricity generated off-site to power buildings and upstream methane leakage), here we are focused on the former. Direct emissions from commercial and residential buildings constituted 12 percent of U.S. energy-related CO_2 emissions in 2019 and were 5 percent higher relative to 2005 (EIA 2020). Building emissions are expected to increase steadily through 2050 due to population and building stock growth unless policies are put into place to rein in emissions. Buildings also have a slow turnover, and much of the existing building stock will remain by midcentury. This means we have one or two investment cycles available for equipment replacement.

Key Results

Important indicators for building decarbonization are increases in energy efficiency and the share of electrification of building energy systems, specifically the use of electric heat pumps and resistance heating. Our analysis reveals the following key insights:

- **In S1, the largest driver of emissions reduction is energy efficiency improvements driven by tax credits**, such as Section 25C for nonbusiness property and Section 179D energy-efficient commercial building deduction, and federal investment in energy efficiency programs, including the Weatherization Assistance Program and state energy efficiency and insulation rebate programs. These tax incentives result in building sector emissions reductions of 7 percent by 2030 and 17 percent by 2050, relative to 2005 (Figure 11).
- **Aggressive building electrification in S2 leads to a 78 percent reduction in building emissions by 2050, relative to 2005.** Tax incentives significantly boost heat pump adoption, expanding their market share. Electric heat pumps reach a market share of about 80 percent nationally for residential and commercial space heating, with variation among census regions. In residential space heating, for instance, the share of heat pumps increases to 77 percent by 2050 in S2, compared to 15 percent in S1 (Figure 12). This is driven by the adoption of building electrification tax credits through 2030, including tax incentives for electric heat pumps at $5,000 per household and a commercial system electrification tax credit at $100 per ton of cooling capacity installed.
- **In S3, electro-technologies make up nearly 100 percent of the market by 2040.** Building sector emissions are reduced by 96 percent by 2050, compared to 2005, with a 21 percent emissions reduction achieved by 2030. Building emissions standards, which phase out the sale of fossil fuel equipment in buildings between 2030 and 2040, further increase the adoption rate of heat pumps in the 2030–40 period (Figure 12).

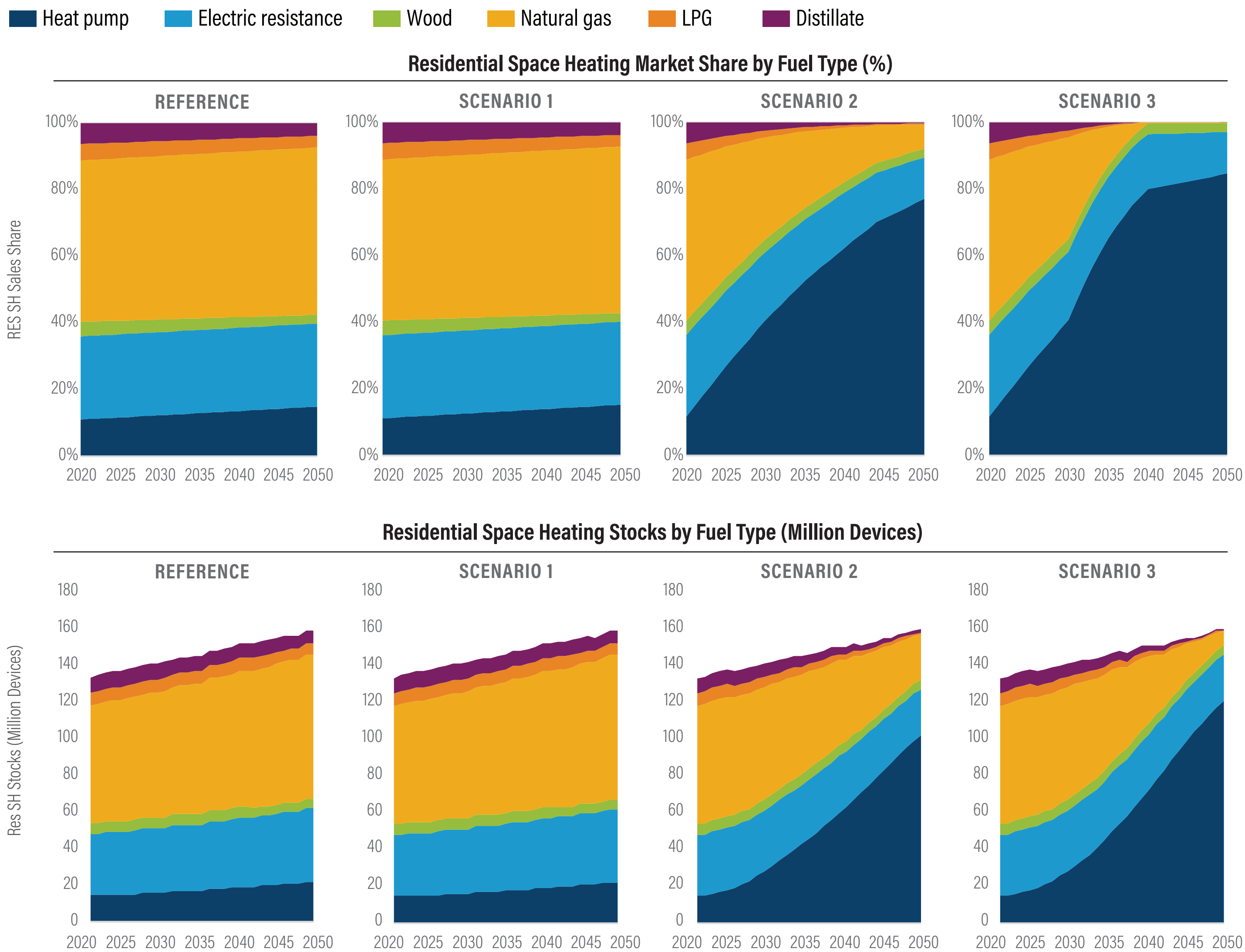
Figure 11 | **Building Emissions by Subsector and across Scenarios, 2050**



Note: Only direct emissions shown; emissions associated with electricity consumption not included.

Source: WRI authors and E3.

Figure 12 | **Residential Space Heating Stocks and Market Share across Scenarios**



Note: LPG = liquefied petroleum gas; Res SH = residential space heating.
Source: WRI authors and E3.

Key Building Blocks and Policy Insights

Electric heat pumps are a key decarbonization tool for reducing building emissions, especially when combined with decarbonization of the electricity sector. While heat pump installations have increased in recent years—one in four U.S. residences uses heat pumps (EIA 2019)—the pace of deployment is not consistent with goals to rapidly reduce building emissions. Given that building equipment can last 10 to 15 years, any effort to fully electrify space and water heating by 2050 must start with aggressive mobilization of the market today.

Consumer tax incentives can be a key component of a federal electrification strategy in combination with other programs that provide funding to subnational governments for engaging in consumer education and outreach, contractor training, and code development, among others. Our analysis includes a $5,000 per household refundable[16] residential building electrification tax credit. However, for many households, waiting to file taxes in order to claim the tax incentives could deter heat pump adoption. For that reason, point-of-sale rebates could be a more influential policy tool. Moreover, a tax credit that is differentiated by climate could be another option given that heat pump systems are more expensive in colder climates. Our analysis also reveals that consumer incentives are most helpful up until 2030, with heat pump adoption reaching 41 percent of the market by 2030 in S2 and S3. After 2030, even though incentives are removed, the market share of heat pumps continues to increase through the next 20 years as cost-parity is attained, reaching 77 percent and 85 percent by 2050 in S2 and S3, respectively.

Building performance standards, which effectively ban the sale of new fossil fuel equipment, can be a useful policy tool to accelerate building electrification. However, while a handful of cities in California and Massachusetts have either banned or are considering banning natural gas use in new construction, some states including Arizona, Oklahoma, Tennessee, and Louisiana have passed laws prohibiting their cities from imposing such gas bans. Proposed measures to ban or discourage the use of fossil fuel, however, only apply to new construction and not the existing stock of buildings. Other pathways to building electrification include consumer incentives, low-cost financing, and changes to building codes.

Energy efficiency improvements will play an important though limited role in reducing building energy demand and curbing emissions. Our analysis reveals that energy efficiency measures such as accelerated adoption of building energy codes and spending on weatherization and appliance rebates can only go so far in reducing building emissions. S1's focus on energy efficiency does not help heat pumps increase their market share over gas to the level needed to fully decarbonize buildings. Improving energy efficiency, however, can provide many benefits, including lowering baseload and peak demand and consequently reducing the need for additional generation and transmission, which can provide significant cost savings in the long term. While our model did not focus on demand response measures, these can provide further opportunities to reduce and optimize energy usage.

5.4 Industry

U.S. industry has proved difficult to decarbonize, though gains in efficiency and reductions in emissions intensity for some subsectors have been notable. While the steel sector has reduced its GHG emissions intensity by over 60 percent since 1990 due to a shift in product focus that enabled a shift in production route from blast furnaces to electric arc furnaces, GHG emissions intensity for cement production fell by only 10 percent over the same period, while total GHG emissions due to cement production rose 22 percent (EPA 2021b). Other large emitters, such as ammonia and lime producers, have also failed to reduce their total emissions. There are many reasons for this, including the trade intensity of these products, which threatens the competitiveness of U.S. producers if increased costs are incurred due to emissions mitigation efforts, as well as slow stock rollover of manufacturing equipment. These and other factors make the industrial sector difficult to decarbonize without sufficient incentives and protections against economic and emissions leakage.

Key Results

Key technologies for decarbonizing the industrial sector are electrification of low- and medium-temperature heating processes, the use of clean fuels such as clean hydrogen for high-temperature heating processes, and carbon capture and storage (CCS). Our analysis reveals the following key insights:

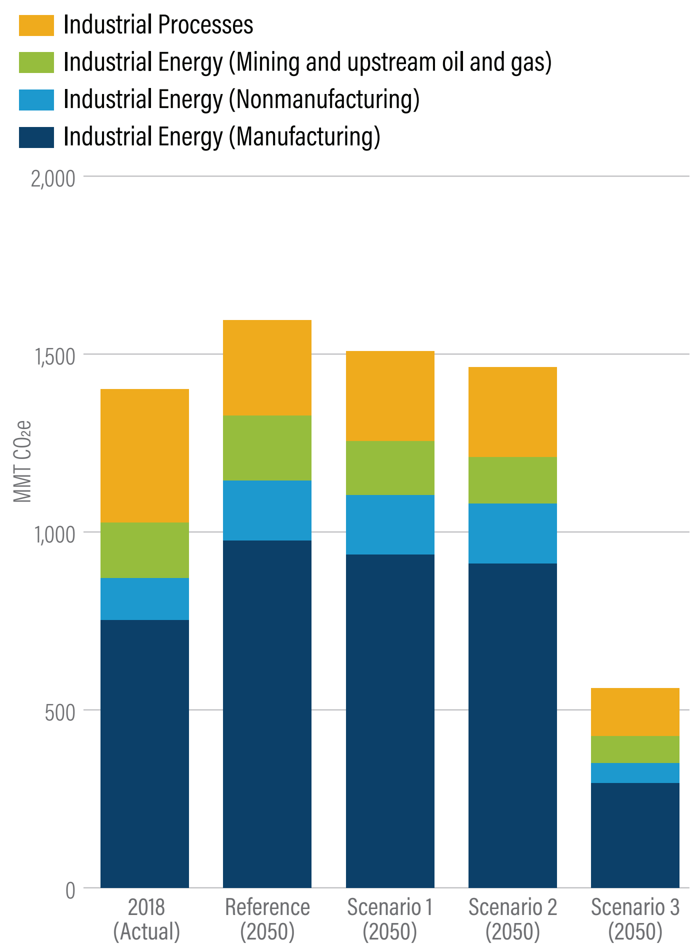
- **Industrial emissions increase through 2050 in the RS, S1, and S2 because of the availability of relatively few low-cost mitigation options**. Extensions and enhancements to the 45Q tax credit result in minimal enrollment and CCS deployment in S1 and S2, with only ammonia production, natural gas processing, and ethanol refining providing cost-effective CCS opportunities. Reductions in upstream oil and gas emissions in these scenarios are mainly due to a reduction in domestic fuel consumption, which results in reduced emissions from drilling, refining, and pipelining, while antileakage measures drive further reductions in fugitive methane emissions.
- **Due to limited cost-effective electrification opportunities, electro-technologies only achieve 2 percent market penetration in 2030 and 6 percent in 2050 as a replacement for natural gas process heating in S1 and S2, respectively.** Existing fossil fuel combustion technologies remain in use due to the cost of replacing these processes with electro-technologies. The use of clean fuels remains low due to the low price of natural gas relative to biofuels, hydrogen, and other clean fuels.
- **An economy-wide emissions cap implemented from 2030 to 2050 in S3 results in the electrification of 44 percent of existing natural gas heat processes and 28 percent of all industrial energy use (7,622 GWh of 27,705 GWh)**. Chemicals manufacturing accounts for 457 gigawatt-hours (GWh) of electricity demand in 2050 in S3, with agriculture (312 GWh), construction (295 GWh), metal-based durables (260 GWh), and food (167 GWh) demanding the bulk of remaining power in the industrial sector.

- **Energy demand for decarbonizing heating processes that can't be electrified is met by hydrogen in S3.** Hydrogen demand reaches 8.5 exajoules (EJ) in 2050 in S3, with industry accounting for 5.8 EJ, or 68 percent of total demand. Hydrogen production in S3 in 2050 is divided between green hydrogen produced from curtailed renewable energy, which accounts for 63 percent of total hydrogen produced, and BECCS hydrogen made from sustainable biomass, which accounts for the remaining 37 percent. A small amount of hydrogen is produced from steam methane reformation with CCS in the mitigation scenarios, but by 2035 it is replaced by electrolytic and biomass-derived hydrogen.
- **Decarbonizing industry and transportation in S3 requires significant amounts of electricity for hydrogen production.** Hydrogen production makes up 19 percent of total industrial energy consumption in 2050 in S3. Economy-wide, 2,165 terawatt-hours (TWh), or 21 percent of the nation's total electricity demand, is devoted to electrolysis for green hydrogen production in 2050 in S3.
- **Remaining energy emissions in the industrial sector in S3 amount to 176 MMT carbon dioxide equivalent (CO_2e) by 2050.** Remaining energy emissions arise mainly from natural gas use in refineries (31 MMT CO_2e), residual uses of liquid petroleum gas in agriculture and construction applications (34 MMT CO_2e), and coal use in food production (10 MMT CO_2e) and iron and steel production (4 MMT CO_2e).
- **Nonenergy emissions amount to 135 MMT CO_2e in S3 in 2050.** The largest contributions to nonenergy emissions are from production of petrochemicals (33 MMT CO_2e), refrigerants (16 MMT CO_2e), adipic acid (16 MMT CO_2e), and lime (15 MMT CO_2e).
- **Non-CO_2 industrial emissions not related to agriculture are due mainly to petroleum and natural gas systems, as well as waste and wastewater treatment.** Methane emissions from petroleum systems and natural gas systems total 39 MMT CO_2e, while methane emissions and nitrous oxide emissions from wastewater treatment total 20 MMT CO_2e and 6 MMT CO_2e, respectively. Landfill emissions, which are mainly due to flaring methane, are responsible for 160 MMT CO_2e in S3 in 2050.

Key Building Blocks and Policy Insights

The industrial sector remains difficult to decarbonize under scenarios where current policy measures are merely enhanced or extended (Figure 13). Dramatic changes in policy, such as the implementation of a cap on emissions, are required to force industrial actors to adopt emissions mitigation technologies. In conjunction, tax credits, research grants, loans, and other sources of funding must be made available to industry in order to drive the development of cleaner and more efficient technologies.

Figure 13 | **Industry Emissions by Subsector and across Scenarios, 2050**



Note: Only direct emissions shown; emissions associated with electricity consumption not included.

Source: WRI authors and E3.

Reform and expansion of the 45Q tax credit can give a boost to CCUS projects. The 45Q at current levels is not sufficient to drive widespread adoption of CCUS technologies in industry. Furthermore, tax credit programs see low enrollment levels even in industrial subsectors where they make economic sense—this is a result of ineffective tax credit design (Saha et al. 2021a) and the complexity of enrollment requirements. Our modeling results provide evidence that tax credits are most effective when complementing policies that provide a clear market signal for low-carbon technologies.

A cap on emissions or a more precise policy tool such as a low-carbon product standard, which can act on one product or a group of products, can drive widespread adoption of electro-technologies for low- and medium-temperature process heating as well as hydrogen in high-temperature heating processes. Policies such as an emissions cap, low-carbon product standards (Fransen et al. 2021; Feldmann and Kennedy 2021), tax incentives (Saha et al. 2021a), and research grants can provide the regulatory requirements as well as the resources for industry to reduce emissions substantially by 2050. A carbon border adjustment is also an important element for protecting trade-exposed industries. Even with these complementary policies in place, electro-technologies only account for 15 percent of final energy in potential applications by 2050 in S3, while clean hydrogen replaces remaining natural gas usage in high-temperature heating processes. However, natural gas still comprises around 7 percent of final energy use in the industrial sector in 2050 in S3, mainly due to its use for fueling chilling and air conditioning units.

5.5 Agriculture and Natural and Working Lands

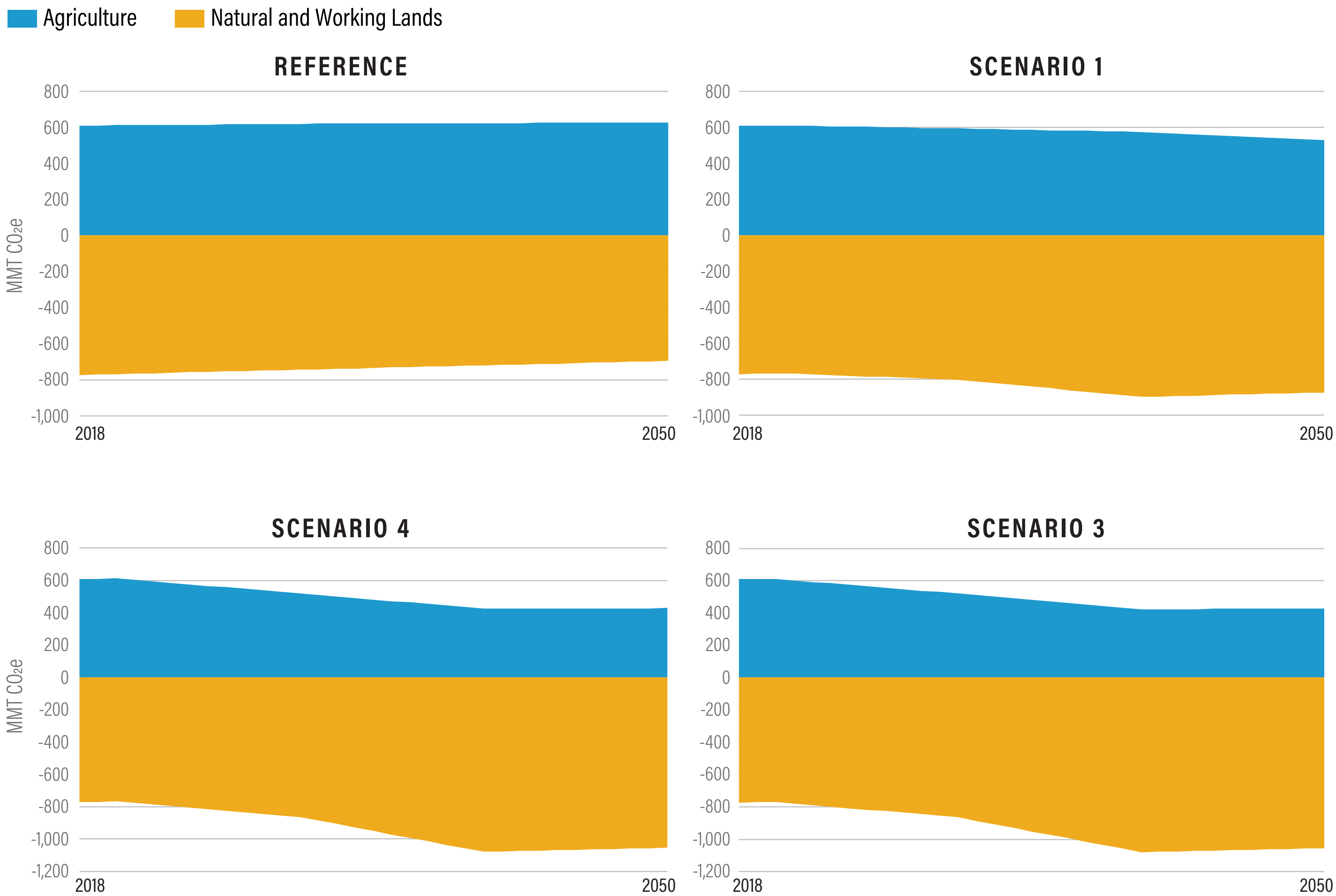
Increasing and protecting the U.S. land carbon sink are necessary complements to direct emissions reductions and technological carbon removal methods such as carbon capture and storage and direct air capture. In 2019, forests, grasslands, and soils offset 12 percent of U.S. emissions. Targeted investment in planting trees, preventing land use change, and mitigating wildfire risk to protect long-term forest carbon sequestration will be required to increase the land carbon sink and reach economy-wide net-zero goals. While agricultural soils can provide a net carbon sink if managed correctly, agriculture as a whole is responsible for approximately 9.5 percent of U.S. emissions. Reducing CO_2, CH_4, and N_2O emissions in this sector will be necessary to reach net zero by 2050.

Key Results

Key insights in the land sector assume that policies designed to increase the land carbon sink using tree-based pathways could plausibly result in increased carbon removals of 180–360 MMT CO_2e per year relative to the reference case (Mulligan et al. 2020). Agricultural emissions reductions, including non-CO_2 emissions reductions from livestock, combined with improved agricultural soil management could additionally cut non-CO_2 emissions and increase soil carbon sequestration, resulting in a net emissions reduction of 200 MMT CO_2e by 2040 (EPA 2019; USDA 2016; Mulligan et al. 2020). S1 assumes current programs will support achievement of 180 MMT CO_2e by 2040, accounting for a business-as-usual land sink degradation, with one-third of that by 2030. S2 and S3 assume that ambitious policy levers will deliver 360 MMT CO_2 per year by 2040 maintained through 2050, and 30 percent of that could be realized by 2030 (Figure 14). These assumptions are the basis for two key insights:

- **Aggressive protection and expansion of the land carbon sink (S2 and S3) will be required to approach net negative emissions by 2050.** Of potential actions to increase carbon sequestration in natural and working lands, tree-based pathways represent the greatest opportunity for natural carbon removal. These pathways, which include reforestation, restocking degraded forests, expanding adoption of agroforestry, and increasing urban tree cover, will require sustained, targeted investment to realize their full potential (Mulligan et al. 2020). Greater carbon sequestration in natural and working lands, alongside emissions reductions, could reduce the need for negative emissions technologies (NETs) in the future, while degradation of the land carbon sink could result in a greater need for NETs.
- **Emissions-reducing agricultural practices along with innovation in soil carbon management, could reduce net agricultural emissions by 32 percent over 2019 levels.** To achieve effective emissions reductions and to maximize agricultural soil carbon sequestration, soil carbon research as well as increased adoption of practices that decrease emissions from enteric fermentation, fertilizer use, and manure from confined animal feeding operations will need to be implemented in a cost-effective manner at scale.

Figure 14 | **Agriculture Emissions and Natural and Working Lands Removals, 2018–50**



Source: WRI authors and E3.

Key Building Blocks and Policy Insights

Without intervention, the land carbon sink is likely to degrade over time. As forests mature, they tend to sequester less carbon, and as climate change increases the instances of disease, drought, and wildfire, lands and forests will have less capacity to sequester carbon (Masson-Delmotte et al. 2021). Ambitious policy efforts and sizable investments are needed to prevent land sink degradation as well as increase sequestration. Federal policy can incentivize adoption of new practices on private lands and can support reforestation and climate-friendly management on state, local, tribal, and federal lands. Expanded research into the climate, food, and timber production impacts of climate-friendly agricultural and forestry practices is also needed.

Investment is necessary to scale up climate-friendly agriculture and forestry techniques. The upfront costs associated with adopting new climate-friendly practices or technologies, such as installing waste-to-energy biomass digesters to reduce methane emissions or establishing agroforestry systems, can present a barrier for landowners. Federal tax credits, cost-share or pay-for-performance programs, and provision of technical assistance through government agencies can help landowners overcome financial and knowledge obstacles. Federal investment is also needed to restock and reforest federal, state, local, and tribal land. A federal investment of $11 billion annually could realize carbon removal potential and provide myriad economic benefits to communities (Saha et al. 2021b).

Research and development are needed to better quantify climate impacts and to increase the scalability of nascent agricultural technologies. The amount by which management practices can sequester carbon in agricultural soils is highly uncertain and needs additional research and field testing (Searchinger and Ranganathan 2020). Across natural and working lands, improvements to greenhouse gas inventory methodologies are also necessary to inform policy and track the impact of land on net-zero targets. Some agricultural technologies—such as perennialized annual crops, which have the potential to sequester more carbon than traditional crops—will also require investment to develop and scale adoption of these crops.

5.6 Carbon Removal

Technological carbon removal will need to play a role in meeting decarbonization goals if direct mitigation measures and natural and working land sinks are not sufficient to reach net zero by 2050 (Mulligan et al. 2020). The production of hydrogen from waste biomass and the production and combustion of biofuels should be accompanied by CCS in order to maximize their decarbonization potential. Direct air capture (DAC) offers greater flexibility for deployment since it does not necessarily have to be co-located with fuel production or combustion, but its cost and energy requirements per ton of CO_2 sequestered present challenges to deployment. Achieving the modeled deployment level of technological carbon removal will require access to storage and pipeline infrastructure, therefore identifying, verifying, and demonstrating geological saline storage opportunities will be crucial to the development of CCS and DAC projects.

Key Results

Bioenergy with carbon capture and storage (BECCS) related to ethanol refining offers near-term opportunities for technological carbon removal by 2025, while DAC and hydrogen BECCS take longer to reach widespread deployment and are only used under strong policy incentives in S3. Our analysis reveals the following key insights:

- **Existing tax incentives do not drive technological carbon removal in the RS.** CCS and DAC continue to be unutilized in the RS, resulting in 0 tons of removal through 2050.
- **Enhanced and extended tax credits in S1 and S2 drive 39 MMT of carbon dioxide removal in ethanol production by 2030, remaining at this level through 2050.** Incentive levels for 45Q were kept at current levels, which only allow for economic deployment of CCS in ethanol refining, natural gas production, and ammonia production.
- **DAC sees zero deployment in the RS, S1, and S2, while in S3 65 MMT CO_2 is stored via DAC by 2050 to offset remaining fossil fuel emissions.** This DAC deployment requires 100 TWh of electricity, or approximately 1.5 TWh per MMT CO_2 removed.
- **CCS in S3 is driven by BECCS hydrogen production and by requiring cement and iron and steel manufacturers to employ CCS to capture process emissions.** Optimized fuel consumption in S3 results in 505 MMT CO_2 removal linked to BECCS H_2 production by 2050. Hydrogen production from biomass coupled with CCS is assumed to remove twice as much carbon as biomethane production from biomass per dollar spent.

Key Building Blocks and Policy Insights

Meeting a net-zero target by 2050 will require technological carbon removal if mitigation options and natural sequestration do not exceed projected abatement capacity. In this case, DAC will play an essential role in offsetting emissions from remaining fossil fuel consumption, and CCS will be crucial to eliminating process emissions in cement and other heavy manufacturing. Our results suggest the following insights about the main policy building blocks for this sector:

In order to incentivize significant industrial CCS and DAC deployment, tax credits greater than the current 45Q level of $50 per ton of CO_2 removed should be made available. The current incentive levels do not drive significant development of CCS or DAC projects in the power sector or in the industrial sector as they are insufficient to facilitate cost recovery. Extending the tax credit for longer than the current 12 years can also increase the financial feasibility of projects and drive greater levels of private sector investment in such projects.

An economy-wide emissions cap, or a cap on industrial emissions specifically, and a low-carbon fuel standard together can drive clean hydrogen production and CCS. Hydrogen production from waste or sustainable biomass combined with CCS results in negative emissions while not impacting the electric grid. In contrast, hydrogen production from carbon-free electricity is a flexible grid resource that can limit curtailment of renewable energy resources. The relative resource potential and cost of these two technologies will determine their relative scales of deployment.

A clean energy standard, in the absence of an explicit or implicit price on carbon, proved necessary in our policy scenarios in order to encourage significant technological carbon removal in the power sector. Tax credits alone did not provide power companies with sufficient incentive to develop CCS or DAC projects.

6. CONCLUSIONS

Our analysis provides evidence that the United States must dramatically enhance its use of policy measures to achieve the goal of a 50–52 percent emissions reduction, compared to 2005 levels, by 2030 and net-zero emissions by 2050. Our modeling results suggest that current levels of tax credits, funding for clean energy research, project development, and financial assistance for consumer-focused programs at the federal, state, and city levels result in only a 34 percent reduction in total GHG emissions by 2050 (RS).

Extending these existing policy measures and layering on enhanced spending and infrastructure packages could get the United States to 50 percent emissions reductions by 2050 in S1. The further introduction of tax credits to cover other low-carbon technologies for which tax credits are not currently available results in a 63 percent reduction in emissions by 2050 in S2. This highlights the important role that tax credits can play in incentivizing the deployment of a suite of low-carbon technologies.

At the same time, our modeling results suggest that in order to reach net-zero emissions in 2050, sector-specific performance standards such as a clean electricity standard and strict emissions standards for the transportation sector must be employed. They become all the more important in the absence of an economy-wide carbon pricing mechanism.

Furthermore, remaining emissions in hard-to-mitigate sectors will need to be offset by enhanced natural and working land sinks and negative emissions technologies. Technological carbon removal will become especially important if direct mitigation measures and natural and working land sinks are not sufficient to reach net zero by 2050.

A comprehensive policy package aimed at achieving U.S. decarbonization goals must also address the slow stock turnover of fossil fuel equipment in all sectors, the trade exposure of emissions-intensive manufactured products, improving tax credit design to maximize decarbonization impact, and transmission and storage challenges associated with a clean electricity grid, among other things.

Finally, the costs of fully decarbonizing the U.S. economy are not prohibitive. Our modeling results suggest that achieving economy-wide, net-zero emissions under reference oil and gas prices only costs $40 billion more than the Reference Scenario in 2030, representing 0.2 percent of U.S. GDP, and actually saves $113 billion by 2050 (or 0.3 percent of GDP) relative to the RS. This potential for cost savings in the long run demonstrates the importance of decarbonizing the economy with effective and efficient policies.

Follow-on work (coming in 2022) to the modeling results presented in this working paper includes estimating the economic benefits accruing from the three policy scenarios, including a discussion of equity considerations in the design of policies.

TECHNICAL APPENDICES

Appendix A. Overview of PATHWAYS and RESOLVE

Estimates of U.S. energy demand, supply, and emissions reductions from 2018 through 2050 under the Reference Scenario and three mitigation scenarios were derived from E3's PATHWAYS and RESOLVE models. These models utilize inputs such as projections of fuel prices, cost- and performance-related characteristics of energy supply- and demand-side infrastructure, and sales share of new devices (e.g., vehicles and building appliances) to provide outputs like annual energy demand and emissions by fuel type, stocks and sales of energy-consuming devices, and electricity supply infrastructure for each simulated year.

PATHWAYS

PATHWAYS is a bottom-up infrastructure model that tracks direct energy use and associated greenhouse gas (GHG) emissions for sectors including buildings, transportation, industry, and fuels production in user-defined policy and market adoption scenarios across nine census divisions in the United States. The model also tracks non-combustion-related emissions and sequestration from agriculture, industrial processes, natural gas and oil systems, waste management, coal mining, and natural and working lands.

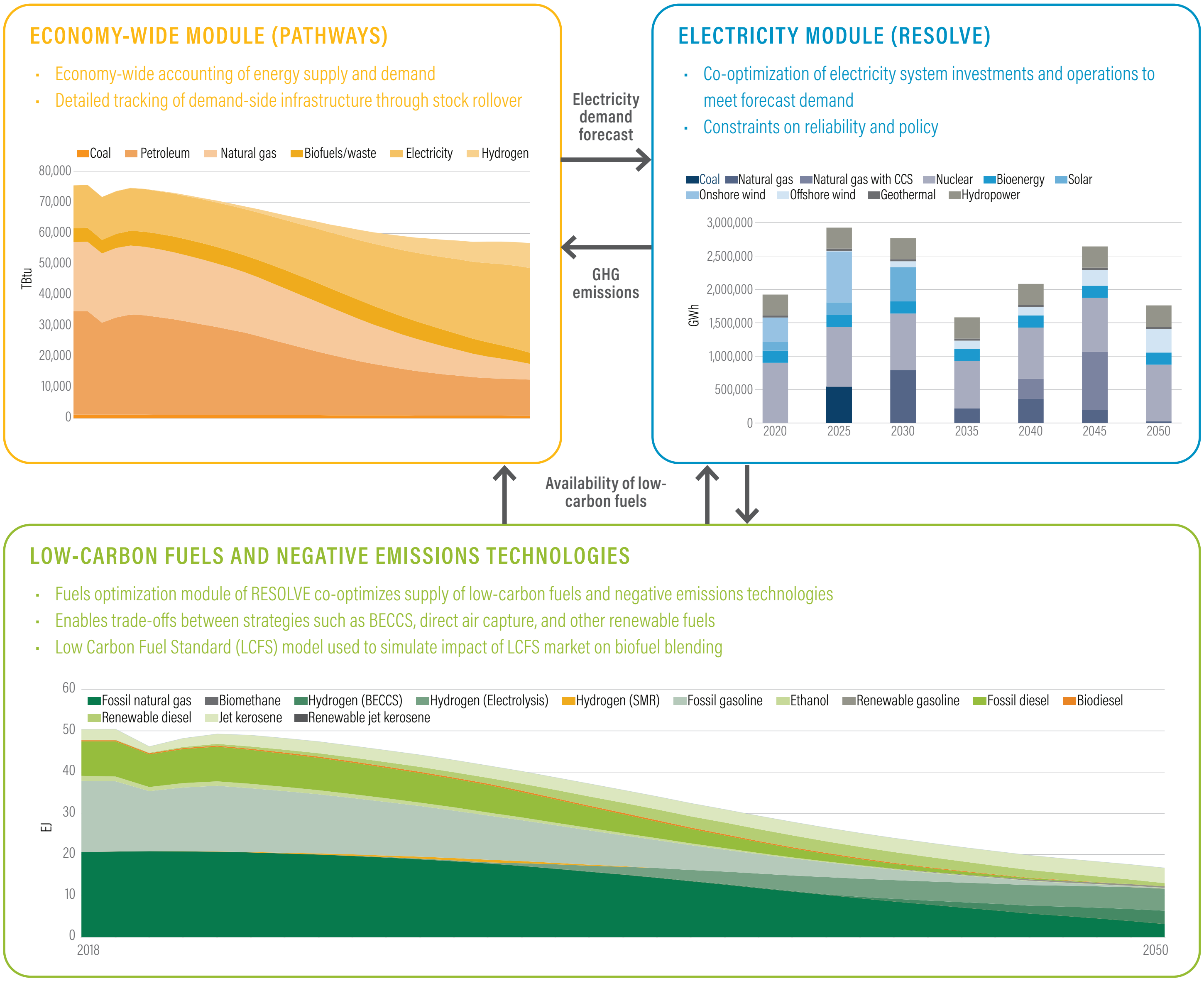
PATHWAYS relies on two approaches: a "stock rollover" approach and a "total energy" approach. The "stock rollover" approach characterizes stock turnover in major equipment and infrastructure categories like buildings and transportation fleets, accounting for the different lifetimes of energy-consuming devices and technologies and changes in performance through drivers like energy efficiency improvements. The "total energy" approach specifies energy consumption by fuel in each simulated year, accounting for scenario-specific assumptions that specify energy efficiency improvements, potential for electrification, and potential for transitioning to low-carbon fuel consumption from fossil fuel combustion.

As shown in Table A2, PATHWAYS uses a "stock rollover" approach for 12 residential building subsectors (e.g., space heating, water heating, lighting), 10 commercial building subsectors, and 5 transportation subsectors (e.g., light-duty automobiles, heavy-duty trucks, buses). For such subsectors, this approach tracks changes in annual sales of new devices, device stocks, and energy demand and emissions as new devices are added and old infrastructure and devices are replaced or retired in each simulated year. For other energy-consuming sectors, such as industry, oil and gas, and waste, PATHWAYS employs the "total energy" approach. Table A3 provides key data sources used to develop inputs for the PATHWAYS model.

RESOLVE

The PATHWAYS model is linked to the power sector and low-carbon fuels supply models as shown in Figure A1. RESOLVE—E3's power sector model—characterizes resources including natural gas, renewable energy, and energy storage among others across the 18 regions shown in Table A1 by fixed and operating costs, technical potential, and performance-related factors. Utilizing electricity demand projections from PATHWAYS, RESOLVE is a capacity expansion model that uses linear optimization to co-optimize investments and operations and choose resources to meet electric load and power system needs reliably, accounting for electric sector GHG emissions or clean energy targets. RESOLVE simulates operations for a subset of representative days (e.g., a typical day for each month of the year), incorporating seasonal and hourly balancing challenges into investment decisions. While RESOLVE's optimization capabilities enable it to choose from a wide range of new resources, it can also retire existing resources that are uneconomical. Additionally, RESOLVE uses a low-carbon fuels module that matches available low-carbon fuels with least-cost conversion processes to co-optimize the supply of low-carbon fuels and negative emissions technologies for energy demand and electricity supply. Figure A2 shows RESOLVE's transmission topology, and Table A4 describes key features of the RESOLVE model.

Figure A1 | **Overview of E3's PATHWAYS and RESOLVE Models**

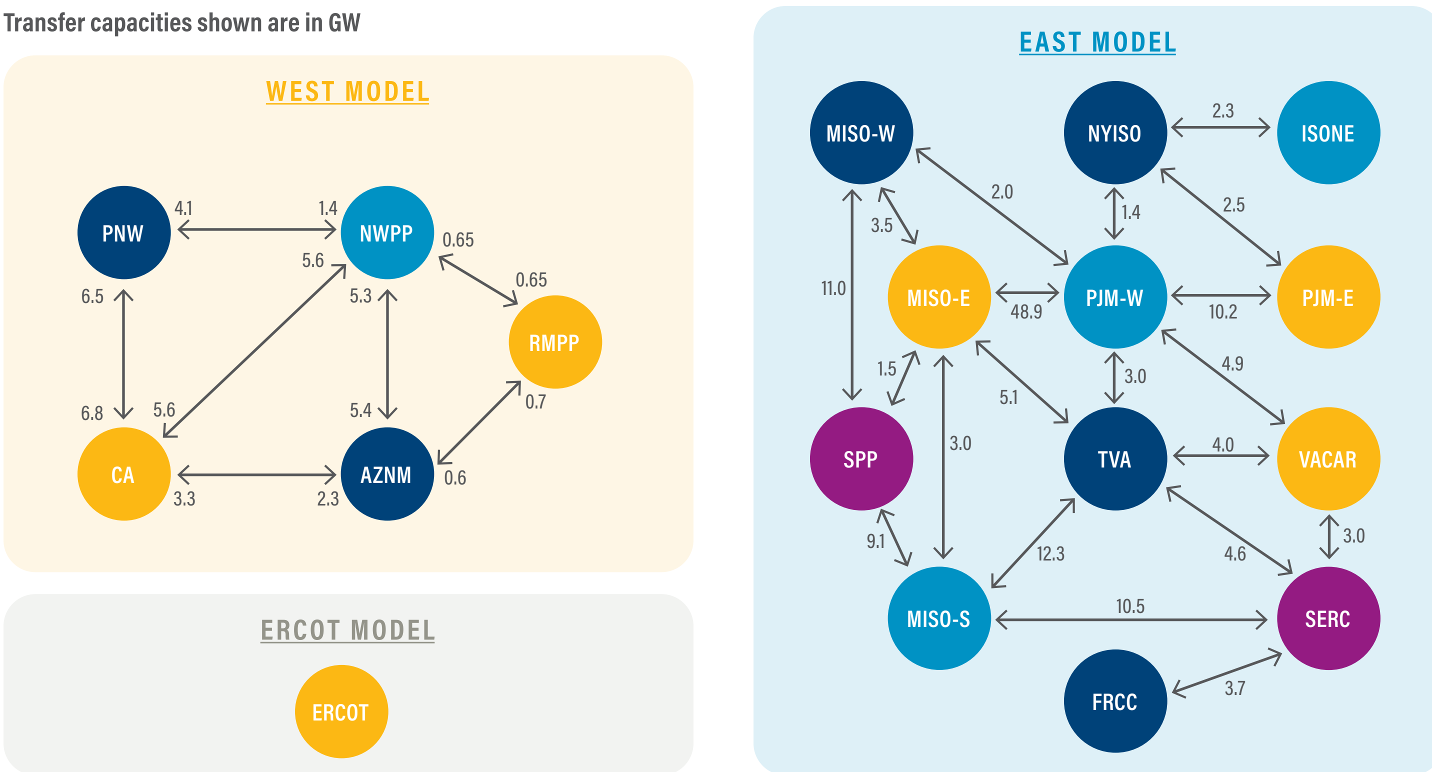


Note: BECCS = bioenergy with carbon capture and storage; EJ = exajoules; GHG = greenhouse gas; GWh = gigawatt-hours; TBtu = trillion British thermal units.

Table A1 | **U.S. Power System Regions in RESOLVE**

RESOLVE REGION:	CORRESPONDING CENSUS DIVISION IN PATHWAYS:
Arizona–New Mexico (AZNM)	Mountain
California Independent System Operator (CAISO)	Pacific
Electric Reliability Council of Texas (ERCOT)	West South Central
Florida Reliability Coordinating Council (FRCC)	South Atlantic
Independent System Operator New England (ISONE)	New England
Midcontinent Independent System Operator–East (MISO-E)	East North Central
Midcontinent Independent System Operator–South (MISO-S)	East South Central
Midcontinent Independent System Operator–West (MISO-W)	West North central
Northwest Power Pool (NWPP)	Mountain
New York Independent System Operator (NYISO)	Middle Atlantic
Pennsylvania, New Jersey, Maryland–East (PJM-E)	Middle Atlantic
Pennsylvania, New Jersey, Maryland–West (PJM-W)	Middle Atlantic
Pacific Northwest (PNW)	Pacific
Rocky Mountain Power Pool (RMPP)	Mountain
Southeastern Electric Reliability Council (SERC)	South Atlantic
Southwest Power Pool (SPP)	West South Central
Tennessee Valley Authority (TVA)	East South Central
Virginia–Carolinas (VACAR)	South Atlantic

Figure A2 | **Transmission Topology in RESOLVE**



Note: GW = gigawatts; AZNM = Arizona–New Mexico; CA = California; ERCOT = Electric Reliability Council of Texas; FRCC = Florida Reliability Coordinating Council; ISONE = Independent System Operator New England; PJM-E = Pennsylvania, New Jersey, Maryland (etc.); MISO-E = Midcontinent Independent System Operator–East; MISO-S = Midcontinent Independent System Operator–South; MISO-W = Midcontinent Independent System Operator–West; NWPP = Northwest Power Pool; NYISO = New York Independent System Operator; PNW = Pacific Northwest; RMPP = Rocky Mountain Power Pool; SERC = Southeastern Electric Reliability Council; SWP = Southwest Power Pool; TVA = Tennessee Valley Authority; VACAR = Virginia-Carolinas.

Table A2 | **Key Modeling Assumptions and Data Sources for PATHWAYS Energy Demand Sectors**

SECTOR	SUBSECTOR	MODELING APPROACH	BENCHMARKING DATA SOURCES	REFERENCE SCENARIO ASSUMPTIONS
Residential	Residential Building Shell	Stock rollover	Energy Information Administration (EIA) Residential Energy Consumption Survey (RECS) 2015, EIA State Energy Data System (SEDS) 2018	Grow stocks with households growth rate
	Residential Central Air Conditioning			Grow stocks with households growth rate, appliance stock share changes based on Annual Energy Outlook (AEO) reference case
	Residential Room Air Conditioning			
	Residential Dishwashing			
	Residential Freezing			
	Residential Reflector Lighting			
	Residential Clothes Washing			
	Residential General Service Lighting			
	Residential Exterior Lighting			
	Residential Linear Fluorescent Lighting			
	Residential Refrigeration			
	Residential Clothes Drying			
	Residential Cooking			
	Residential Water Heating			
	Residential Single-Family Space Heating			
	Residential Multifamily Space Heating			
	Residential Other	Total energy by fuel	SEDS 2018	Grow demand with households growth rate
Commercial	Commercial Air Conditioning	Stock rollover	EIA Commercial Building Energy Consumption Survey (CBECS) 2012, SEDS 2018	Grow demand with commercial square footage growth rate, appliance stock share changes based on AEO reference case
	Commercial High-Intensity Discharge Lighting			
	Commercial Linear Fluorescent Lighting			
	Commercial General Service Lighting			
	Commercial Refrigeration			
	Commercial Ventilation			
	Commercial Cooking			
	Commercial Water Heating			
	Commercial Space Heating			
	Commercial Other	Total energy by fuel	SEDS 2018	Grow demand with commercial square footage growth rate based on AEO reference case

Table A2 | **Key Modeling Assumptions and Data Sources for PATHWAYS Energy Demand Sectors (Cont'd)**

SECTOR	SUBSECTOR	MODELING APPROACH	BENCHMARKING DATA SOURCES	REFERENCE SCENARIO ASSUMPTIONS
Industrial	Industry Agriculture	Total energy by fuel	EIA Manufacturing Energy Consumption Survey (MECS) 2014, SEDS 2018, EIA Natural Gas Annual (NGA) 2018, EIA Annual Refinery Report (ARR) 2019	Subsector-specific growth rates by fuel based on AEO reference case
	Industry Aluminum			
	Industry Cement and Lime			
	Industry Chemicals			
	Industry Construction			
	Industry Food			
	Industry Glass			
	Industry Iron and Steel			
	Industry Metal-Based Durables			
	Industry Mining and Upstream Oil and Gas			
	Industry Other Manufacturing			
	Industry Paper			
	Industry Plastics			
	Industry Refining			
	Industry Wood			
Transportation	Transportation Light-Duty Vehicle (LDV) Cars	Stock rollover	EPA MOVES Onroad Technical Reports (MOVES) 2016, FHWA Highway Statistics Series (FHWA) 2018, SEDS 2018	Vehicle miles traveled growth rates and vehicle stock share changes from AEO reference case (discussed further in Appendix B)
	Transportation LDV Trucks			
	Transportation Medium-Duty Vehicles			
	Transportation Heavy-Duty Vehicles			
	Transportation Buses			
	Transportation Aviation	Total energy by fuel	SEDS 2018	Aviation fuel demand growth rate from AEO reference case
	Transportation Other			Other transportation fuel demand growth rate from AEO reference case

Table A3 | PATHWAYS Benchmarking Data Sources

SOURCE	DATA YEAR
Energy Information Administration (EIA) State Energy Data System	2018
EIA Residential Energy Consumption Survey	2015
EIA Commercial Building Energy Consumption Survey	2012
EIA Manufacturing Energy Consumption Survey	2014 (some preliminary 2018 data available)
EIA Natural Gas Annual	2018
EIA Annual Refinery Report	2019
EPA MOVES Onroad Technical Reports	2016
FHWA Highway Statistics Series	2018
EIA Annual Energy Outlook	2020

Table A4 | RESOLVE Power Sector Reference Scenario Assumptions

CATEGORY	ASSUMPTIONS

Existing Resources	▪ Model relies on proprietary E3 database of existing resources and planned retirements, current as of early 2020.
	▪ Modeled resources include the following:
	  ▪ Natural gas generation: simple cycle combustion turbines (CTs), combined cycle gas turbines (CCGTs), CCGTs with carbon capture and storage (CCS only modeled in policy scenarios and modeling assumed CCS as new build)
	  ▪ Renewable generation: solar PV, onshore wind, offshore wind
	  ▪ Energy storage: lithium-ion battery storage (>= 4 hours), flow batteries
	  ▪ Additional resource options: advanced nuclear or nuclear small modular reactors (SMRs), blending hydrogen into gas generators (model allows hydrogen to be burned in gas generators—assuming new gas generators are built to accommodate hydrogen by 2050—and model does not conduct detailed economic comparisons of blending hydrogen in new CTs versus burning hydrogen exclusively as it does not model specific units)
	▪ Each resource has the following characteristics:
	  ▪ Fixed costs (capital, interconnection, fixed operations and maintenance (O&M), financing, taxes) and operating costs (fuel costs, carbon pricing, variable O&M)
	  ▪ Potential (technical or other limits on developable potential)
	  ▪ Performance (operating characteristics, including operating constraints, hourly profiles, and capacity contributions)

Load Forecast	▪ Based on economy-wide PATHWAYS modeling for Reference Scenario and each policy scenario. Energy efficiency, load electrification, and other load modifier categories are included in load forecasts.
Resource Prices	▪ 2020 National Renewable Energy Laboratory Annual Technology Baseline and Regional Energy Deployment System data supplemented with E3 Research (includes investment tax credit and production tax credit).
Fuel Prices	▪ Gas: E3 forecast based on New York Mercantile Exchange forwards and Energy Information Administration (EIA) futures as of 2020. ▪ Coal, uranium: Forecast based on EIA Annual Energy Outlook (AEO) 2020 and SNL contracts.

Table A4 | **RESOLVE Power Sector Reference Scenario Assumptions (Cont'd)**

CATEGORY	ASSUMPTIONS
Storage and Offshore Wind Targets	▪ State-level mandates and targets are included. Near-term (2025) mandated capacity is lower than the targets, which is expected because of current build trends. By 2030, mandates are back on track.
Economic Retirements	▪ Model allows coal, gas, and oil resources to retire half their capacity by 2025 and all capacity by 2030 if the going-forward costs are greater than benefits provided to system.
Nuclear	▪ Model keeps all nuclear online until it is up for relicensing, then allows retirement if economical.
Transmission	▪ Transmission limits between regions from proprietary database. No transmission connection between East, West, or Electric Reliability Council of Texas assumed in the model.
Reliability Accounting	▪ Planning reserve margin (PRM) for regions based on North American Electric Reliability Corporation Reliability Assessment (about 15% PRM for most zones).

Appendix B. Reference Scenario Assumptions

Key Drivers and Assumptions

Table B1 summarizes assumptions for key drivers of energy demand, supply, and emissions under the Reference Scenario (RS). Our RS generally follows the reference case in the Annual Energy Outlook (AEO) 2020 of the Energy Information Administration (EIA). However, near-term adjustments were made to total vehicle miles traveled (VMT) and aviation fuel demand to account for the impacts of COVID-19 on energy consumption and emissions. As shown in Figure B1, total VMT drops by 12 percent in 2020 compared to 2019, while aviation fuel demand is 41 percent lower in 2020 relative to 2019 levels. These declines in 2020 and multiyear recovery to business-as-usual levels for both categories were based on data from the EIA's Short-Term Energy Outlook report from September 2020.

Table B1 | **Reference Scenario Key Drivers and Assumptions**

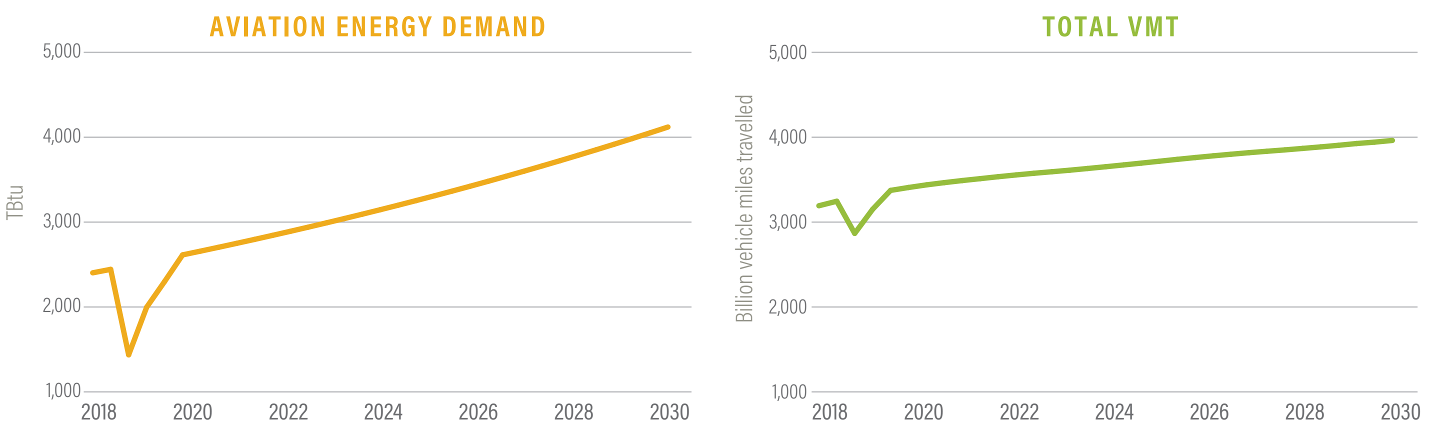
SECTOR	DRIVER	2020–50 COMPOUND ANNUAL GROWTH RATE
Economy-wide	Population	0.5%
	Real gross domestic product	1.9%
Buildings	Households	0.6%
	Commercial square footage	1.0%
	Heating degree days	–0.5%
	Cooling degree days	0.8%
Transportation	Total vehicle miles traveled	0.7%
Industry	Industrial fuel use	0.7%

In addition to COVID-19 adjustments, some additional assumptions were modified from the 2020 AEO to reflect existing trends and economics for some sectors. In the transportation sector, the 2020 AEO assumes that light-duty vehicle (LDV) electric vehicles (EVs) achieve a national market share of around 13 percent by 2050, but based on announced state targets, state zero-emissions vehicle programs, and BNEF's EV Outlook 2020, LDV EVs achieve a national market share of 36 percent by 2050 in the Reference Scenario (Figure B2). In the buildings sector, while the 2020 AEO assumes building shell improvements consistent with 100 percent sales of efficient building shells by 2040 in the PATHWAYS model, this assumption was relaxed to a constant 40 percent to match the share of population in states that have adopted the 2018 International Energy Conservation Code.

Included Policies and Assumptions

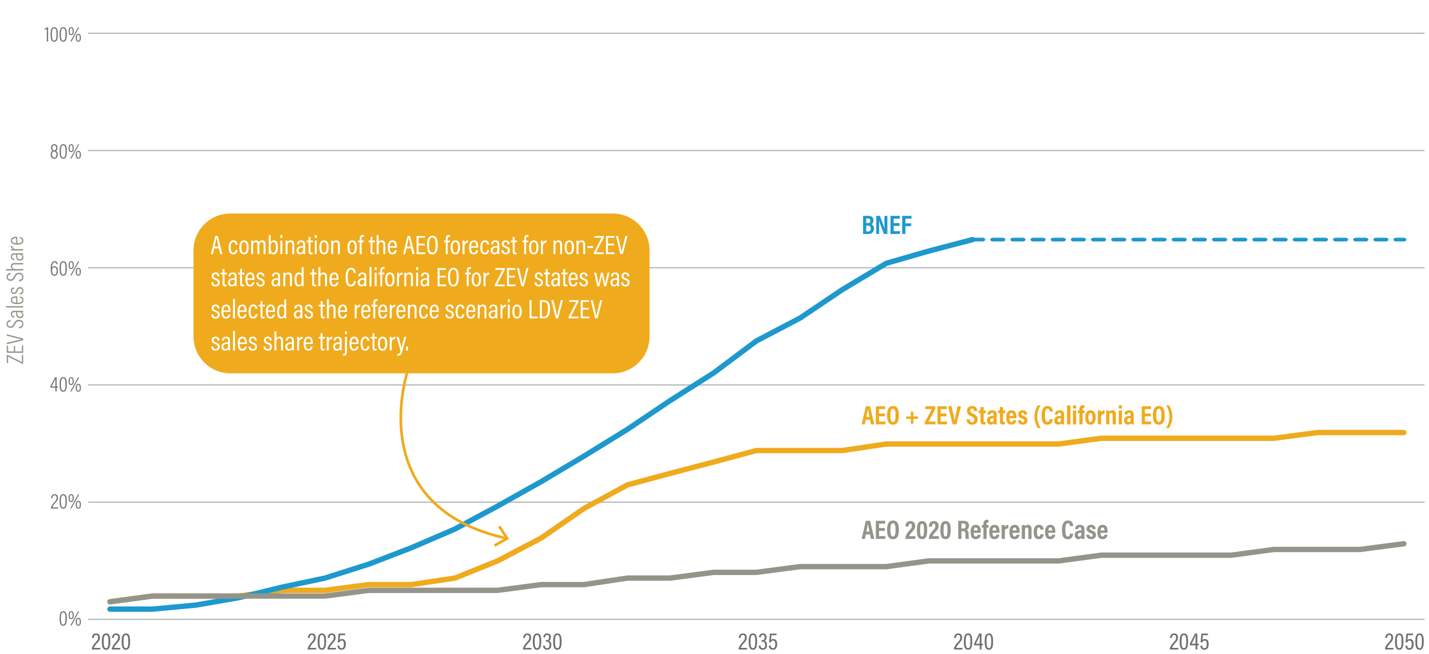
The Reference Scenario accounted for existing federal policies supporting clean energy and low-carbon technology deployment in different sectors. These included policies like the production tax credit and investment tax credit in the power sector and tax credits for plug-in electric vehicles in the transportation sector, among others. This scenario also incorporated binding state-level actions, such as Renewable Portfolio Standard targets and announced zero-emissions vehicle targets. Table B2 describes federal and state policy assumptions and how they are implemented in PATHWAYS and RESOLVE.

Figure B1 | **COVID-19 Adjustments in the Reference Scenario**



Note: TBtu = trillion British thermal units; VMT = vehicle miles traveled.

Figure B2 | **LDV Zero-Emissions Vehicle (ZEV) Sales Trajectory in the Reference Scenario**



Note: AEO = Annual Energy Outlook; BNEF = Bloomberg New Energy Finance; CARB = California Air Resources Board; EO = executive order; LDV = light-duty vehicle; ZEV = zero-emissions vehicle.

Table B2 | **Key Federal and State Policy Assumptions in the Reference Scenario**

SECTOR	REFERENCE SCENARIO ASSUMPTIONS	MODELING IMPLEMENTATION
Power	**STATE**	
	■ Existing state Renewable Portfolio Standard (RPS) targets, including technology-specific carve-outs and mandates.	■ Weighted average of state RPS targets by zone (no utility targets in reference case). Assumptions from Database of State Incentives for Renewables (as of September 2020).
	■ California Cap and Trade Program, Regional Greenhouse Gas Initiative (RGGI).	■ Carbon price impacts investment and operations decisions. California price based on California Energy Commission Integrated Energy Policy Report forecast; RGGI price based on average floor and ceiling price trajectories.
	FEDERAL	
	■ Investment tax credit available for solar, batteries, and offshore wind (30% in 2020, 26% in 2025, 10% in 2030–50).	■ Modeled as reduction in capital investment (solar/batteries: 30% in 2020, 26% in 2025, 10% in 2030–50; offshore wind: 30% in 2020–25, expires after 2025).
	■ Production tax credit available for new onshore wind resources, expiring after 2035 (modeled as reduction in capital investment based on assumed production: $23/MWh in 2020, $14/MWh in 2025, $0 in 2030–50).	■ Modeled as reduction in capital investment based on assumed production: $23/MWh in 2020, $14/MWh in 2025, $0 in 2030–50.
	■ License extensions and economic retirements of existing nuclear facilities.	■ All units can be relicensed at the end of current license period, but model can also retire them if not economical.
	■ Planned retirements and economic retirements of existing fossil energy facilities.	■ Economic retirements allowed (up to 50% of current capacity can retire by 2025).
Transportation	**STATE**	
	■ California Low-Emission Vehicle Program (zero-emissions vehicle [ZEV] states assumed to meet minimum requirements from California Air Resources Board [CARB] ZEV program and Executive Order transitioning to 100% sales of ZEV light-duty vehicles [LDVs] by 2035).	■ Battery-electric, plug-in hybrid electric, and hydrogen fuel cell vehicle adoption from Annual Energy Outlook (AEO) reference case used as input for non-ZEV states, while current ZEV states are assumed to meet minimum requirements from CARB ZEV program and California EO transitioning to 100% sales of ZEV LDVs by 2035.
	FEDERAL	
	■ LDV Combined Corporate Average Fuel Economy (CAFE) Standards (extended through 2026). ■ Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles. ■ Existing $7,500 tax credit with manufacturer cap (200,000 vehicles per manufacturer).	■ Existing average on-road efficiencies and new internal combustion vehicle efficiencies from National Energy Modeling System (NEMS) used as inputs. ■ Tax credits explicitly modeled outside PATHWAYS to estimate adoption impacts. Tax credits were applied to vehicle capital costs in the vehicle adoption model; the adoption model estimates vehicle adoption trajectories based on consumer economics metrics and least-cost economics.

Table B2 | **Key Federal and State Policy Assumptions in the Reference Scenario (Cont'd)**

SECTOR	REFERENCE SCENARIO ASSUMPTIONS	MODELING IMPLEMENTATION
Buildings	**FEDERAL**	
	■ Existing efficiency standards and incentives for building upgrades and efficient appliances.	■ Building equipment efficiencies from NEMS used as inputs. ■ Building shell efficiency penetration. ■ Sales of efficient building equipment, aligned with AEO reference case. ■ AEO fuel prices used as inputs.
Industry and Carbon Capture and Storage	**STATE**	
	■ California Assembly Bill 32: Emissions Cap-and-Trade.	
	FEDERAL	
	■ Industrial equipment efficiency standards for boilers, furnaces, electric motors, etc. ■ Section 45Q investment tax credit for carbon capture and storage.	■ Initial fuel demand and annual growth rates for each fuel aligned with AEO reference case outputs for three subsectors: ■ Manufacturing ■ Oil and gas ■ Other ■ AEO fuel prices used as inputs.
Fuels	■ California and Oregon Low Carbon Fuel Standard (LCFS).	■ LCFS market explicitly modeled to account for impact of electrification.
Non-CO_2	■ National hydrofluorocarbon (HFC) phasedown in line with the Kigali Amendment. ■ New Source Performance Standards (NSPS) methane regulations.	■ Phasedown of HFCs according to Kigali Amendment. ■ Reductions in fugitive emissions according to NSPS regulations.

Appendix C. Mitigation Scenario Assumptions

Scenarios 1–3 (S1–S3) built on the Reference Scenario by incorporating additional measures directed toward scaling up deployment of existing cost-effective technologies over the next decade and encouraging innovation of emerging clean energy technologies needed in later decades. S1 focused on the extension of existing tax incentives along with increases in spending programs that target infrastructure to help drive early adoption of clean energy and energy efficient technology required to kick-start broader sector transformation. S2 included the addition of advanced tax credits and other novel incentives requiring federal spending to drive broader adoption compared to existing incentives and increase the pace of deployment of clean energy and energy efficient technology. S3 included the addition of stringent sector-specific performance standards and economy-wide emissions cap that drive the sector-level transformation required to achieve net-zero emissions by 2050 across the economy. Tables C1–C6 describe key policy assumptions for these mitigation scenarios and their implementation in PATHWAYS and RESOLVE.

Tax credits for electric vehicle (EV) and heat purchase were modeled explicitly outside of PATHWAYS to estimate adoption impacts as shown in Figures C1 and C2. For heat pumps, the available tax credit was applied to the upfront capital cost, and adoption estimates were derived from an adoption S-curve based on a Bass diffusion model, which estimates the share of customer-deciders choosing to electrify based on estimated payback periods. The pace of adoption is determined by year-to-year changes in economics, while the adoption rate is determined by the economic payback in the previous year, with adoption accelerating if economics substantially improve. A similar modeling framework was implemented for EV tax credits. The available tax credit was applied to the upfront cost of an EV, and adoption estimates were calculated from a similar adoption S-curve based on the Bass diffusion model.

Table C1 | **Overview of Power Sector Policy Assumptions and Modeling Implementation for Scenarios 1–3**

CATEGORY	SCENARIO 1	SCENARIO 2	SCENARIO 3
Renewables	**POLICIES**		
	30% investment tax credit (ITC) extended through 2035 for all zero-carbon technologies, drops to 10% through 2050.	40% ITC 2020–50 for advanced nuclear, carbon capture and storage (CCS), and flow batteries and 30% ITC for transmission. Same as Scenario 1 for other zero-carbon technologies.	Same as Scenario 2. + Clean Electricity Standard (CES) of 80% reduction by 2030 and 100% by 2035.
	IMPLEMENTATION IN RESOLVE		
	ITC modeled as reduction in capital investment.	Same as Scenario 1.	CES modeled to provide credit for generation based on emissions intensity relative to the highest-emitting resource on the system (coal). This target for the standard is modeled like a Renewable Portfolio Standard—a percentage of retail sales. Solar, wind, hydro, biomass or biogas, geothermal, nuclear, and CCS receive full credit, while gas generators receive partial credit (gas combined cycles have a higher partial credit [61%] because they are more efficient; gas steam turbines have a lower partial credit [48%] because they are less efficient; gas combustion turbines have the lowest partial credit [42%] because they are the least efficient gas plant).

Table C2 | **Overview of Transportation Sector Policy Assumptions and Modeling Implementation for Scenarios 1–3**

CATEGORY	SCENARIO 1	SCENARIO 2	SCENARIO 3
Light-Duty Vehicles	**POLICIES**		
	$7,500 tax credit (manufacturer cap removed) through 2030. Section 30C infrastructure incentives through 2035. Corporate Average Fuel Economy (CAFE) standards extended through 2026.	$10K total incentives from electric vehicle (EV) credit and retirement voucher through 2035, $5K retirement voucher post-2035. Section 30C infrastructure incentives through 2035. Same as Scenario 1 for CAFE standards.	Tax credits same as Scenario 2 through 2034 + 100% zero-emissions tailpipe standard by 2035. CAFE improvements (5% annual increase in light-duty vehicle (LDV) fuel economy for model year [MY] 2027–31).
	IMPLEMENTATION IN PATHWAYS		
	Tax credits explicitly modeled outside PATHWAYS to estimate adoption impacts. Tax credit is applied to vehicle capital costs in vehicle adoption model that estimates adoption trajectories based on consumer economics metrics and least-cost economics. LDV fuel economy improves through 2026, then constant.	Same as Scenario 1.	Share of battery electric vehicles (BEVs) in LDV sales reaches 75% by 2030 and 100% by 2040 in Scenario 3. 5% annual increase in LDV fuel economy from MY 2027 through MY 2031.
Medium-and Heavy-Duty Vehicles	**POLICIES**		
	Advanced Clean Trucks rule in California.	Same as Scenario 1. + $7,250 credit for medium-duty vehicle (MDV) EVs and $13,750 for heavy-duty vehicle (HDV) EVs through 2050. $20,000 credit for MDV fuel cell electric vehicles (FCEVs) through 2050 and $40,000 through 2030 and $31,000 from 2031 through 2050 for HDV FCEVs.	Tax credits same as Scenario 2 through 2039 + 100% zero-emissions tailpipe standard by 2040.
	IMPLEMENTATION IN PATHWAYS		
	Share of BEVs in MDV sales reaches 14% by 2030 (27% by 2050) and share of BEVs in HDV sales reaches 8% by 2030 (stays at 8% by 2050). Share of FCEVs in MDV sales is 0% sales by 2030 and 2% by 2050 and share of FCEVs in HDV sales is 3% by 2030 and 7% by 2050.	Tax credits explicitly modeled outside PATHWAYS to estimate adoption impacts. Tax credit is applied to vehicle capital costs in vehicle adoption model that estimates adoption trajectories based on consumer economics metrics and least-cost economics.	Share of zero-emissions vehicles (ZEVs) in MDV sales reaches 29% by 2030 and 100% by 2050, while ZEVs represent 11% of HDV sales by 2030 and 100% by 2050 in Scenario 3.

Table C3 | **Overview of Buildings Sector Policy Assumptions and Modeling Implementation for Scenarios 1–3**

CATEGORY	SCENARIO 1	SCENARIO 2	SCENARIO 3
Building Shell Efficiency	**POLICIES**		
	State Energy Efficiency and Insulation rebate and weatherization spending Building Code Adoption Incentives Extension for 25C Energy Property Tax Credit. S2137 Energy Savings and Industrial Competitiveness Act to accelerate states, tribal areas, and territories to review and adopt latest codes, 2018 IECC and ASHRAE 90.1. 45L EE Home Credit. 179D Commercial Property Energy Efficiency Credit through 2030.	Same as Scenario 1.	Same as Scenario 1.
	IMPLEMENTATION IN PATHWAYS		
	75% sales of high-efficiency building shells by 2040.	Same as Scenario 1	Same as Scenario 1
Appliance Efficiency	**POLICIES**		
	25C Energy Property Tax Credit extension	Same as Scenario 1	Same as Scenario 1
	IMPLEMENTATION IN PATHWAYS		
	100% sales of high-efficiency appliances by 2030.	Same as Scenario 1	Same as Scenario 1
Residential Space Heating and Commercial Space Heating	**POLICIES**		
	No additional policies.	Residential energy-savings dependent tax credit for electrification ($5,000 tax credit per household for heat pump purchase) through 2050. Commercial System size dependent tax credit ($100/ton of cooling capacity) through 2030.	Modeled tax credit adoption through 2030, phase out all fossil fuel devices by 2040
	IMPLEMENTATION IN PATHWAYS		
		Tax credits explicitly modeled outside PATHWAYS to estimate adoption impacts. Tax credit is applied to heat pump capital costs in heat pump adoption model that estimates adoption trajectories based on consumer economics metrics and least-cost economics.	41% electric heat pump sales by 2030 and 85% by 2050 (remainder electric resistance and wood stoves). 42% electric heat pump sales by 2050 and 93% by 2050.

Table C4 | **Overview of Industry Sector Policy Assumptions and Modeling Implementation for Scenarios 1–3**

CATEGORY	SCENARIO 1	SCENARIO 2	SCENARIO 3
Industrial Carbon Capture and Storage (CCS)	**POLICIES**		
	Section 45Q.	Same as Scenario 1.	Same as Scenario 1 + CCS for all cement and iron and steel production.
	IMPLEMENTATION IN PATHWAYS		
	CCS for processes with abatement costs at or near $50/tCO_2$ (ammonia production, natural gas processing, ethanol refining).	Same as Scenario 1.	CCS for all cement and iron and steel production and processes with abatement costs are at or near $50/tCO_2$.
Energy Efficiency, Electrification, Hydrogen Fuel-Switching	**POLICIES**		
	Incentives for "low-hanging fruit," where electrification provides efficiency or cost benefits (impacts estimated by National Renewable Energy Laboratory [NREL] Electrification Futures Study [EFS]).	Same as Scenario 1.	Incentives for development of electro-technologies (impacts estimated by NREL EFS). Emissions pricing or cap for industry.
	IMPLEMENTATION IN PATHWAYS		
	About 2% of natural gas use for process heat electrified by 2030 and 6% by 2050 (estimate of impacts based on NREL EFS).	Same as Scenario 1.	5% improvement in energy efficiency (EE) by 2030 for manufacturing and 16% by 2050 (full economic potential of manufacturing EE based on U.S. Department of Energy estimate). About 15% of natural gas use for process heat electrified by 2030 and 44% by 2050 (estimate based on NREL EFS). Nonelectrified process heat and boiler fuel demand converted to H_2 by 2050 (about 900 trillion British thermal units [Tbtu] by 2030 and 6,600 Tbtu by 2050).

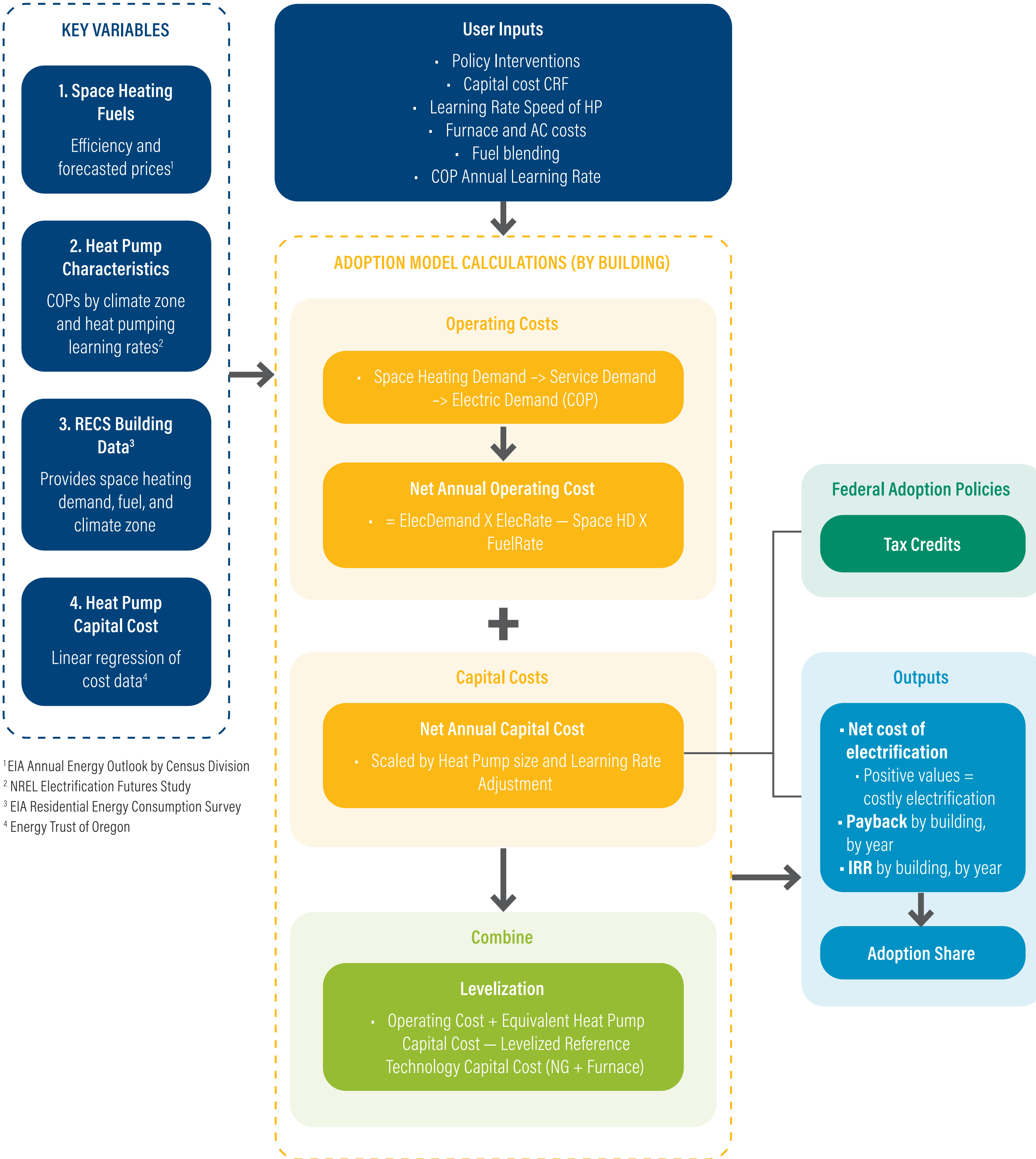
Table C5 | **Overview of Low-Carbon Fuels Policy Assumptions and Modeling Implementation for Scenarios 1–3**

CATEGORY	SCENARIO 1	SCENARIO 2	SCENARIO 3
Renewable Fuel Standard (RFS) and Low Carbon Fuel Standard (LCFS)	**POLICIES**		
	Volume requirements linearly increased based on historical trends (to 16.1% blending by 2030 and 24.4% by 2050). California and Oregon LCFS: linear increase in carbon intensity reductions after 2030.	Same as Scenario 1.	RFS phased out. U.S.-wide LCFS covering all fuel demands post-2030 with net-zero emissions constraint by 2050. Replaces RFS.
	IMPLEMENTATION IN PATHWAYS		
	Renewable diesel is assumed to be marginal fuel to meet RFS blend requirements. LCFS market explicitly modeled to account for impact of electrification.	Same as Scenario 1.	Modeled using fuels optimization module of RESOLVE.

Table C6 | **Overview of Non-energy Sector Policy Assumptions and Modeling Implementation for Scenarios 1–3**

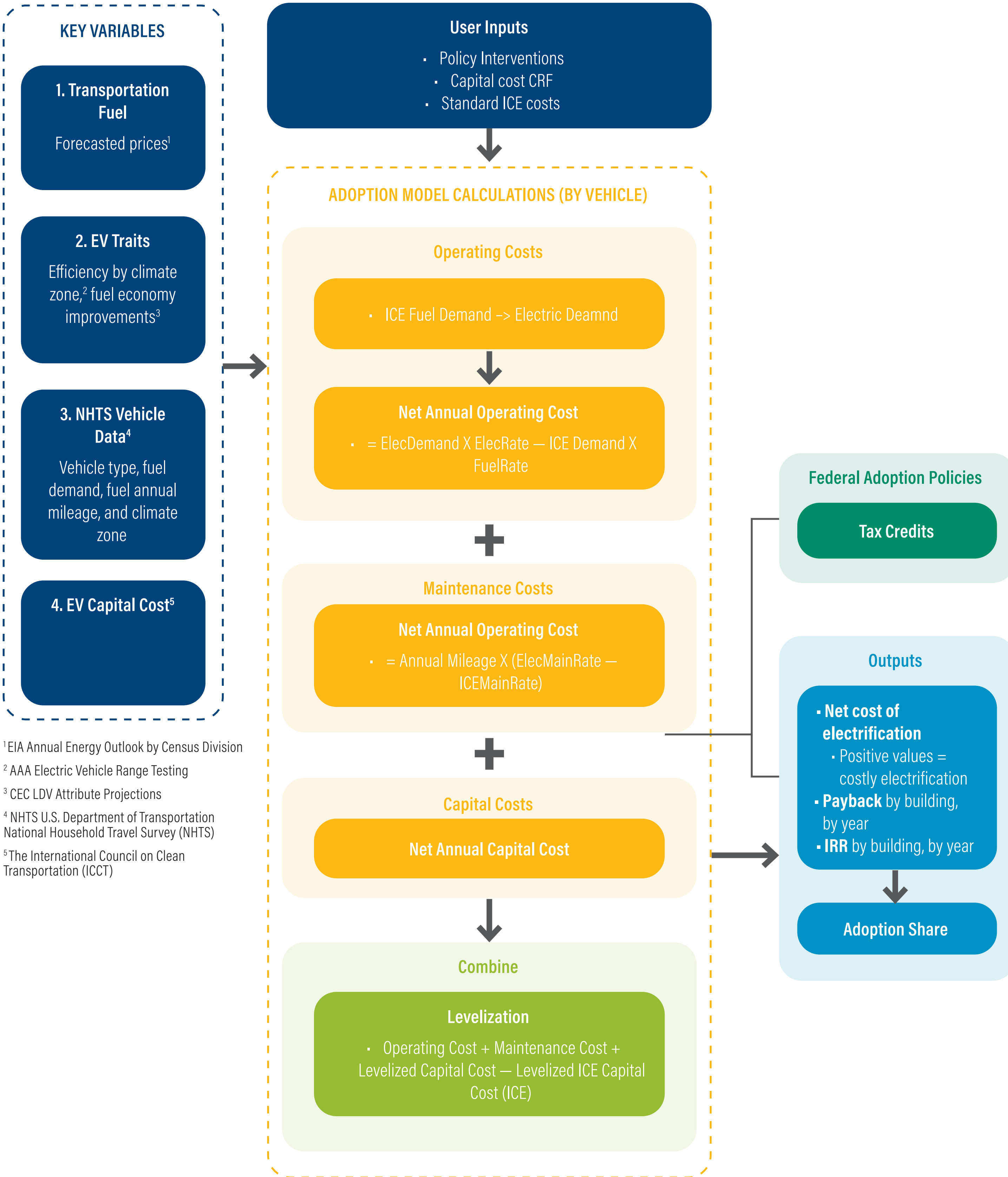
CATEGORY	SCENARIO 1	SCENARIO 2	SCENARIO 3
Hydrofluorocarbons	**POLICIES**		
	Kigali Amendment (same as Reference Scenario).	Same as Scenario 1.	Same as Scenario 1.
	IMPLEMENTATION IN PATHWAYS		
	36% reduction by 2030 and 90% reduction by 2050.	Same as Scenario 1.	Same as Scenario 1.
Agriculture	**POLICIES**		
	Soil carbon management, root crops, N_2O reductions, CH_4 reductions from WRI CarbonShot (lower end).	Soil carbon management, root crops, N_2O reductions, CH_4 reductions from WRI CarbonShot (higher end).	Same as Scenario 2.
	IMPLEMENTATION IN PATHWAYS		
	25 million metric tons (MMT) reduction by 2030 and 100 MMT reduction by 2050)	100 MMT reduction by 2030 and 200 MMT reduction by 2050).	Same as Scenario 2.
Natural and Working Lands	**POLICIES**		
	Reforestation, agroforestry, wildfire management measures from WRI CarbonShot report (lower end).	Reforestation, agroforestry, wildfire management measures from WRI CarbonShot report (higher end).	Same as Scenario 2.
	IMPLEMENTATION IN PATHWAYS		
	60 MMT increase in land sink by 2030 and 180 MMT increase in land sink by 2050).	120 MMT increase in land sink by 2030 and 360 MMT increase in land sink by 2050.	Same as Scenario 2.
Methane	**POLICIES**		
	New Source Performance Standards methane regulations (same as Reference Scenario).	Same as Scenario 1.	Aggressive reductions in fugitive methane emissions based on the EPA's 2019 Non-CO_2 Greenhouse Gas Emission Projections and Mitigation Potential report.
	IMPLEMENTATION IN PATHWAYS		
	Same as Reference Scenario.	Same as Scenario 1.	60% reduction in fugitive methane emissions in Scenario 3.

Figure C1 | **Residential Heat Pump Adoption Modeling Framework**



[1] EIA Annual Energy Outlook by Census Division
[2] NREL Electrification Futures Study
[3] EIA Residential Energy Consumption Survey
[4] Energy Trust of Oregon

Figure C2 | EV Adoption Modeling Framework



[1] EIA Annual Energy Outlook by Census Division

[2] AAA Electric Vehicle Range Testing

[3] CEC LDV Attribute Projections

[4] NHTS U.S. Department of Transportation National Household Travel Survey (NHTS)

[5] The International Council on Clean Transportation (ICCT)

Appendix D. Summary of Data Sources

Table D1 | **Data Sources for Emerging Technology Costs**

SECTOR	TECHNOLOGY/APPLICATION	COST CATEGORY	DATA SOURCE
Power	Resources: ■ Renewable generation solar photovoltaic, onshore wind, offshore wind) ■ Energy storage: Lithium-ion battery storage (>= 4 hours) ■ Flow batteries ■ Natural gas generation: simple cycle combustion turbines (CTs), combined cycle gas turbines (CCGTs), CCGTs with carbon capture and storage (CCS) (only modeled in Scenarios 1–3)	Capital and operating cost	Based on proprietary E3 database of existing resources and planned retirements (current as of early 2020). Underlying data for E3 database based on National Renewable Energy Laboratory (NREL) Annual Technology Baseline and Regional Energy Deployment System data.
Transportation	Light-duty vehicle zero-emissions vehicles (ZEVs)	Capital cost	ICCT 2019
	Medium- and heavy-duty vehicle ZEVs	Capital cost	CARB 2019
Buildings	Heat pumps	Capital cost and operating cost	Energy Trust of Oregon NREL 2017
Industrial CCS	Iron and steel	First-of-a-kind and nth-of-a-kind costs	Global CCS Institute 2017
	Cement		
	Natural gas processing		
	Fertilizer production		
	Bioenergy with carbon capture and storage (BECCS) (ethanol refining)		
Negative Emissions Technologies (NETs)	Direct air capture	Carbon capture cost	National Academy of Sciences 2019
	BECCS (biomass gasification to H_2)	Carbon capture cost and cost per unit	NREL 2018 case studies
Hydrogen	Electrolysis	Capital cost	BloombergNEF 2020 (learning rates based on University of California, Irvine 2020)
	BECCS (Biomass gasification to H_2)	Carbon capture cost and cost per unit	NREL 2018 case studies

Table D2 | **Data Sources for Fuel Prices**

FUEL	DATA SOURCE
Electricity	RESOLVE output
Natural gas	Annual Energy Outlook (AEO) 2020 (Natural Gas)
Wood	SEDS 2018 (Wood and Biomass Waste)
Ethanol	AEO 2020 (Wholesale Ethanol)
Gasoline	AEO 2020 (Motor Gasoline)
Solar	RESOLVE output
Kerosene	AEO 2020 (Propane)
Diesel	AEO 2020 (Distillate Fuel Oil)
Liquified petroleum gas	AEO 2020 (Propane)
Hydrogen	Fuels optimization output
Coal unspecified	AEO 2020 (Other Coal)
Coal with CCS	E3 assumption
Residual fuel oil	AEO 2020 (Residual Fuel Oil)
Petroleum coke	AEO 2020 (Residual Fuel Oil)
Still gas	AEO 2020 (Residual Fuel Oil)
Jet kerosene	AEO 2020 (Jet Fuel)
Renewable gasoline	Fuels optimization output
Miscellaneous petroleum	AEO 2020 (Residual Fuel Oil)
Asphalt and road oil	AEO 2020 (Residual Fuel Oil)
Waste	SEDS 2018 (Wood and Biomass Waste)
LPG feedstocks	AEO 2020 (Propane)
Natural gas feedstocks	AEO 2020 (Natural Gas)
Petrochemical feedstocks	AEO 2020 (Residual Fuel Oil)
CNG	AEO 2020 (Natural Gas)
Liquid hydrogen	Fuels optimization output
Biomass	SEDS 2018 (Wood and Biomass Waste)
Biodiesel	Fuels optimization output
Renewable diesel	Fuels optimization output
Biogas	Fuels optimization output
Industry electrification	RESOLVE output

Appendix E. Supplementary Modeling Results

Table E1 | Gross GHG Emissions and Net GHG Emissions and Removals (MMT CO_2e)

SECTOR	REFERENCE SCENARIO			SCENARIO 1			SCENARIO 2			SCENARIO 3		
	2020	2030	2050	2020	2030	2050	2020	2030	2050	2020	2030	2050
Electricity Generation	1,595	467	298	1,595	318	243	1,596	331	288	1,595	304	9
Transportation	1,550	1,592	1,381	1,552	1,444	954	1,547	1,392	769	1,548	1,335	342
Industrial	1,041	1,120	1,329	1,041	1,102	1,255	1,041	1,093	1,210	1,041	952	426
Residential	347	323	282	346	302	245	346	267	64	346	263	14
Commercial	284	286	302	283	274	273	283	232	72	283	229	9
Agriculture	611	619	627	611	594	527	611	519	427	611	519	427
Industrial Processes	377	353	267	377	340	253	377	340	253	377	293	135
Natural Gas and Oil Systems	284	334	348	284	298	278	284	288	230	284	166	65
Waste Management	161	175	212	161	175	212	161	175	212	161	166	198
Coal Mining	63	52	43	63	49	18	63	49	18	44	9	2
Natural and Working Lands	–769	–744	–696	–769	–804	–876	–769	–864	–1,056	–769	–864	–1,056
Technological Carbon Removal	0	0	0	0	–39	–39	0	–39	–39	0	–32	–571
Net Total	**5,546**	**4,577**	**4,392**	**5,546**	**4,053**	**3,342**	**5,541**	**3,784**	**2,446**	**5,523**	**3,339**	**0**

Table E2 | **Final Energy Demand by Fuel Type (Trillion British Thermal Units)**

FUEL TYPE	REFERENCE SCENARIO			SCENARIO 1			SCENARIO 2			SCENARIO 3		
	2020	2030	2050	2020	2030	2050	2020	2030	2050	2020	2030	2050
Coal	1,181	1,120	1,036	1,181	1,114	1,009	1,181	1,110	978	1,181	1,055	800
Petroleum	29,867	31,378	30,869	29,887	29,234	24,673	29,823	28,299	20,759	29,836	26,739	11,775
Natural gas	22,568	23,296	25,806	22,539	22,479	23,616	22,539	21,178	17,472	22,536	19,664	5,061
Biofuels/ waste	4,398	4,454	4,500	4,316	4,781	5,413	4,393	5,346	5,700	4,394	5,405	3,598
Electricity	13,865	13,635	15,622	13,868	13,957	17,241	13,870	14,526	21,234	13,866	15,025	27,570
Hydrogen	0	24	293	0	24	293	0	24	932	0	883	8,092

Table E3 | **Electricity Demand by Sector (Terawatt-Hours)**

SECTOR	REFERENCE SCENARIO			SCENARIO 1			SCENARIO 2			SCENARIO 3		
	2020	2030	2050	2020	2030	2050	2020	2030	2050	2020	2030	2050
Buildings	2,934	2,724	2,776	2,929	2,634	2,695	2,929	2,792	3,690	2,929	2,792	3,945
Industrial	1,117	1,198	1,392	1,117	1,189	1,354	1,117	1,184	1,331	1,117	1,253	2,234
Transportation	12	73	411	18	268	1,004	19	281	1,203	18	358	1,901
Electrolysis	0	0	0	0	0	0	0	3	249	0	113	2,165
Direct Air Capture	0	0	0	0	0	0	0	0	0	0	0	100

ENDNOTES

1. While the AEO 2020 does not account for the impacts of COVID-19, given that it was published in January 2020, adjustments were made in the modeling to total vehicle miles traveled and aviation fuel demand to account for the impacts of the pandemic on energy consumption and emissions.
2. Performance standards can be considered a building block for carbon pricing. For instance, tradable performance standards can be a policy tool to address emissions in industry. This would set the carbon emissions benchmark against which a firm's performance would be evaluated. Firms with emissions higher than the benchmark would have to pay, while firms with emissions lower than the benchmark would receive credits, which could then be sold to other firms with higher emissions abatement costs (Fischer 2019).
3. Currently California and 11 states in the Northeast have a cap-and-trade system. The latter is called the Regional Greenhouse Gas Initiative (RGGI) and works to limit CO_2 emissions from the power sector. Oregon unsuccessfully tried to create a cap-and-trade mechanism in 2019.
4. Carbon price has entered the debate in Congress in recent weeks, with Senate Finance Committee chair Ron Wyden (D-OR) and Senator Sheldon Whitehouse (D-RI) publicly supporting it as part of the reconciliation package. It is still unclear, though, whether carbon price will make it into the final reconciliation bill (Sobczyk et al. 2021).
5. Reference oil price here refers to the reference case oil price trajectory in the EIA's Annual Energy Outlook (AEO) 2020. Under this price trajectory, the price of Brent crude oil reaches $105 per barrel by 2050 (in 2019 dollars).
6. While costs of the net-zero scenario are reported as a percentage of U.S. GDP in 2030 and 2050 based on the EIA's AEO 2020, uncertainty in GDP projections should be noted, since forecasts in the AEO are based on various assumptions related to key drivers of the economy that do not account for economic shocks or disruptions.
7. Low oil price trajectory here refers to the Low Oil Price case in AEO 2020. Under this trajectory, the price of Brent crude oil reaches $46 per barrel by 2050 (in 2019 dollars).
8. High oil price trajectory here refers to the High Oil Price case in AEO 2020. Under this trajectory, the price of Brent crude oil reaches $183 per barrel by 2050 (in 2019 dollars).
9. The possibility of nuclear power plants prematurely retiring is influenced by power market conditions and policy changes. In September 2021, Illinois approved $700 million in subsidies over a five-year period to prevent the retirements of two nuclear power plants (Gardner 2021).
10. Recent analysis from Williams et al. (2021) shows that retaining existing gas capacity but running it much less (i.e., with < 10 percent capacity factor) is the most cost-effective way to retain reliability in a net-zero emissions power sector. In a high variable renewable energy scenario, gas would play an important role in providing reliability for a limited number of hours per year instead of providing bulk power.
11. Even though recent research has shown that most coal power plants are uneconomical compared to renewable energy, this doesn't by itself cause existing coal plants to shut down. Replacing coal plants with renewable energy can be a more complicated process, especially when coal plants are owned and operated by vertical monopolies that are insulated from market forces and the state regulatory system allows plant owners to recover costs for expenses related to the coal plant outside of the market (Daniel 2019).
12. Firm energy resources are technologies that can provide electricity reliably and on demand, while also being able to sustain that output for weeks or months.
13. Total nuclear generation increases as we move from S1 to S3. Total nuclear generation stands at 684,601 GWh in 2050 in S1, 771,876 GWh in S2, and 848,862 GWh in S3.
14. This study assessed potential emissions reductions resulting from tighter CAFE standards through a sensitivity analysis. This sensitivity analysis added in a 5 percent annual increase in LDV fuel economy from MY 2027 through MY 2031 after a 1.5 percent annual increase until MY 2026 as outlined under the SAFE rule in the RS, S1, and S2 to compare transportation emissions under these scenarios, with and without the tighter CAFE standards.
15. This study assessed potential emissions reductions resulting from lower LDV VMT through a sensitivity analysis. This sensitivity analysis assumed a 3 percent and 10 percent reduction in LDV VMT by 2030 relative to 2020 levels based on LDV VMT trends reported by the U.S. Federal Highway Administration (2020) and Chong (2020) and layered in these assumptions in the reference and mitigation scenarios to compare transportation emissions under these scenarios, with and without the assumed LDV VMT reductions.
16. Most current tax credits are nonrefundable, meaning they can be used by individuals with sufficient tax liability. This reduces their value because many individuals do not owe enough in taxes to take advantage of them. Tax credit refundability allows recipients to monetize the credit irrespective of how much they owe in taxes.

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