Duke NICHOLAS INSTITUTE *for* ENERGY, ENVIRONMENT & SUSTAINABILITY

Pathways to Net-Zero for the US Energy Transition

Jackson Ewing, Martin Ross, Amy Pickle, Robert Stout, and Brian Murray

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A Report of Energy Pathways USA

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Energy Pathways USA is convened by the Nicholas Institute for Energy, Environment & Sustainability based at Duke University, in collaboration with the Energy Transitions Commission. This report constitutes a collective view of Energy Pathways USA. Members of Energy Pathways USA endorse the general thrust of the arguments made in this report but should not be taken as agreeing with every finding or recommendation. The companies involved have not been asked to formally endorse the report.

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INTRODUCTION: TOWARD NET-ZERO IN THE UNITED STATES

Various public and private sector initiatives aim for the United States (US) to transition to an economy-wide net-zero greenhouse gas (GHG) emission footprint by 2050. The near- and long-term pathways toward this goal are uncertain and defy strict predictability. The outcome is far from guaranteed, and the stakes are high. With some three-quarters of GHG emissions stemming from fossil fuel combustion, the US must rapidly scale clean electricity production while concurrently electrifying high energy–use sectors and developing new technologies for emission sources that are difficult to electrify. At this juncture, the necessary timeline for climate action suggests a steady, incrementalistic approach will be insufficient to meet the need. Circumstances require the urgent combination of public policy implementation, technological progress, and changes to operational norms and behaviors by both public and private sector actors.

There are reasons for optimism. While business-as-usual trendlines for the US fall far short of net-zero goals, recent legislation with climate implications appears poised to accelerate America's energy transition pace. The Bipartisan Infrastructure Law (BIL) (2021) and the Inflation Reduction Act (IRA) (2022) both use incentives and the public purse, combined with selective regulation, to create opportunities for decarbonizing the US economy in ways and at speeds that would have seemed unlikely in the recent past. However, while these efforts take on landmark size in the history of US climate efforts, their scale should be kept in context. Together, the two laws enable roughly $1 trillion in public investment over the next 10 years, not all of which goes toward the energy transition. Compare this to projections that the cumulative gross domestic product (GDP) of the US will be more than $300 trillion over the same period, establishing this as an investment of some one-third of one percent of GDP (CBO 2022, 7). Put another way, while the IRA steers the largest volume of public resources—including roughly $369 billion in financial provisions—toward addressing climate change in the history of federal policy, this figure pales in comparison to the $1.9 trillion spent on the American Rescue Plan in a single year. More will be required from both public and private sectors for midcentury net-zero goals to become reality.

New US legislation must therefore galvanize momentum for scaling up the deployment of established technologies and systems and accelerate the development and marketability of those that are more nascent. Subsidies, mandates, and regulatory constraints have a history of catalyzing demand shifts, innovation, price reductions, and new economies of scale—at times through virtuous cycles that drive the development of new sectors (Ip 2022). Rapid declines in the cost of photovoltaic module manufacturing, which fell some 96% between 1980 and 2012, offer a historical marker. Roughly 30% of this decline has been attributed to public and private research and development, with another 60% coming from "learning-by-doing" improvements in manufacturing processes (Kavlak, McNerney, and Trancik 2018). These price declines, along with those for wind, are slowing down, but the processes that drove them offer a window into the potential of the BIL and especially the IRA. If implemented effectively, these policies can lower the costs, hasten the uptake, and strengthen the performance of already competitive solar, wind, and battery sectors, while setting the stage for rapid price competitiveness and wider readiness improvements in next-generation technologies and infrastructure needed to decarbonize the wider US economy.

This report by Energy Pathways USA is a brief examination of the current trendlines, challenges, and opportunities for meeting the US net-zero objective. Energy Pathways USA is an autonomous regional initiative of the global Energy Transitions Commission, and works with leading private sector companies, public bodies, nongovernmental organizations, and thought leaders to advance the US net-zero agenda. The report encompasses three main sections that (1) highlight critical observations about past and present US emissions trends, (2) discuss leading analyses of potential US emissions trajectories out to 2050, and (3) frame the domestic and federal policy landscape for net-zero efforts.

The report concludes by presenting a selection of key challenges and opportunities to the US net-zero project that require further attention. These include the need to advance targeted modeling for clean electricity and wide-ranging electrification, which together represent the foundation for US net-zero outcomes; necessary progress on project siting, licensing, and materials extraction to develop new energy assets; the need to effectively deploy IRA loan finance and guarantees to bolster equitable investments; the necessity of advancing state and regional coordination, particularly for grid systems; and the current and potential impacts of clean energy standards and carbon pricing for US net-zero prospects.

The report seeks to strengthen the evidence base on what will be required for a robust US energy transition, and to elucidate key barriers and pathways toward net-zero goals. It also serves as the foundation for future work by Energy Pathways USA, which will provide in-depth and ongoing analysis across these topics.

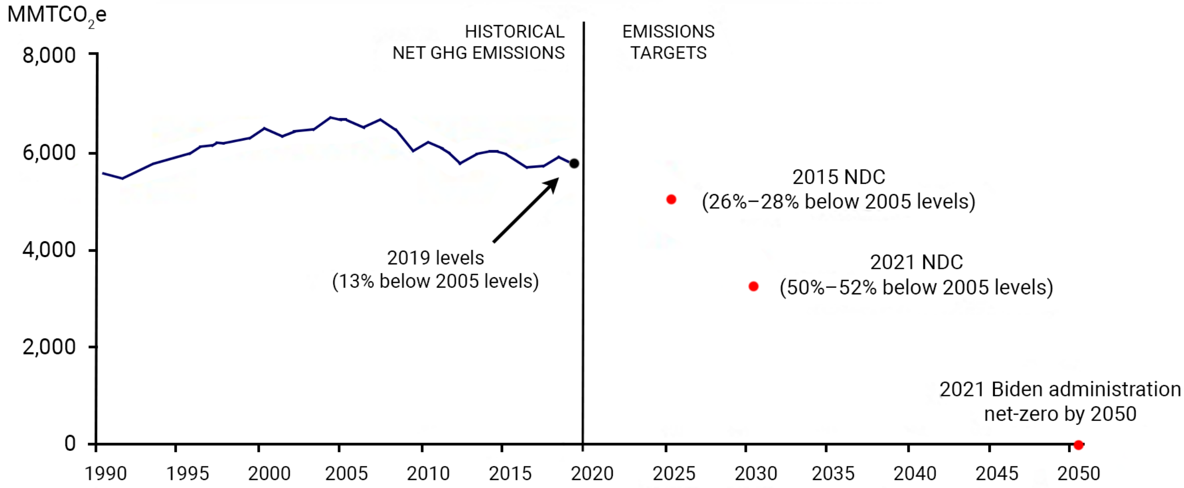
US EMISSIONS HISTORY AND BUSINESS-AS-USUAL DIRECTION

The United States is the world's largest economy and has been the world's top energy consumer for much of the post-industrial era, being surpassed by China only in the last 15 years. The US is likewise the single largest national contributor to cumulative global GHG emissions, even before accounting for emissions embodied in imported goods and services. As of 2020, this relative contribution represented 25% of all global CO_2 emissions emitted since the beginning of the industrial revolution (Ritchie 2019). In per capita terms, US energy use is comparatively high, but has declined by 1.8% per year since 2000. The US population has grown while total energy consumption has been remained relatively stable.

The Biden administration is proactively pursuing a US energy transition. Using international Paris Agreement pledges as a starting point, the Biden administration has updated the US nationally determined contributions (NDCs) to the agreement with a GHG emissions target of 50% to 52% below 2005 levels by 2030 and economy-wide net-zero emissions "no later than 2050" (The White House 2021a). This is a substantial increase in US ambition, moving from 2015 NDC targets of 26% to 28% reductions below 2005's levels by 2025 and 80% below 2005 levels by 2050. Business-as-usual (BAU) scenarios, unsurprisingly, do not place the US on track to meet these Paris Agreement climate commitments, or for meeting the Biden administration's midcentury net-zero ambitions (Figure 1).

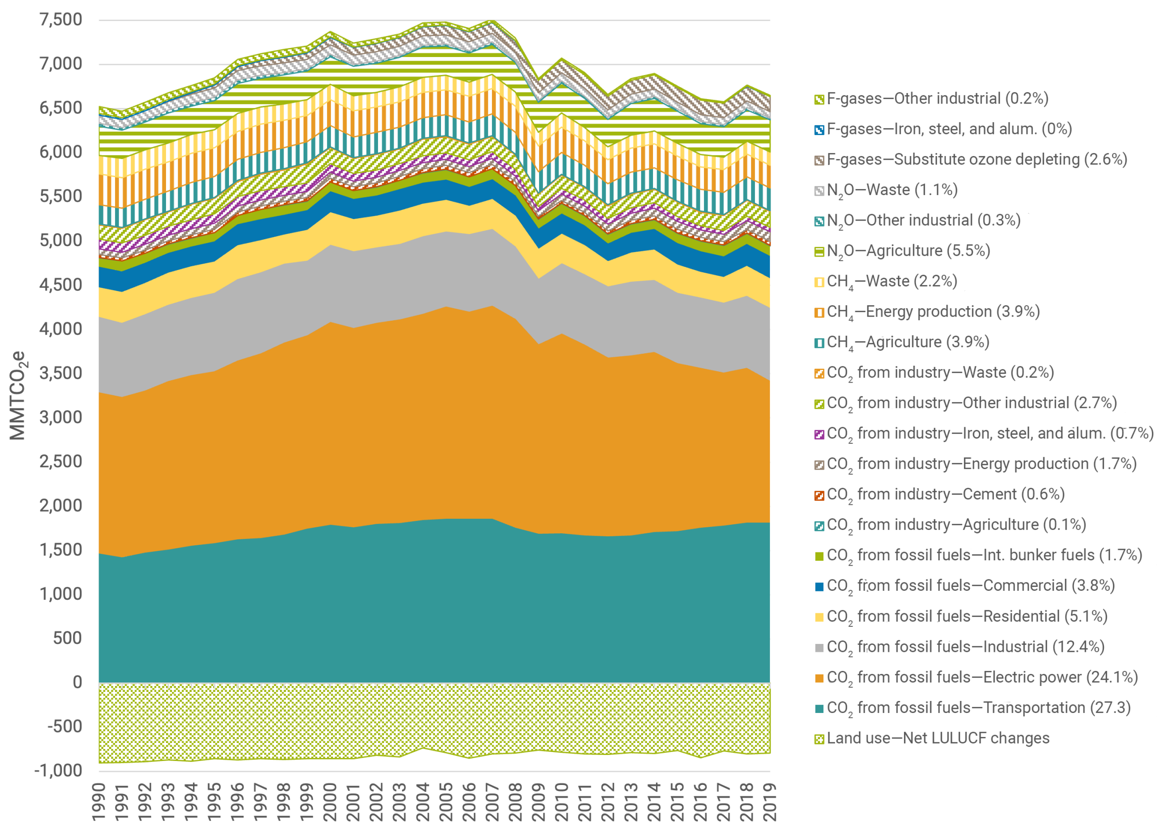
Figure 2 shows historical trends in overall GHG emissions in the United States since 1990. The six largest categories of CO_2 emissions are those from fossil fuel combustion, which comprised 74.4% of all US GHG emissions as of 2019. The largest—and growing—share is from transportation, at 27.3% of all emissions. Prior to 2010, the electric power sector was the largest source with one-third of all emissions; however, coal plant retirements and a continuing shift to natural gas and renewable generation reduced its share to 24.1% by 2019. These sources are followed by industrial (12.4%) and residential sectors (5.1%), respectively.

Figure 1. US net GHG emissions (1990–2019) and future emissions targets



Source: Adapted from EPA (2022).

Figure 2. Historical US GHG emissions by gas and source

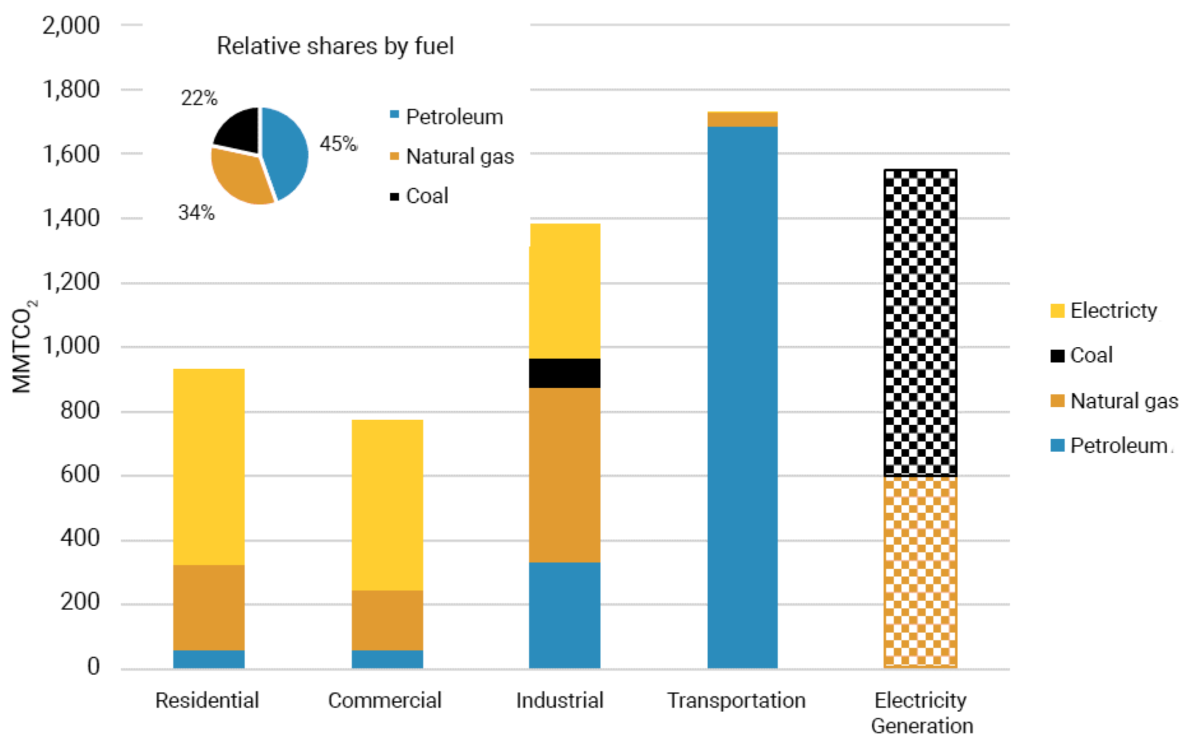


Source: EPA (2022).
Abbreviation: LULUCF = land use, land-use change, and forestry

Carbon dioxide emissions from industrial sources—unrelated to the burning of fossil fuels—accounted for 6.0% of all US GHG in 2019, with most of these emissions coming from cement manufacturing, energy production, and the iron and steel industries. Methane emissions in 2019 were around 10% of all emissions, roughly 4% of which came from agriculture (mainly enteric fermentation and manure), 4% from energy production (natural gas systems and coal mining), and 2% from wastes (wastewater treatment and burning). Nitrous oxide was 6.9% of the total in 2019, largely from agriculture, and fluorinated gases were 2.8%, largely from the substitution of chemicals away from ozone-depleting substances.

Figure 3 complements these data by assigning fossil fuel CO_2 emissions to sectors by fuel type for the year 2021. In this assignment, emissions associated with electricity generation are shared out across consumers of the electricity; hence the right-hand column for the electricity sector replicates the emissions that have already been included in yellow across the other sectors. By fuel, 45% of CO_2 emissions are associated with consumption of petroleum, mainly in the transportation sector. Natural gas use causes 34% of CO_2 emissions and is split across the industrial, residential, and commercial sectors, where industrial use is the largest component of the total. Most coal is used for electricity generation, aside from a small amount in the industrial sector. Emissions associated with electricity consumption are the largest share of total residential and commercial emissions and represent an important component of industrial emissions.

Figure 3. US energy-related CO_2 emissions by sector and fossil fuel in 2021

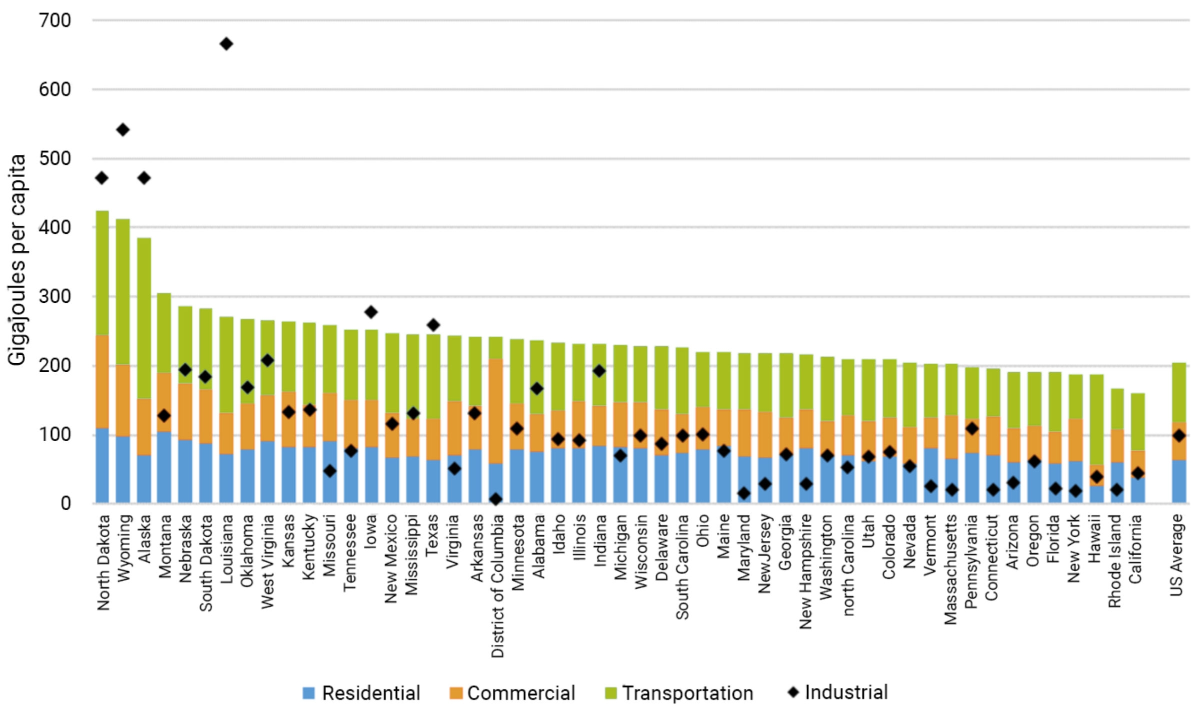


Source: EIA (2022).

These trends in energy consumption, energy production, and broader characteristics in commerce, housing, and transportation vary widely across the US. Figure 4 ranks US states by energy consumption per capita across the combination of residential, commercial, and transport sectors. In general terms, states with the smallest populations have the highest per capita energy use. This could be attributable to higher transport needs because of more dispersed populations, a hypothesis worth examining in assessing the impacts of national versus regional or local policy interventions. These states are clustered broadly in the middle of the country, with per capita energy consumption declining as the ranking moves toward the East and West Coasts. Residential and commercial use also roughly follows weather patterns measured by heating degree days, with colder states using more energy for heating purposes. Income distributions (not shown) also follow a similar—though inverse—ranking across states, where poorer states are more concentrated in the center of the nation, use more energy per capita, and thus could face higher burdens if emissions reductions cause energy prices to rise.

Figure 4 also superimposes industrial energy use per capita (black diamonds) on the ranking of states' energy consumption in the residential, commercial, and transportation sectors. One of the largest factors influencing these data is the inclusion of energy used in the energy production process, which is categorized as industrial. This explains, for example, why Louisiana, with its petroleum refineries, has industrial energy use that is 6.5 times the national average (it also has a relatively small population when measuring in per capita terms). Texas also has much of the nation's refining industry and, partly in consequence, has energy use that is more than 2.5 times

Figure 4. Ranking US states by energy consumption per capita



Source: EIA (2022).

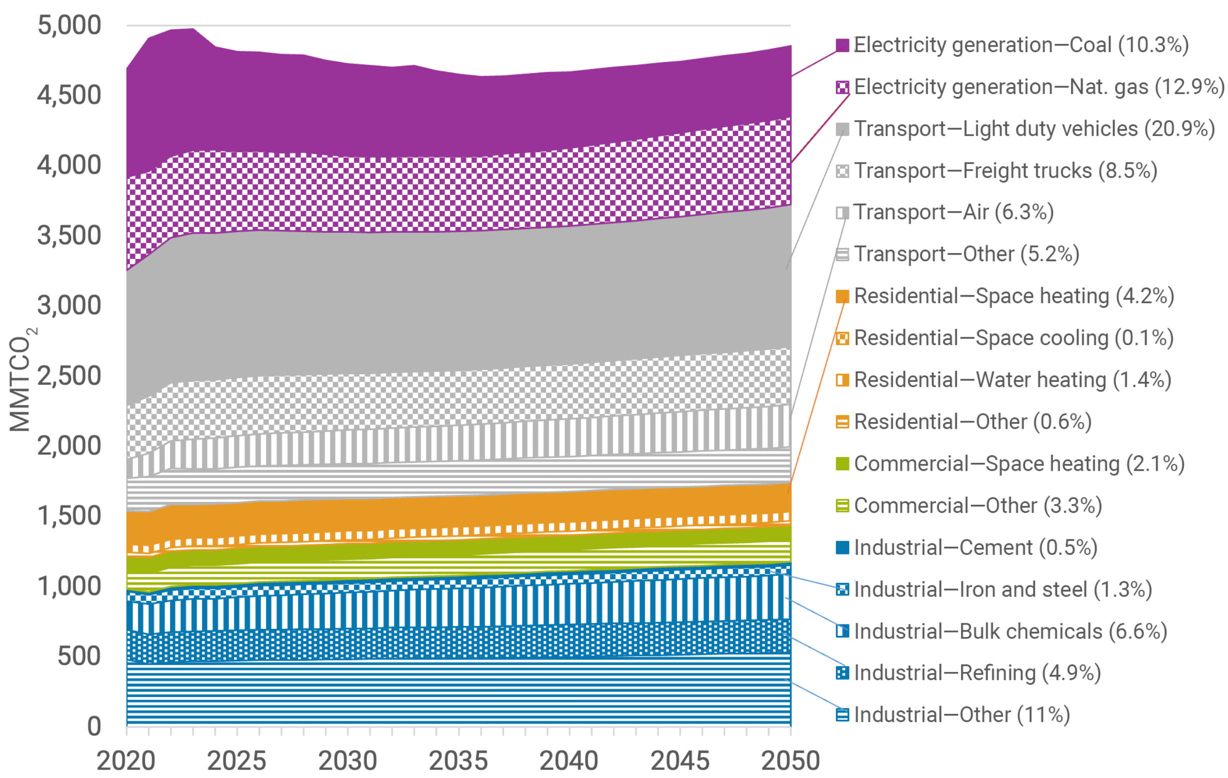
the US average, but that is lower than Louisiana's because its population is higher. More generally, industrial use still follows the rough distribution of energy use in other sectors, where central states have much higher energy use per person than those on the coasts. For the East and West Coasts, the greater emphasis on service industries (reflected in the commercial sector) and a manufacturing base less-focused on heavy or energy-intensive industries sees them toward the bottom of the ranking.

Business-as-Usual Projections

Setting aside US emissions' geographic distribution within the country, understanding net-zero pathways for the nation as a whole begins with examining which sectors of the economy will produce most of the future emissions in the absence of new climate policies. While recent legislation detailed in the Policy Landscape section of this report will impact these pathways, they provide a vital baseline for level-setting future analysis and action. Figure 5 breaks the US Energy Information Administration's (EIA) Annual Energy Outlook 2022 (AEO) Reference case emission forecast (EIA 2022)—which represents the absence of new policies or BAU—into several broad categories.

Currently, electricity generation causes around 30% of US CO_2 emissions related to energy consumption. By 2050, under BAU pathways, electricity generation's share of emissions is expected to fall somewhat to 23%, but this forecast does not suggest a continuation of recent historical

Figure 5. CO_2 emissions by sector (AEO Reference case)



Source: Calculations based on EIA (2022).

trends that led to substantial reductions in coal-fired emissions. Light-duty vehicles (LDVs) are responsible for around 21% of total forecasted emissions, a share that remains consistent through 2050. Overall, the AEO is conservative in its forecasts of electric-vehicle adoption (given its reliance solely on current policies), and consequently roughly 44% of all expected CO_2 emissions in 2050 come from just two sources—electricity generation and LDVs. These sectors have in common the fact that there are technology options in use today that could substantially reduce or eliminate these emissions, and that future policies could be enacted to amplify the adoption of those technologies in ways not captured by BAU.

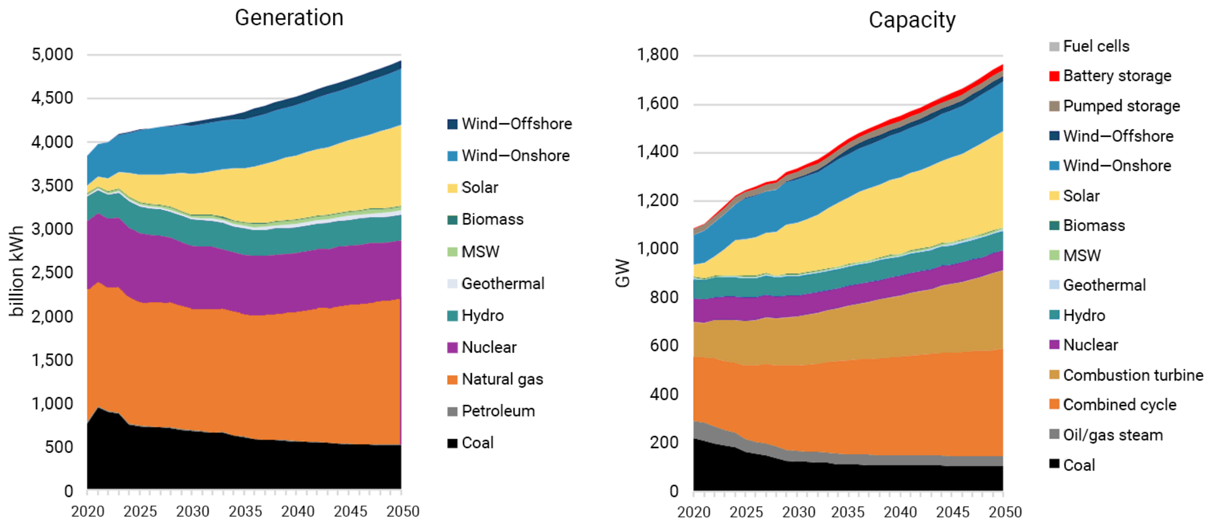
The remaining emissions from the transportation sector—freight trucks at 8.5% of total emissions in 2050, aviation at 6.3%, and all other sources at 5.2%—are among the largest remaining source categories across the economy in the 2050 reference case baseline. However, these modes of transport have fewer and/or potentially more costly emissions-reduction opportunities than do LDVs. In the residential and commercial sectors, one-half of the energy needs are already expected to be supplied by electricity; which presumably could be decarbonized using technologies available today. The remaining energy consumption in these two sectors—mainly natural gas—each contributes 5% to 6% of total emissions. Space heating represents the largest share of residential energy demand and is also an important part of overall commercial energy consumption.

The broadly defined industrial sector emits around 20% of US energy-related CO_2 emissions currently, a share that is expected to increase toward 25% by 2050 in the BAU scenario. Reduction opportunities in the cement and iron and steel industries either have been or are being developed. However, any substantial lowering of industrial emissions will depend on additional technology development in areas such as the bulk chemicals industry, which is expected to represent 6.6% of all US energy-related CO_2 emissions in 2050. Emissions-reduction technologies in this area—and in the inclusive "other" category—may vary substantially across specific products and industries, potentially making emissions reductions for these sources difficult, and pose more technological challenges than for decarbonizing most other sectors. Replacing feedstock with nonfossil alternatives is challenging in many instances, particularly steel and cement production, given high heat requirements, established production systems, and the untested nature of many alternative feedstocks for commercial application (Cleary 2022). Electrified industrial processes are likewise often more expensive than traditional fossil energy systems.

In the AEO Reference case (again, without climate policies from 2022 onward and without the impacts of recent legislation), forecasts of electricity generation by type of unit in Figure 6 show some decline in coal generation in the near term, but substantial coal capacity still remains in 2050. Natural gas expands somewhat, with the largest change in gas-combustion turbine capacity that can be used to provide reliability services as renewables increase production over time. Onshore wind does not see sustained expansion throughout the forecast horizon, although some offshore wind enters the system (partially in response to mandates such as those in Virginia's Clean Economy Act [2020]and recent federal leasing of up to 30 GW of potential offshore wind on the East Coast). The biggest persistent change in the central reference forecast is in solar photovoltaics, which build on their recent growth as installation costs continue to decline. Some battery storage becomes cost-competitive in the forecast—and some is mandated—but most reliability needs in the reference case are met by peaking gas turbines.

Figure 7 ranks industries' energy consumption based on energy use as of 2020, focusing on the "industrial-other" category plus cement and iron and steel.

Figure 6. Electricity generation and capacity by type (AEO Reference case)



Source: EIA (2022).

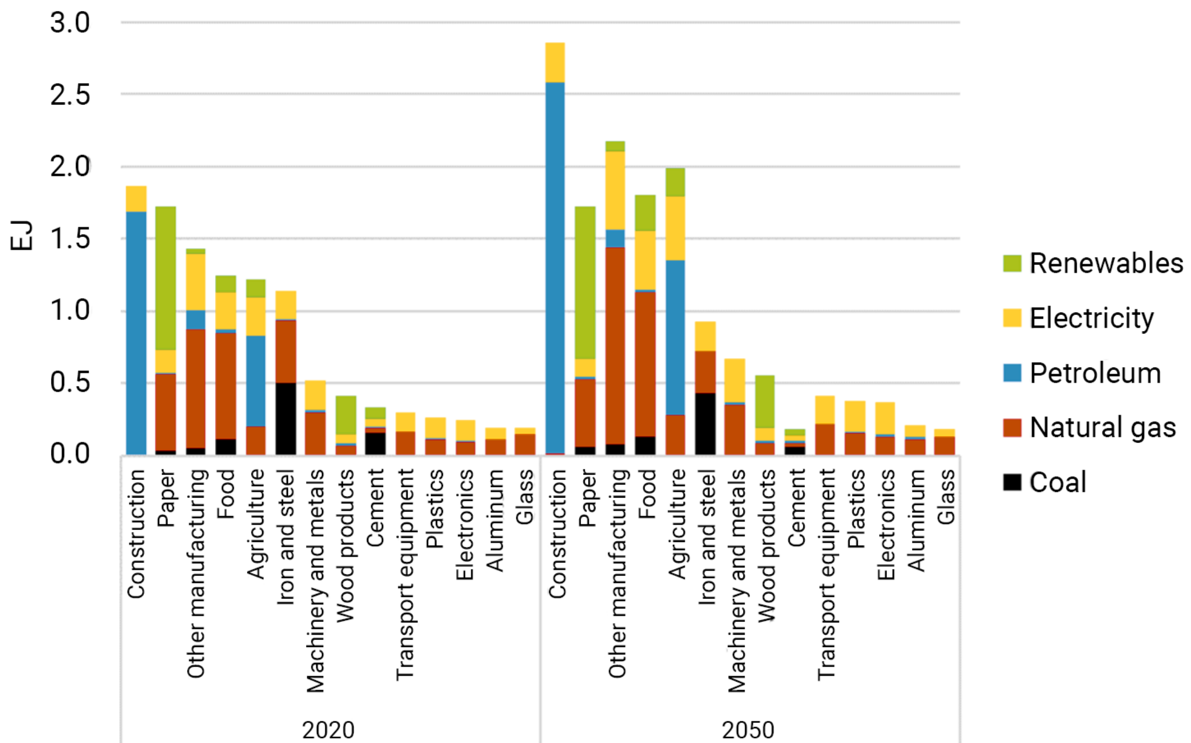
The construction industry faces the largest expansion in absolute energy terms, concentrated in petroleum use—largely by heavy vehicles—suggesting some potential difficulties with achieving future emissions reductions. Food and agriculture energy use also increases significantly, even ignoring GHG emissions from the sector beyond those from energy consumption. Other manufacturing sectors likewise expand, largely on the back of natural gas.

Historical energy and emissions characteristics and BAU trends provide a necessary window into the US decarbonization challenge. BAU is clearly inadequate for meeting US net-zero goals. Rather, multiple pathways exist by which the US economy might evolve away from past energy systems, each of which strongly leverage clean electricity production, transmission, and flexible availability as the future backbone of power use and the low-carbon electrification of high-emitting sectors. The following section summarizes some of the leading analyses of such pathways and helps clarify the need for further strategies to reach net-zero in the US.

POTENTIAL NET-ZERO TRAJECTORIES—EVIDENCE FROM RECENT STUDIES

Several high-profile, quantitatively focused analyses have explored the steps that need to be taken to reach net-zero GHG emissions in the United States by 2050. Comparing these analyses highlights broad areas of consensus and alternative views and elevates key considerations for developing interim steps toward 2050 goals, technology needs, policy objectives, and possible sequencing and prioritization. This section—along with Appendix A—draws from the following reports: the Intergovernmental Panel on Climate Change's (IPCC's) *Sixth Assessment Report Climate Change 2022: Mitigation of Climate Change* (IPCC 2022), the Energy Transitions Commission's *Making Mission Possible: Delivering a Net-Zero Economy* (ETC 2020), the International Energy Agency's

Figure 7. Industrial energy consumption by sector and fuel (AEO Reference case)



Source: EIA (2022).

(IEA's) *Net Zero by 2050: A Roadmap for the Global Energy Sector* (IEA 2021), the Princeton Rapid Energy Policy Evaluation and Analysis Toolkit (REPEAT) project's *Net-Zero America: Potential Pathways, Infrastructure, and Impacts* (Larson et al. 2021), and the National Academy of Sciences' (NAS') *Accelerating Decarbonization of the U.S. Energy System* (NAS 2021).

On balance, these studies reach consistent conclusions about possible pathways to net-zero emissions. Foundationally, reaching net-zero emissions by 2050 is technically feasible since the types of technologies needed to decarbonize emissions-intensive sectors are either known or in development. While the deployment trajectories of these technologies contain many uncertainties, cost estimates are generally relatively small as a percentage of future GDP and in comparison to spending that would have occurred on energy in the absence of net-zero–oriented climate policies (current policies are discussed in the following main section).

Technology and infrastructure, however, must be deployed at unprecedented rates in most sectors by 2030 to meet 2050 goals. Because the US must rapidly scale up emission-reducing technology implementation in the very near term, the studies generally identify wind and solar electricity generation and the electrification of vehicles as core early drivers of emission reductions. Electrification by households and businesses (space heating and cooling, water heating, etc.) must also accelerate, while deploying or preparing to deploy advanced—less established—technology opportunities will be essential to reduce emissions from sources that are more difficult to abate, such as certain industrial processes and some forms of transportation (e.g., aviation). As such, research and development (R&D) is needed to quickly scale solutions such as advanced batteries, hydrogen electrolyzers, and direct air capture (DAC), among others.

Collectively, these studies suggest critical steps for each of the following main components of the energy transition: clean electricity generation, electrification of end uses, and industrial process decarbonization. For clean electricity generation, wind and solar production represent the earliest and largest sources of reductions in most recent studies. The Princeton study—in four out of their five main scenarios—quadruples wind and solar to 600 GW by 2030, capable of supplying one-half of US electricity. Existing coal plants in the US (along with other advanced economies in global scenarios) would need to cease operation by 2030 or 2035 (IPCC 2022; IEA 2021; Larson et al. 2021). As new generation comes online, high-voltage transmission will expand by 60% by 2030 (Larson et al. 2021). The grid will also need to accommodate more information, be more resilient, and maintain reliability, all of which will require significant grid modernization. Overall, net-zero emissions from electricity comes shortly after 2030 for the US and by 2035 in advanced economies (IEA 2021).

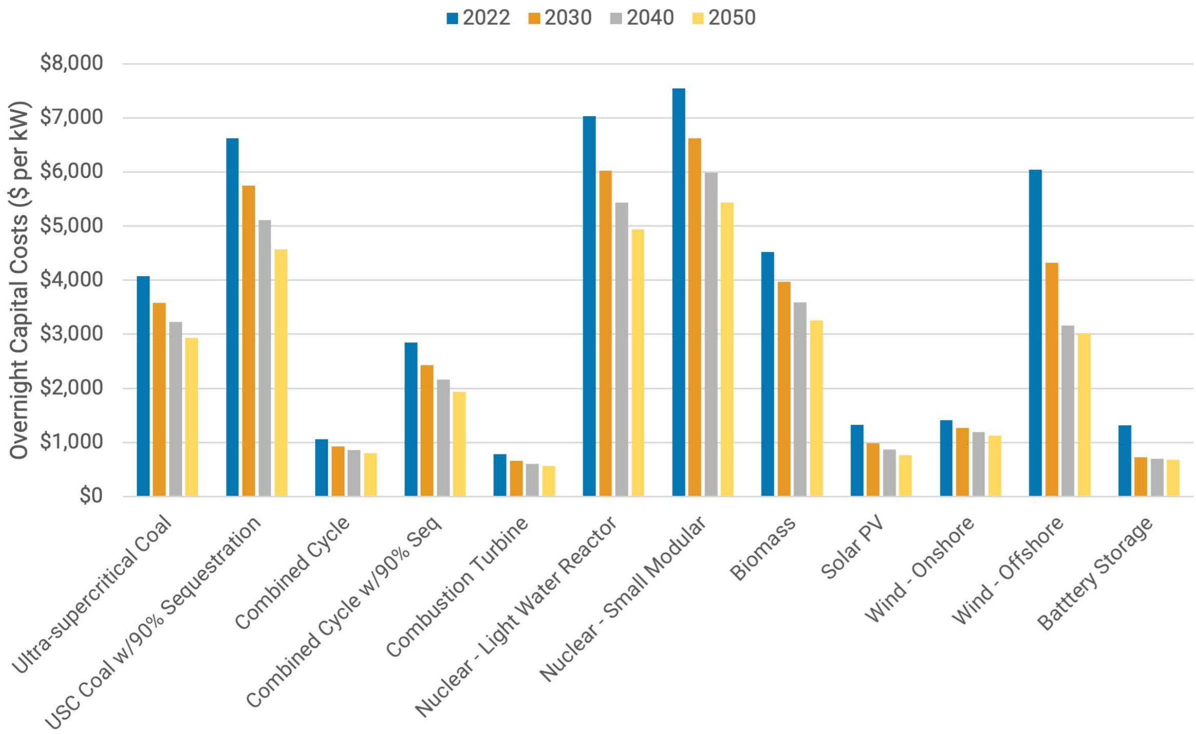
Alongside cleaning the grid, transportation and buildings must electrify to replace fossil fuels now being used for these purposes. The net-zero analyses identify electric vehicles (EVs) as an early source of emissions reduction. In the Princeton report, more than 50 million light-duty EVs are on the road in the US, with more than 3 million public chargers by 2030. Buildings are electrified, primarily through shifting residential heating and air conditioning from natural gas and oil to heat pumps powered by electricity. For example, the Princeton report doubles the share of heat pumps in residential homes by 2030. Hydrogen as a fuel source plays an important role between 2030 and 2050, both in providing flexibility to the electric grid and in reducing industrial emissions. The studies differ on whether the aviation sector can reduce aviation fuel and switch to low-emission alternatives. Finally, all studies anticipate that additional carbon management will be required to meet the net-zero goal. Carbon capture, utilization, and storage (CCUS)—both as part of the power generation mix and industrial processes—is an essential component of the energy transition and would thus influence the future role of fossil fuels in the energy mix. However, the studies disagree on the role of biomass as a component of future energy supplies. Each of these topics is explored in more detail throughout the remainder of this section.

Clean Electricity Generation

The types of models used in these quantitative analyses estimate how the electricity sector will respond to future market conditions (e.g., natural gas prices) and climate policies. These response estimates are largely controlled by their forecasts of technology options and their capital and operating costs, which must be tempered by the changes to these costs that will accompany shifts in the net-zero policy landscape discussed subsequently in this report. Figure 8 illustrates the assumptions on overnight (upfront capital) costs that underlie the AEO Reference case results, in the absence of a comprehensive net-zero policy. For climate analysis, emphasis is usually placed on solar photovoltaic costs and, to a lesser extent, onshore and offshore wind trends. However, potential issues such as transmission availability and system reliability may also place importance on technologies such as advanced nuclear reactors or carbon capture on fossil units.

There are important differences among these projections on electricity generation and capacity (Figures 9 and 10) that shed light on pathway alternatives. The AEO 2022 reference case assumes more solar use, and the Princeton report projects more on gas combined cycle and onshore wind.

Figure 8. AEO 2022 Reference case trends in capacity costs



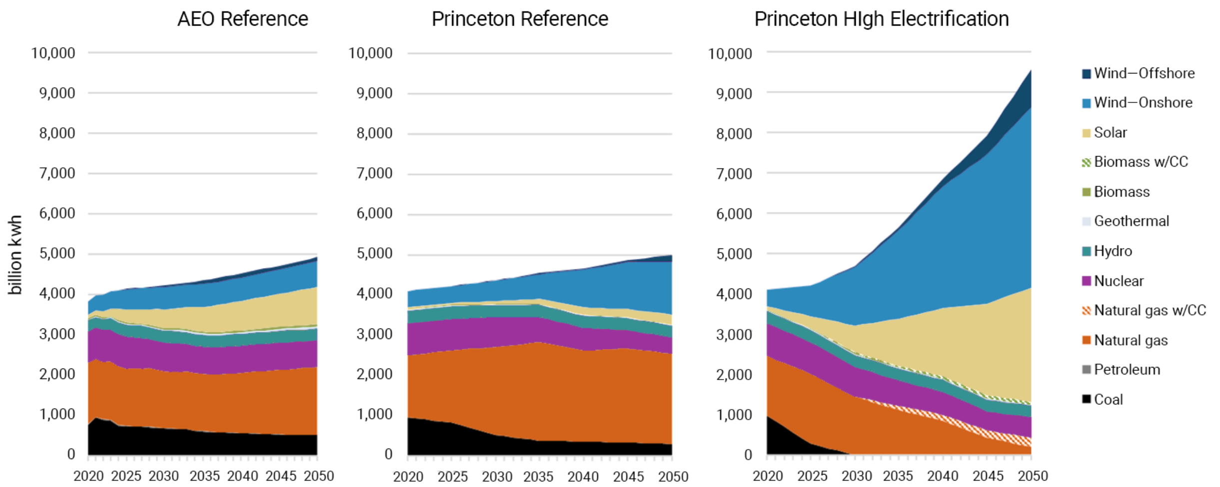
Source: EIA (2022).

In the Princeton high electrification pathway to net-zero, unabated fossil generation is mostly gone by 2050 (coal is gone by 2030), as solar and wind generation dominate the mix. The Princeton study assumes that gas plants can cofire with up to 60% hydrogen, but the analysis is unclear about how much of the remaining gas generation is cofired in this fashion in this scenario.

Analyses typically forecast that significant increases in transmission capacity will be necessary to support the dramatic expansions of renewable generation seeking to interconnect to the transmission system over the next several decades. The location of these wind and solar resources, along with the overall increase in electricity demand from electrification, lead the Princeton analysis to estimate that high-voltage line capacity will need to expand by more than 200% from present-day levels (Figure 11). Reforms at the Federal Energy Regulatory Commission and in both Regional Transmission Organizations (RTOs) and Independent System Operators (ISOs) are needed to facilitate the siting and cost allocation of new regional or interregional transmission. Current regulatory frameworks will make it challenging to construct sufficient transmission in time to meet national and subnational decarbonization goals. If such construction proves infeasible for technical, siting, or political reasons, the system will have to adjust in different ways to provide clean electricity while simultaneously meeting growing demand.

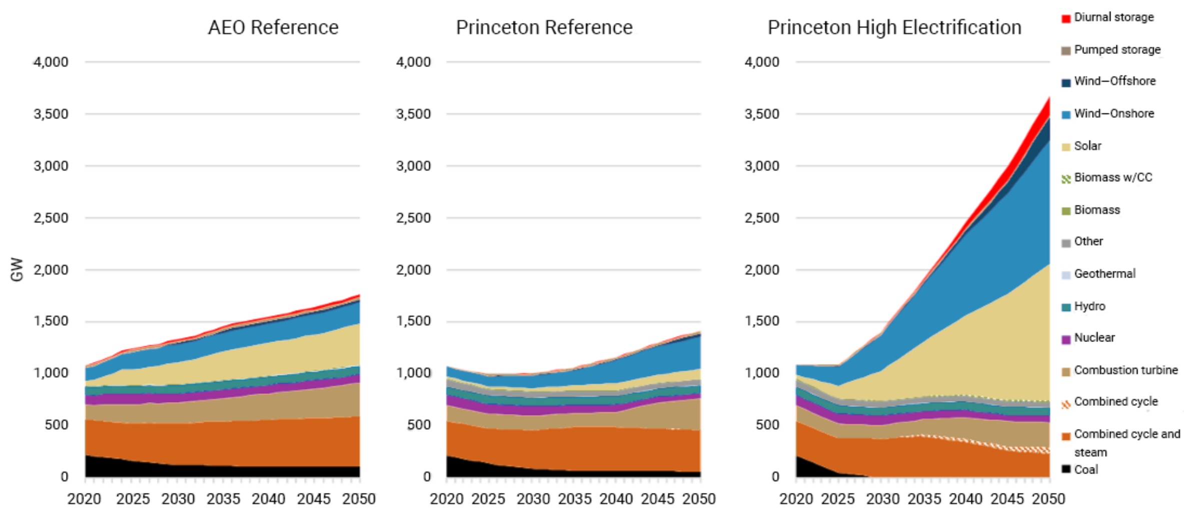
The implications of assumptions about the reliability of power systems are among the most crucial areas that need to be addressed in any net-zero modeling that moves the system toward substantial shares of variable renewable generation. The Princeton modeling uses nonoperating fossil units to

Figure 9. US electricity generation—Comparative projections



Source: Adapted from Larson et al. (2021) and EIA (2022).

Figure 10. US electricity capacity—Comparative projections

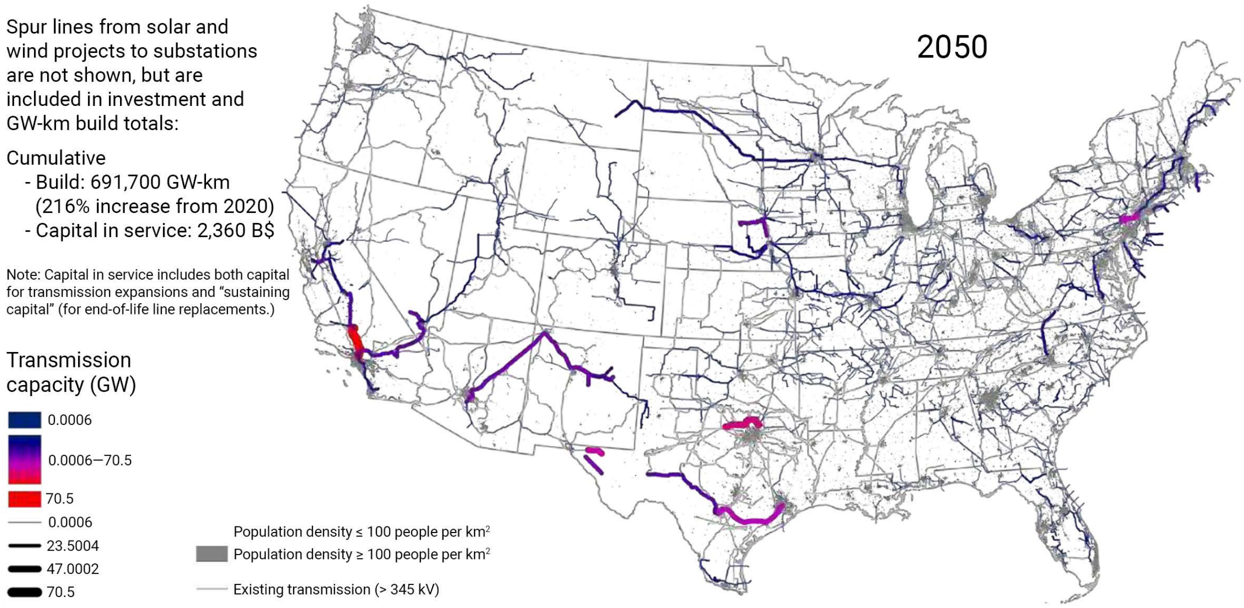


Source: Adapted from Larson et al. (2021) and EIA (2022).

ensure that the system has enough available quick-start capacity to meet sudden spikes in demand or unexpected outages of units. IEA global estimates likewise also see a large role in developed countries for hydroelectricity and nuclear units to supply relatively large capacities. Hydrogen backup has an important role, with more limited reliance on natural gas to remain available in the long term to ensure the grid functions properly.

Clean electricity is a necessary foundation of broader decarbonization of the US economy. Clean electricity innovation and infrastructure development and integration are paramount to prospects for cleaning industry, building and household energy usage, and—most pressingly—transportation.

Figure 11. Princeton transmission expansion in the high electrification case



Source: Larson et al. (2021).

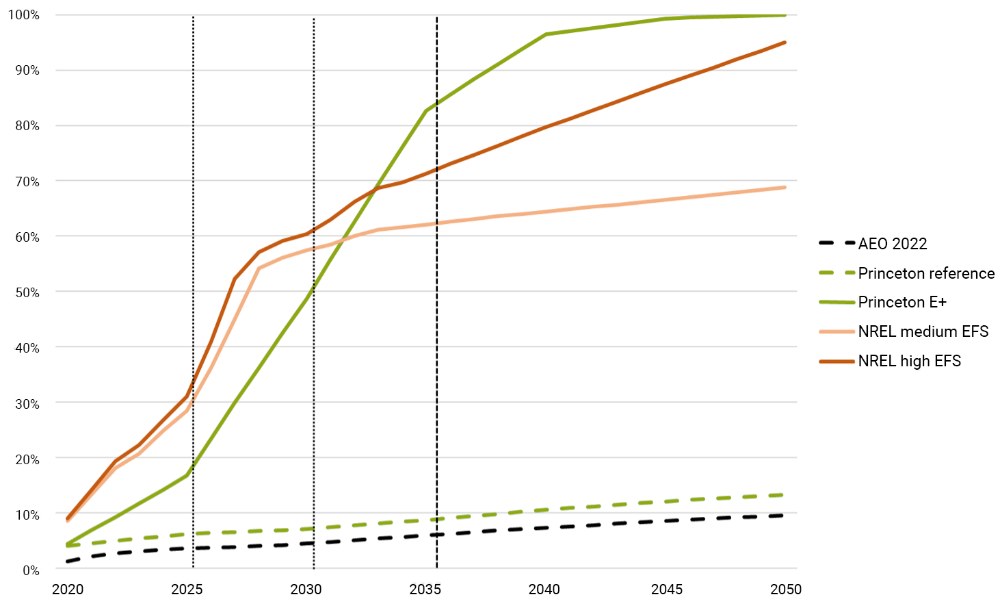
The needs of these sectors will increase the lift required of clean electricity far beyond the replacement of fossil fuels for energy generation, and create challenges and opportunities for creating more modern, intertwined energy systems from production to final use. The following sections introduce electrification trends and projections across multiple sectors, representing a next step that must occur in tandem with clean electricity developments for net-zero targets to be reached.

Electrification: Light-Duty Vehicles

As seen across the range of net-zero policy analyses, converting the fleet of LDVs to EVs is a critical step for lowering economy-wide emissions. Figure 12 compares EV sales market share scenarios across multiple studies: the AEO Reference case forecast for EV sales (without new climate policies) as a percentage of the total LDV market, to the forecasts from the National Renewable Energy Laboratory's (NREL's) Electrification Futures Study ("medium" and "high" electrification trends) (Zhou and Mai 2021), and analysis from the Princeton net-zero study.

AEO estimates of EV adoption are historically on the conservative side of forecasts, and would appear particularly so when compared to the expectations of vehicle manufacturers. The previous NREL forecasts in their electrification study (Zhou and Mai 2021) appeared optimistic when originally proposed, but have since been exceeded by more recent studies and industry goals. In a net-zero policy scenario, the Princeton modeling reaches a 100% EV sales share by 2050, but is only around 50% in 2030 and 85% by 2035 (see Figure 15), which is lower than some expectations within the industry (or those used in the IEA modeling that assumed 60% of global vehicle sales were electric by 2030).

Figure 12. Electric vehicle sales forecasts as a percent of total light-duty vehicle sales



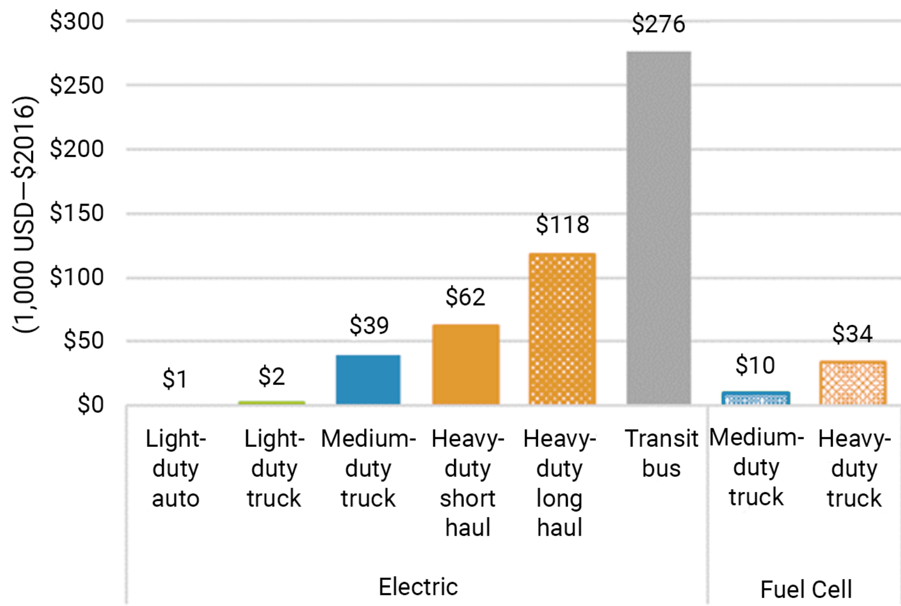
Source: IEA (2021), Larson et al. (2021), and Zhou and Mai (2021).
Abbreviation: EFS = Electrification Futures Study

Analyzing vehicle sales trends is difficult—assumptions about vehicle costs, stock turnover, and people's willingness to adopt new technology are hard to incorporate fully into broad economy-wide models. Unlike electricity generation, where assumed adoption of least-cost technologies appears to be a reasonable characterization of the sector's behavior, cost premiums for vehicle types are only one component of the EV adoption decision. More than a century of observing vehicle purchases clearly shows that buyers do not simply buy the least costly option to travel; rather, there are many features from style to safety to convenience that determine purchases. This will also be true of EV purchase decisions, particularly as they raise—and must resolve—unique issues of driving range and access to charging.

Figure 13 illustrates assumptions in the Princeton analysis regarding the cost premiums for electric and fuel-cell vehicles in 2030, compared to conventional internal-combustion vehicles. LDVs have essentially reached cost parity by 2030, but a combination of stock turnover assumptions and constraints on EV adoption to proxy concerns about the new technology, range limitations, and the availability of charging stations can still limit EV growth.

As the stock of EVs expands and their overall electricity needs grow, when the vehicles are charged—and how those patterns match up with renewable generation—will have significant effects on how vehicle electrification will impact electricity generators. This point is highlighted in Figure 14, which compares the AEO Reference case forecast for electricity generation in the United States by type of fuel. The Princeton high electrification scenario implies that generation will need to reach 7,000 TWh by 2050 to supply EVs, instead of the 5,000 TWh that were required prior to the conversion of the light-duty fleet to EVs. Note that this 40% increase in electricity demand at this stage includes only demands from LDVs, not the demands associated with electrifying any other vehicles or sectors of the economy.

Figure 13. Princeton assumptions about electric vehicle cost premiums in 2030



Source: Larson et al. (2021).

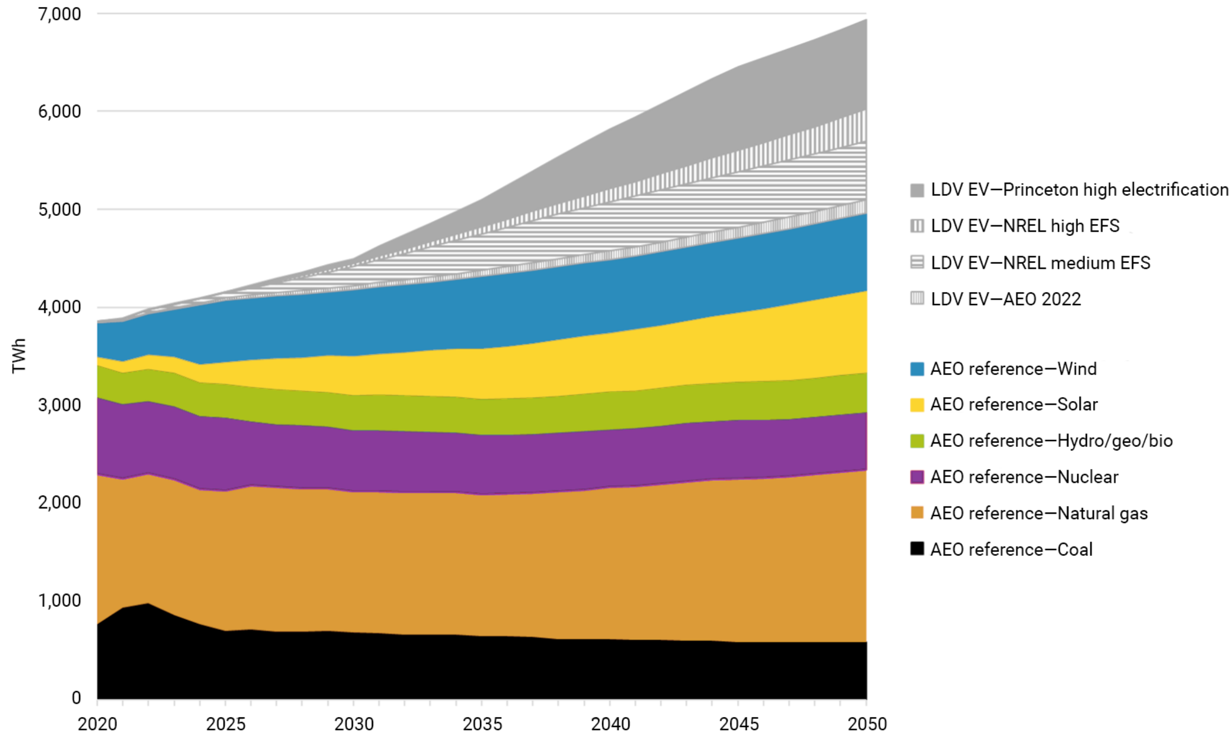
Electrification and Other Options: Medium/Heavy-Duty Vehicles

Medium- to heavy-duty vehicles are forecast to contribute around 8.5% of total US energy-related CO_2 emissions through 2050 in the AEO Reference case, which is slightly higher than the global average of 7.3% (ETC 2019). Unlike most LDVs that are used for short daily trips, heavier transport (cargo trucks, buses, and so on) can operate as either short- or long-haul vehicles. These different modes of transport lend themselves to a wider array of technology choices than are expected in LDVs (Figure 15).

The forecasted mix of energy sources for heavy vehicles across the available net-zero analyses suggests that electrification will be only one of several approaches to emissions reductions. Globally, the ETC analysis separates the responses into three categories of roughly equal importance: demand management (logistical efficiency), energy efficiency (engines and aerodynamics), and decarbonization options (electrification, hydrogen fuel cells, and other liquid fuels such as biofuels) (ETC 2019). As shown in Figure 15, the Princeton study splits trucking between battery and fuel cell vehicles for the US, with heavier trucks relying more on fuel cells.

Biofuels are not a contributor to emissions reductions in the Princeton study, which is also true in the global ETC examination of heavy transport (ETC 2019). ETC points out uncertainties in the true carbon intensity of biofuels, which might affect their treatment and pricing under a net-zero policy, and suggests that biofuels will not be able to compete on a cost basis with electric drivetrains in the long term. The IEA divides global transport technologies by daily driving distance between batteries and fuel cells and sees biofuels supplying 10% of energy needs in heavy transport in 2050, but direct most of the available biofuels and zero-carbon synthetic fuels toward hard-to-abate transportation areas (i.e., aviation and shipping).

Figure 14. AEO Reference case generation plus incremental demand from electric vehicles

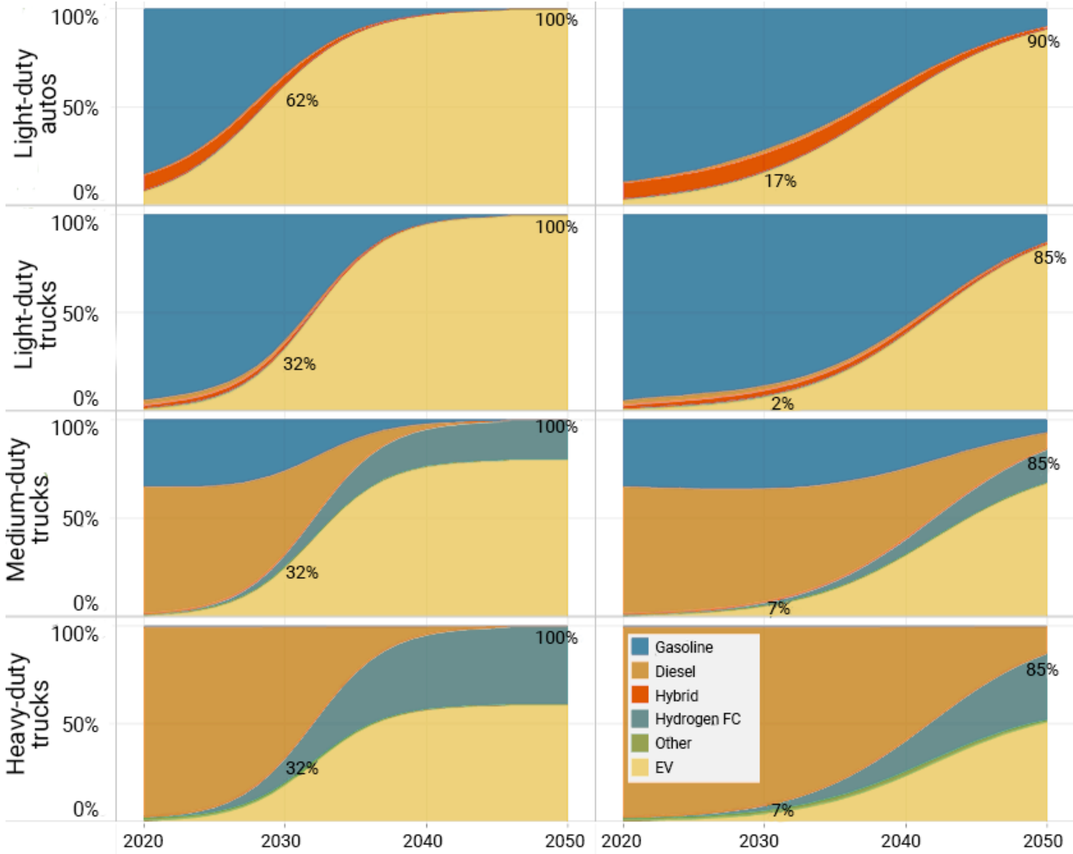


Source: Adapted from Larson et al. (2021), EIA (2022), and Zhou and Mai (2021).

Given its outsized presence in the US emissions footprint, truck electrification must be a major decarbonization priority. The noncommercial, subjective consumer preference considerations that significantly affect the uptake of LDVs (as noted previously) appear to be less impactful with medium-to-heavy–duty vehicles. The conclusions across the surveyed studies suggest that zero- and low-carbon trucks are already technically feasible, and that the best technology options for each type of vehicle will depend on how they are used. Charging for short-haul electric trucks that can be done overnight will make electrification preferable in this area and can be scaled up in the relative near term with the right policies and incentives. Electrification of longer-haul trucking is more technically challenging, with long ranges leading to longer charging times, with debate around charging-time length trajectories currently unresolved.

Cost comparisons and resulting time horizons for cleaning medium- to heavy-duty vehicle operations likewise vary, as do projections of wider transportation shifts that affect trucking needs. Even where direct vehicle electrification is not pursued, clean electricity sourcing retains primacy as the cost competitiveness of fuel cell vehicles is controlled by the cost of hydrogen, which is in turn dependent on the price of electricity if it is derived from electrolysis. This calculus is unlikely to be altered by biofuels, which are not anticipated to play a major role in decarbonizing heavy road transport.

Figure 15. Princeton report sales trends for light versus medium versus heavy vehicles



Source: Adapted from Larson et al. (2021), p. 46.

Electrification: Residential and Commercial Buildings

Emissions associated with fossil fuel use in buildings (and not accounting for upstream emissions from electricity used in buildings) are a smaller share of expected CO_2 emissions in US forecasts than electric power, transportation, and industrial sources, yet are important to consider for technological and behavioral reasons. Over the next three decades, forecast (AEO Reference case), fossil energy consumption in the residential sector is responsible for around 6.5% of US energy-related CO_2 emissions (excluding indirect emissions from electricity use), and the commercial sector is responsible for an additional 5.5% (see Figure 5). More than one-half of these emissions are related to space heating, with water heating in residential homes as the next largest share. Both sources have technology options available today that can shift heating needs from fossil fuels (natural gas and, to a much lesser extent, petroleum) toward electricity.

The most energy-efficient method for heating most buildings is air-source heat pumps that take advantage of temperature differentials between the indoors and outdoors of buildings. These heat pumps run on electricity and are backed up by electric resistance heating for particularly cold periods or times of the day when occupants wish to raise the heat quickly. The heat pumps also supply cooling needs in the summer through the same temperature differential process.

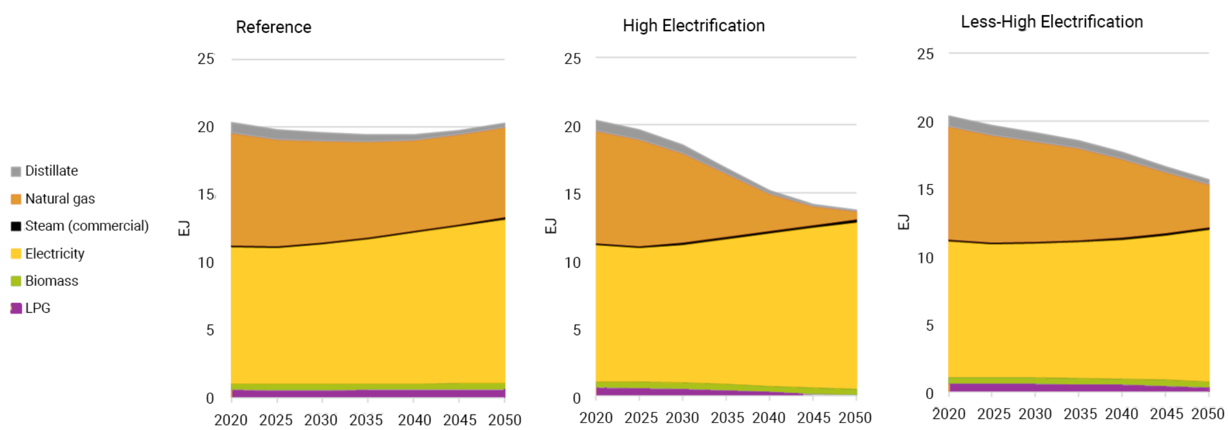
In the US, the Princeton high electrification scenario estimates that the market share for heat pumps is likely to grow from around 20% currently to 90% by 2050 in the residential sector. Heat pump penetration in the commercial sector is closer to 10% today and expected to reach 80% by 2050. Assumptions made in different technology pathways in their study about overall electrification trends influence how quickly these types of units displace fossil heating. The Princeton high electrification case displaces most natural gas heating by 2035, while the less-high case only eliminates most gas heat by 2045 (Figure 16). Similar trends are seen in commercial buildings, although the switch away from natural gas is more prolonged in this sector. Total energy use declines in the net-zero scenarios as more efficient electric equipment displaces natural gas heating and cooking, without the need for substantial increases in total electricity use.

Broadly put, leading projections assume that demand for residential energy-related services does not change in the net-zero scenarios. In other words, that behavior does not meaningfully change or respond to prices. Most fossil energy in heating, cooling, and cooking is replaced with electricity by 2035, though adoption varies significantly across US climate zones. By 2050 between 80% to 100% of all space and water heating and cooking are electric, with total energy use declining through efficiency improvements. Both residential and commercial buildings transition away from natural gas, with the commercial sector moving slower. These and other projections rest on technology cost models and a number of assumptions on issues such as behavioral change, the (in) elasticity of different energy options, energy prices and demands, and interactions with policies such as carbon prices or efficiency standards. Further assessments are possible that can more directly capture these and other factors.

Electrification and Other Options: Industry

With expected energy-related CO_2 emissions comprising almost one-quarter of all US emissions in 2050, decarbonizing the industrial sector will be a critical component of meeting net-zero goals. Reducing these emissions is expected to require a wide array of strategies beyond just electrification, depending on the specific type of manufacturing. This section looks across industries and technology options to see where opportunities are expected to exist to switch

Figure 16. Princeton report energy use in residential and commercial buildings



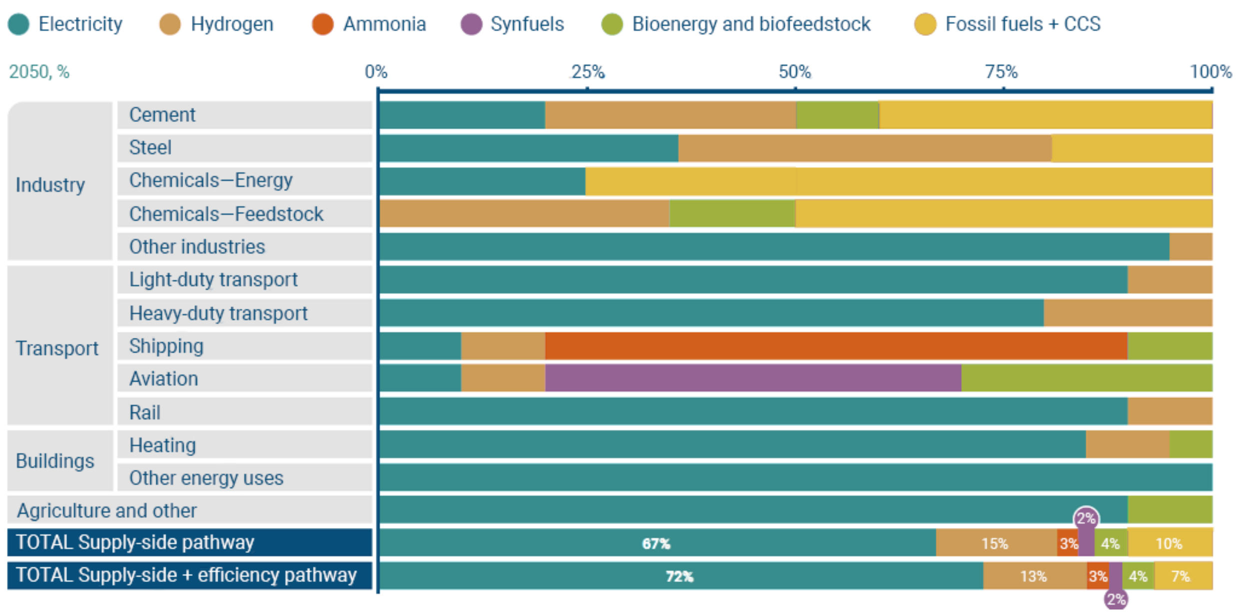
Source: Larson et al. (2021).

industrial energy consumption into electricity and where other areas should be evaluated because electrification is either not feasible or not cost-effective.

Past studies of heavy industry decarbonization at global levels have been more likely to diverge in their conclusions than expected electrification pathways in other sectors of the economy. The IEA finds that—in advanced economies—there is little change in industrial production volumes from 2020 across major industrial emissions sources, but chemicals, steel and cement are almost fully decarbonized. Meanwhile, globally, the IEA sees a combination of CCUS, electrification, biomass, efficiency, and hydrogen all playing roles in substantially lowering (by 95%) industrial emissions by 2050; however, significant amounts of fossil fuels with CCUS remain in the sector. In contrast, the ETC (2020) report expects industrial electrification to play a larger role than does IEA (Figure 17). Electricity use in a zero-carbon economy covers energy needs for the majority of industries; chemical feedstocks are largely made up of a combination of hydrogen and fossil fuels where carbon capture has been used, along with limited amounts of bioenergy. The shares of fossil fuels with CCUS are similar to those of electricity, with substantial amounts of hydrogen in the energy mix. For comparison, other sectors of the economy—aside from shipping and aviation—are much more heavily electrified.

In contrast to the globally focused conclusions from IEA and ETC, the Princeton report forecasts much more limited electrification in the US industrial sector as a whole (Figure 18). Fossil energy consumption (with or without CCUS) remains largely unchanged between 2020 and 2050 in the high electrification case, aside from the small increase in electricity use and a reduction in natural gas. Energy consumption by industry (across all fuel types) show substantial declines in energy for petroleum refining, but limited changes in other parts of the industrial sector. Bulk chemicals continue to grow as an energy consumer, but without switching into other energy sources. Had

Figure 17. ETC energy mix projections in a global net-zero economy



Source: ETC (2020).

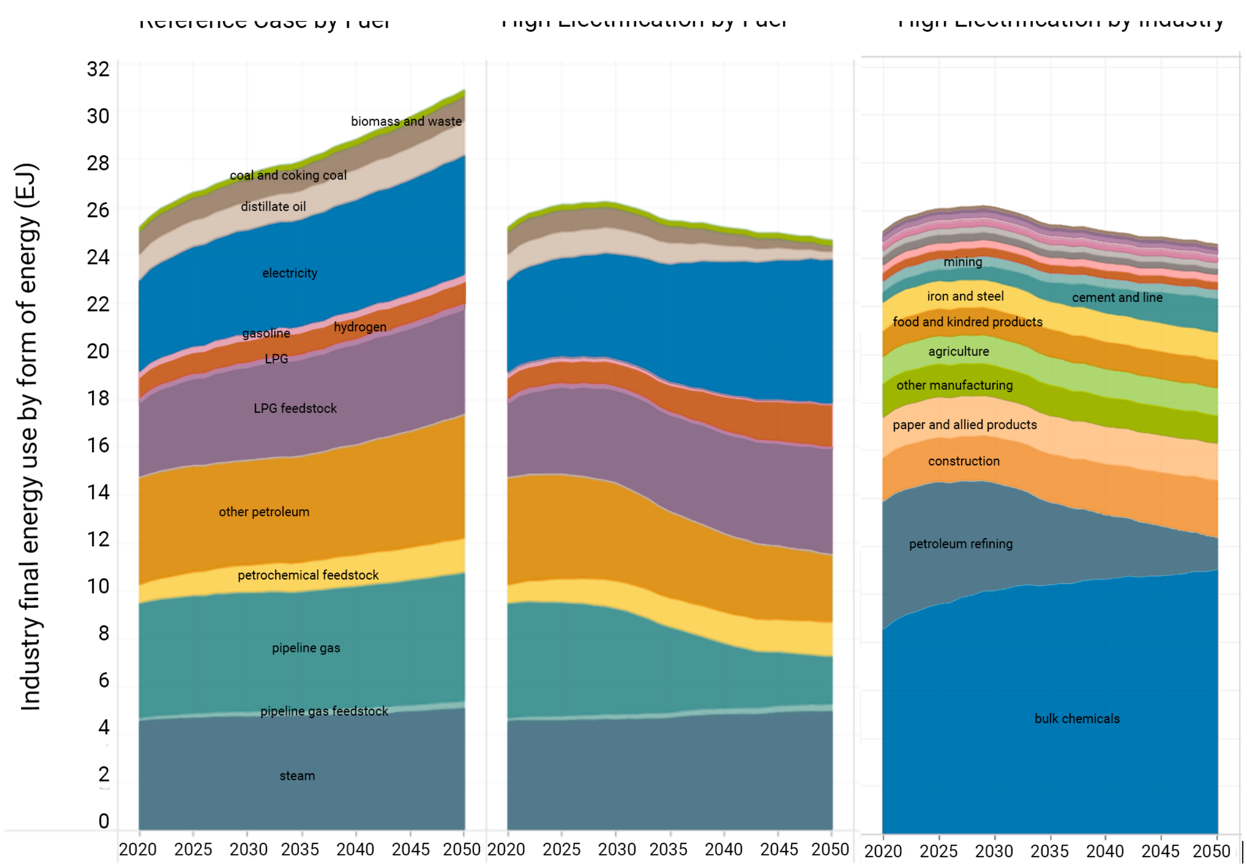
they made this switch, the amount of hydrogen in the industrial sector as a whole would have increased commensurately.

The Princeton investigation of US cement and steel industries (Figure 19) expects cement to operate with 100% of its capacity employing carbon capture by 2050, in contrast to the global findings by ETC. Similarly, the US steel industry is fully electrified by 2050 in the net-zero policy pathways.

As with transportation, and despite some projections seeing significant fossil use with CCUS, industrial decarbonization depends substantially on clean electricity production, transmission, and ready availability. This is true across scenarios because of the need for clean electricity used directly in industrial processes, indirectly in the creation of new feedstocks like green hydrogen, and even in cases with continuing fossil use with CCUS as this will not comprehensively cover industrial needs in net-zero scenarios. Such clean electricity expansion—with resulting economy-wide decarbonization potential—depends to significant degrees on conducive policy environments.

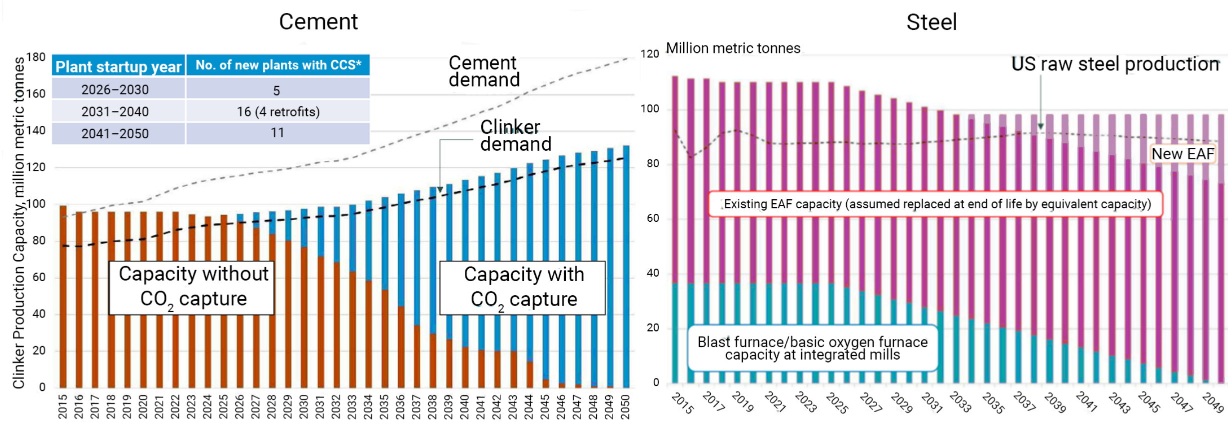
DAC technologies could alter these decarbonization scenarios in industrial sectors and beyond. While not yet commercially operational at scale, some analyses find DAC to be increasingly commercially viable and able to deliver substantial emissions reductions alongside secure geological storage (BPC 2021). With cost estimates declining from up to $1,000 per ton of CO_2

Figure 18. Princeton report industrial energy consumption by fuel type and industry



Source: Larson et al. (2021).

Figure 19. Princeton report cement and steel production investigation



Source: Larson et al. (2021).

captured a decade ago to roughly $100–$250 per ton estimated for future large-scale facilities, potential future price declines could bolster the case for widespread DAC deployment (AEIC 2021). A 1 million ton per year DAC facility is currently being planned in the Permian Basin, a sign that industrial-level efforts may be in the offing. Like many of the technologies and pathways explored in this and the previous section, DAC efforts are entering a new policy landscape with emerging incentives and finance options that could lead to accelerated deployment.

Potential Roles for Clean Fuels

Alternative electrification scenarios to those presented in the previous sections envisage a growing role for renewable natural gas (RNG) and hybrid configurations that combine clean hydrogen and fossil-free natural gas—particularly for heating. Analyses underpinning these scenarios question the viability and cost-effectiveness of heating demands being met wholly or largely by electricity, particularly in cold climates, and highlight the potential importance of fuel back-ups to meet emergency needs (Ameresco 2022, EPRI 2022, Brown 2021, National Grid 2022, E3 2022). Resulting scenarios see the partial electrification of domestic and commercial heating networks combined with the use of fossil-free gas and networked geothermal sources.

RNG, captured from sources such as waste management and agricultural systems that would otherwise emit methane, enjoys a comparatively low lifecycle carbon intensity when displacing fossil natural gas (Garg and Weitz 2019; CDP 2022). RNG can also be stored and transported through existing gas networks and is usable with existing appliances and domestic and commercial systems currently operating on fossil gas. Its current usage and availability are small but could expand with new investments and infrastructure. For instance, National Grid—servicing a customer base in the Northeast—estimates that it will ultimately procure 10% to 20% of the annual Eastern US RNG supply, meeting the gas demand for both its residential and commercial customers (National Grid 2022). These inputs will only succeed as part of a net-zero solution if they effectively combine with increased electrification, increased building and heating system efficiency, and effective synergies with other non-electric sources—particularly hydrogen.

These alternative electrification scenarios also envision the blending of hydrogen with natural gas or RNG at significant volumes running through existing gas networks, and then being used in customer appliances without significant upgrades to infrastructure or equipment. When coupled with wind or solar resources that are able to produce more electricity than the grid needs, which can then be stored for later use, these scenarios suggest that the resulting green hydrogen could play significant roles in long-duration renewable energy storage and as a source of fuel for power generation, transportation, and particularly heating—especially in instances where electrification without clean fuels might prove suboptimal in terms of cost, reliability, customer preference, or otherwise. In parts of the US pursuing offshore wind, including areas along the eastern seaboard with high current gas demand, multiple projects propose electrolysis-driven hydrogen production and, as the following section details, “hydrogen hubs” are gaining federal and state-level support.

The resulting decarbonization scenario sees local and piped sources of RNG increase at the same time that expanding renewable energy capacity provides higher volumes of clean hydrogen. When combined with greater grid electrification, efficiency gains that reduce demand, and additions from networked geothermal, these clean fuels contribute to an integrated system that provides low-carbon heating. Major buildouts would be needed in each of these categories for this scenario to come to fruition. The next phase of this research will thus examine and assess this alternative approach in further detail as part of an overall assessment of potential US electrification pathways. As the following section demonstrates, the trajectory of the electrification–clean fuel intersection and broader possibilities for the shape of net-zero pathways are markedly affected by a shifting policy landscape.

THE US DECARBONIZATION POLICY LANDSCAPE

While the US has enjoyed emissions declines for nearly two decades, the prior two sections of this report have revealed that such BAU trends (excluding recent legislation) are insufficient to meet the US’s net-zero goals and, by extension, the climate change challenge. This insufficiency results both from the difficulty of evolving beyond the entrenched energy, economic, and social systems that fuel the US emissions profile, and from a policy environment that, particularly at the federal level, was often misaligned with ambitious decarbonization efforts. Nascent changes to this policy environment are creating opportunities for energy transitions at greater pace and scale than those captured in the historical trends and future projections presented here thus far and are explored further in this section.

Like any country, the US requires widespread federal and subnational policies to bring about reductions from the millions of discrete sources of GHG emissions. The previous sections of this report analyze central high-emitting sectors that, in turn, have high mitigation potential. Reaching this potential will require effective federal and subnational policies in the form of a mix of incentive-based and regulatory approaches that directly and indirectly affect national energy transition and decarbonization trajectories. This section offers an overview of key existing policies, their drivers, and their potential implications.

Key Federal Executive and Legislative Actions

The Biden administration’s NDC to address global climate change pledges to eliminate carbon emissions from the electricity sector by 2035 through a combination of efficiency gains; carbon-free electricity; electrifying transport, buildings, and select industry; and scaling up new energy sources and carriers (The White House 2021b). Prior to the recent passage of major federal legislation, NDC and other climate goals were pursued largely through executive action at the federal level. For instance, Executive Order 14008, "Tackling the Climate Crisis at Home and Abroad," stipulates that the federal budget process is a conduit through which agencies shall prioritize action on climate change (Executive Office of the President 2021). This formed the basis for FY22 Biden administration budgetary requests of billions in increased federal spending and lending to support GHG reductions, including for clean energy projects and workforce development ($2 billion); clean energy, storage, and transmission projects for rural areas ($6.5 billion); efficiency grants ($1.7 billion); federal EV procurement ($600 million); the remediation of abandoned oil and gas wells to reduce methane leakage ($580 million); investment in the EV market including rebates, battery manufacturing, charging infrastructure, and more ($174 billion); and research, design, and demonstration (RD&D) in clean energy innovation across nondefense agencies ($10 billion) (OMB 2021, 20). These requests were scaled back but not eliminated during budget reconciliation processes, and President Biden's FY23 budget redoubles climate and energy transition spending requests. Such budgetary outlays and reconciliation processes for finalizing them have waned in relevance, however, with 2021–2022 legislative outcomes.

More durable energy transition and climate mitigation policy is possible through congressional legislation. Yet, except for irregular flurries of legislative effort to price and trade carbon[1] and more recent interest in implementing a national border carbon adjustment,[2] there had been relatively scant legislative efforts to nationally regulate GHG emissions or create wholesale energy transition policies. US legislation was typically more indirect and/or more granular, such as through adjustments to federal fuel efficiency standards, tax incentives for renewable energy, and CCUS efforts.[3]

Two vital exceptions to this norm now take primacy in the US net-zero policy landscape: the Bipartisan Infrastructure Law (BIL) (2021), and the Inflation Reduction Act (IRA) (2022). Both the BIL and especially the IRA promise significant potential impact and, given their foundation in law, will prove more robust than the previously discussed executive actions. The BIL includes significant funding for transmission and grid improvements ($75 billion), increasing resilience of the nation's natural and physical infrastructure ($50 billion), investing in a national EV charging infrastructure ($7.5 billion), and reducing methane emissions from orphaned oil and gas wells ($4.7 billion). Perhaps most notably in terms of galvanizing emerging, nascent and future clean energy pathways, the BIL funded the creation of the US Department of Energy (DOE) Office of Clean Energy Demonstrations (OCED) to support demonstration projects in clean hydrogen, carbon capture, grid-scale energy storage, small modular reactors, and beyond. With over $20 billion in initial funding, the OCED will fund major R&D and proof-of-concept projects that seek to galvanize follow-on private sector investment to deploy clean technologies.[4] Where successful,

[1] Most notably through the American Clean Energy and Security Act (colloquially the Waxman-Markey Act) in 2009 and, to a lesser extent, the American Power Act (colloquially the Kerry-Lieberman Act) in 2010.

[2] Most notably the FAIR Transition and Competition Act (colloquially the Coons-Peters Act) in 2021.

[3] See for example: Sherlock, M. F., *Energy Tax Provisions: Overview and Budgetary Cost, CRS Report R46865 (Washington, DC: Congressional Research Service, 2021),* https://crsreports.congress.gov/product/pdf/R/R46865; and Folger, P., *Carbon Capture and Sequestration (CCS) in the United States, CRS Report R44902 (Washington, DC: Congressional Research Service, 2022),* https://sgp.fas.org/crs/misc/R44902.pdf.

[4] For a brief introduction of this OCED mandate see: https://www.energy.gov/articles/doe-establishes-new-office-clean-energy-demonstrations-under-bipartisan-infrastructure-law.

these investments may yield outsized energy transition dividends beyond those currently foreseen and modeled.

However, these successes notwithstanding, the BIL's intended investments in energy transition sectors were pared down substantially from the Biden administration's original goals. Major funding for RD&D in clean technology areas such as utility-scale energy storage, CCUS, hydrogen, floating offshore wind, and more did not clear the legislative process. Major culls to investments in clean energy manufacturing and training, along with tax credit schemes for clean energy manufacturing facilities, reduce the BIL's energy transition heft, as does its failure to retain stipulations that would reform tax preferences for fossil fuels. Such mixed outcomes demonstrate the headwinds faced by climate and energy transition policies in the US, which—while still on display—did not preclude the passage of the IRA in August 2022. Despite its name, the IRA is the most targeted and potentially impactful piece of domestic US climate legislation of the twenty-first century to date.

A reconstitution of the Build Back Better Act of 2021, which passed the US House of Representatives but stalled in the Senate, the IRA delivers a series of incentives to drive the national energy transition (among other aims). These incentives primarily take the form of clean energy tax credits along with programs and pools of finance for commercial and emerging clean technologies, infrastructure, and products. Fees and punitive regulations (e.g., for methane leaks from oil and gas operations) are part of the IRA, but to lesser degrees than positive incentives. Table 1 provides the core energy transition components of the IRA, which are too expansive to comprehensively summarize here.[5]

In total, the IRA commits roughly $369 billion[6] in funding for climate and clean energy provisions and specifically incentivizes the development of a domestic US supply chain to produce clean energy. It also conditions the issuance of renewable energy leases on federal lands on the offering of land for oil and gas development, as well as the completion of multiple 2022 lease auctions that were previously canceled. However, there is no requirement that oil and gas leases actually be sold, and recent years have seen declines in industry interest in developing oil and gas resources on federal land (Webb 2022). This fossil-fuel support resulted from political compromises that ultimately led to the IRA's successful passage and has the potential to temper to some extent the nature, timing, and/or scope of its effects on the energy transition. However, initial analysis suggests the IRA will have major impacts on US emissions reduction efforts.

Three initial early IRA assessments warrant attention. The Rhodium Group estimates that the IRA will reduce US net emissions by 32% to 42% below 2005 levels by 2030, compared to 24% to 35% without it (Figure 20), and scale clean generation to supply up to 81% of all electricity (Larsen et al. 2022).The Princeton REPEAT project comes to relatively similar conclusions (Figure 21), estimating that the IRA will cut annual emissions in 2030 by roughly 1 billion metric tons beyond that which would have occurred without it, closing approximately two-thirds of the previous emissions gap between BAU trends and the national target of a 50% reduction from 2005 by 2030 (Jenkins et al. 2022).

[5] For an effective summary see: https://bipartisanpolicy.org/blog/inflation-reduction-act-summary-energy-climate-provisions/.

[6] Importantly, this oft-cited figure is a projection based on the amount of investment expected, and tax credits for hydrogen and renewable energy are not necessarily capped at this or any other figure.

Table 1. Inflation Reduction Act—Key energy transition components

Provision	Key Components
New clean hydrogen production tax credit	• Creates a new 10-year incentive for clean hydrogen production with four tiers • Projects must begin construction by 2033 • Eligibility includes retrofit facilities
New advanced manufacturing production tax credit	• Tax credit for producing clean energy components in the US • Includes solar components, wind turbine and offshore wind components, inverters, many battery components, and critical minerals • Begins to phase out in 2029 and phases out completely in 2032
Nuclear power production tax credit	• Nuclear power production credit[a] • Available to facilities already in service in 2024, ends after 2032
Extension of renewable electricity production tax credit[b]	• Extends existing production tax credit (PTC) for geothermal, wind, closed- and open-loop biomass, landfill gas, municipal solid waste, hydropower, and marine and hydrokinetic facilities to 2024 • Increases hydropower, municipal solid waste, and marine and hydrokinetic credit to full value (previously halved) • Strikes the offshore wind credit phaseout for facilities placed into service before 2022
New clean electricity production tax credit	• Creates a PTC credit of 1.5 cents per kWh of electricity produced and sold or stored at facilities placed into service after 2024 with zero or negative GHG emissions • Credits phase out in 2032 or when emission targets are achieved
Extension of energy investment tax credit	• Extends existing energy investment tax credit for applicable energy projects in most cases to 2024 and maintains a 10% or 30% credit
New clean electricity investment tax credit (ITC)	• Creates ITC credit of 30% of the investment in the year the facility is placed in service • Clean electricity projects smaller than 5 MW can include the costs of interconnection under the ITC • Credits are set to phase out in 2032 or when emission targets are achieved, whichever is later
Advanced energy project credit	• Extends 30% investment tax credit to low-carbon industrial heat, carbon capture, transport, utilization and storage systems, and equipment for recycling, waste reduction, and energy efficiency • Expands credit to include projects at manufacturing facilities that want to reduce their GHG emissions by at least 20% • Tax credit is funded at $10 billion for eligible projects
Fuel tax credits	• Creates a new technology-neutral two-year tax credit for low-carbon transportation fuel[c]
New sustainable aviation fuel credit	• Creates an incentive to lower aviation transportation emissions[d]

Clean vehicle tax credits	• Maintains $7,500 consumer credit for purchasing qualified new clean vehicles, including EVs, plug-in hybrids, and hydrogen fuel cell vehicles[e] • Creates a $4,000 consumer tax credit for purchasing previously owned clean noncommercial vehicles, including EVs and plug-in hybrids[f] • Creates a $7,500 commercial tax credit for purchasing qualified clean class 1–3 vehicles, including EVs • Credit increases to $40,000 for class 4 and above commercial vehicles
Residential energy efficiency	• Extends credit through 2034 for residential solar, wind, geothermal, and biomass fuel[g] • Expands eligibility to battery storage technology • Extends credit for energy efficiency home improvements through 2032[h] • Funds $4.3 billion through 2031 to DOE for state energy offices to provide rebates for whole-house energy saving retrofits • Funds $4.3 billion through 2031 for grants from DOE to states and tribes to implement a high-efficiency electric home rebate program • Provides up to $14,000 in tax credits per household, including $8,000 for heat pumps, $1,750 for heat pump water heaters, and $840 for electric stoves[i]
Energy innovation	• Creates new $5.8 billion program under the OCED for emissions-reducing projects in iron, steel, concrete, glass, pulp, paper, ceramics, and chemical production • Funds DOE National Laboratory improvements[j] • Funds $150 million for the Office of Fossil Energy and Carbon Management, $150 million for the Office of Nuclear Energy, and $150 million for the Office of Energy Efficiency and Renewable Energy for infrastructure and general plant projects through 2027 • Provides $700 million in additional funding to the DOE Advanced Nuclear Fuel Availability program through 2026
Offshore wind	• Makes $100 million available for the planning, modeling, analysis, and development of interregional transmission and optimized integration of energy generated from offshore wind • Requires an oil and gas lease sale of 60 million acres in the prior year for offshore wind lease issuance through 2032 • Lifts the offshore wind moratorium in the southeastern US and Eastern Gulf and allows leasing in the US territories
Oil and gas	• Increases offshore oil and gas royalty rates to a minimum of 16.66% from 12.5% through 2032 • Increases onshore oil and gas leasing minimum bid from $2 to $10 per acre through 2032 • Increases annual rental rates for new onshore oil and gas leases
Methane emissions reduction program	• Funds $1.55 billion for EPA to provide incentives, grants, contracts, loans, and rebates for facilities, well operators, and communities to enable methane emission reduction activities[k] • Establishes a maximum annual methane waste emission rate of 25,000 metric tons of CO_2e per facility and imposes penalties at $900 per ton in 2024, increasing to $1,500 per ton by 2026, with exceptions for operators in compliance with EPA regulations (thus providing a regulatory backstop)

Investments in the permitting process	• Funds $760 million through 2026 for DOE grants to facilitate and accelerate the siting and permitting of interstate transmission projects • Funds $350 million through 2026 for the Environmental Review Improvement Fund[l]
Clean energy financing	• DOE Loan Programs Office (LPO) provides over $40 billion in available loan and loan guarantees[m] • Creates Energy Infrastructure Reinvestment Financing program with $5 billion to carry out program authorities and $250 billion in loan authority through 2026[n] • Creates Greenhouse Gas Reduction Fund to enable EPA to make grants to state, local, regional, and tribal programs that provide financial support to low- and zero-carbon technologies and projects[o] • Provides $2 billion in grants through 2031 to retool existing auto manufacturing facilities for domestic production of clean vehicles • Funds $500 million to carry out the Defense Production Act (1950) for critical mineral processing and heat pumps • Funds $10 million to EPA for new grants to support advanced biofuel industries that provide 50% GHG emission reduction compared to conventional fuels • Provides $500 million until 2031 for competitive grants to support blending, storing, supplying, or distributing biofuels with higher levels of ethanol and biodiesel

[a] 1.5 cents multiplied by kilowatt-hours of electricity produced minus 16% of the facility's gross recipients in excess of 2.5 cents per kilowatt-hour.

[b] Many PTCs and ITCs in the IRA apply a 10% bonus for meeting domestic manufacturing requirements for steel, iron, or manufactured components and a 10% bonus for facilities located in brownfield sites or fossil fuel communities.

[c] Maximum credit is $1 per gallon (or $1.75 per gallon for sustainable aviation fuel) multiplied by an emissions factor. The emissions factor is calculated proportional to a maximum emission rate standard of 50 kilograms of CO_2e per 1 MMBtu.

[d] Credit starts at $1.25 per gallon for aviation fuel that reduces GHG emissions by 50% and increases by 1 cent for each additional percent reduction, maxing at $1.75 per gallon.

[e] A certain percentage of the critical minerals used in battery components are not extracted or processed in the US or a free trade agreement country or recycled in North America. The percentage required increases from 40% in 2024 to 80% in 2026. It determines a maximum cost of $80,000 per vehicle for vans, SUVs, and pickups; $55,000 for other vehicles; and an income eligibility limit of $150,000 or $300,000 for joint filers.

[f] Sets a maximum sale price of $25,000. Model must be at least two years older than the year of sale. Implements an income eligibility limit of $75,000 or $150,000 for joint filers.

[g] Maintains the previous credit rate but adjusts the project dates. Applies a 30% credit for projects started between 2022 and 2032. Credit decreases to 26% for projects started in 2033 and 22% for projects started in 2034.

[h] Increases credit from 10% to 30%. Replaces lifetime cap on credits with a $1,200 annual credit limit, including $600 for windows and $500 for doors. Increases limit to $2,000 for heat pumps and biomass stoves, removes eligibility on roofs, expands credit to cover the cost of home energy audits up to $150 and electrical panel upgrades up to $600.

[i] Includes further rebates for improvements to electrical panels or wiring and home insulation or sealant. Eligible recipients must fall below 150% of the area median income.

[j] Specifically, $133.2 million for laboratory infrastructure projects, $321.6 million for laboratory facilities, $800.7 million for laboratory construction and equipment, $294.5 million for energy sciences projects.

[k] Including monitoring, reporting, source plugging, obtaining technical and financial assistance, installing innovative solutions, mitigating negative health impacts, and performing environmental restoration.

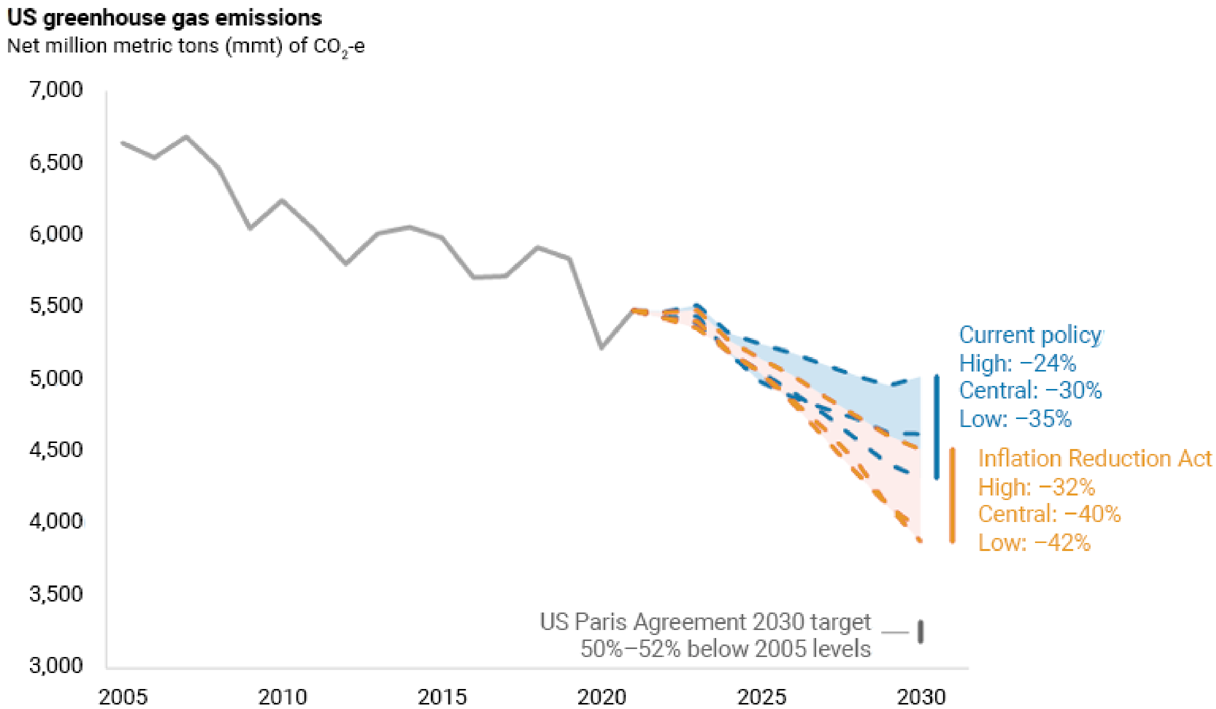
[l] Part of the Fixing America's Surface Transportation (FAST) Act that seeks to accelerate and streamline the environmental review process. Provides $40 million through 2026 for EPA to invest in staffing and equipment that enables more accurate and timely environmental reviews. The IRA also provides $100 million through 2026 for EPA to develop review documents and speed the environmental review process, and $20 million through 2026 for NOAA to invest in staffing and equipment that lead to more accurate and timely reviews.

[m] Funding falls under three programs: $21.9 billion for Title 17 (innovation), $15.1 billion for Advance Vehicles Technology Manufacturing (AVTM), and $2 billion for the Tribal Energy Loan Guarantee Program (TELGP).

[n] Projects must retool, repower, repurpose, or replace energy infrastructure that has ceased operation or enable operating energy infrastructure to avoid, reduce, utilize, or sequester GHG emissions.

[o] Provides $11.97 billion through 2024 to make grants for eligible financial entities, $15 billion through 2024 to make grants for eligible entities to provide financial and technical support and support the deployment of clean energy technologies in low-income and disadvantaged communities, and $30 million for administrative costs of the program through 2031.

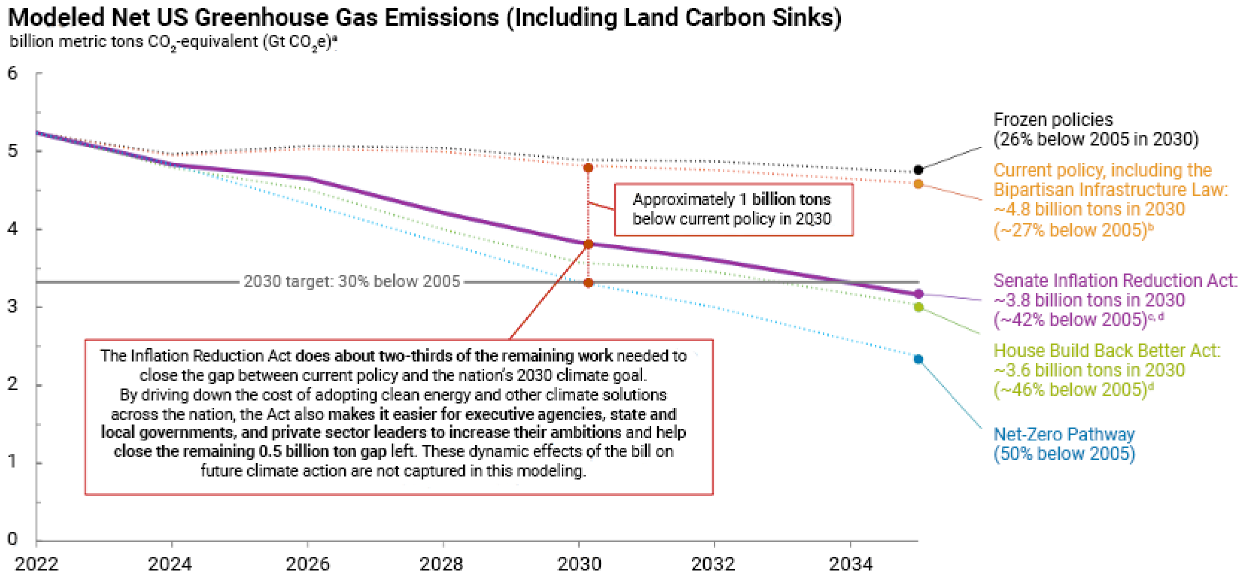
Figure 20. Rhodium Group projection of IRA emissions impact



Source: The range reflects uncertainty around future fossil fuel prices, economic growth, and clean technology costs. It corresponds with high, central, and low emissions scenarios detailed in Taking Stock 2022 (Larsen et al. 2022).

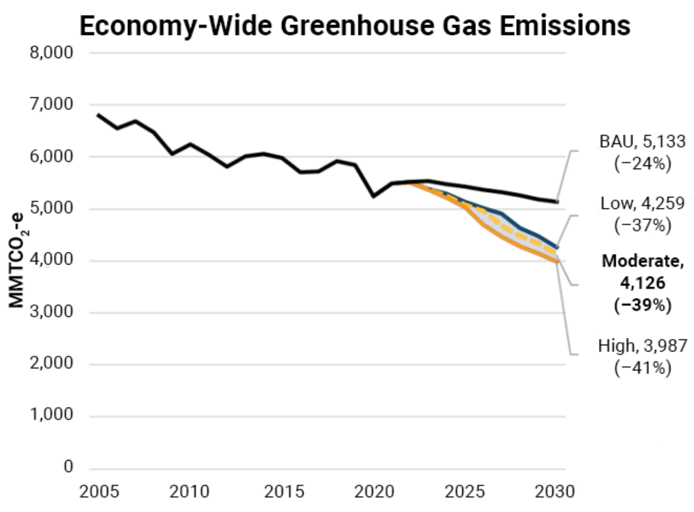
Very much in the same vein, Energy Innovation estimates that the IRA could cut GHG emissions 37% to 41% below 2005 levels (Figure 22), and that for every ton of emissions increases generated by IRA oil and gas provisions, more than 24 tons of emissions are avoided by the other provisions (Mahajan et al. 2022).

Figure 21. Princeton projection of IRA emissions impact



Source: Adapted from Larson et al. (2021).
[a] CO_2 equivalent emissions calculations use IPCC AR 100-year global warming potential as per EPA Inventory of Greenhouse Gas Emissions and Sinks. All values should be regarded as approximate given uncertainty in future outcomes.
[b] Modeled emissions reduce any changes in passenger and freight miles traveled due to surface transportation, rail, and transit investments in IIJA. According to the Georgetown Climate Center, emissions impact of these changes depends heavily on state implementation of funding.
[c] Results reflect preliminary modeling based on the July 27, 2022, draft legislation.
d Results reflect average of estimated high and low oil and gas production scenarios, which span ±20 Mt CO_2e in 2030. Impact on land carbon sinks based on analysis by Energy Innovation (Jenkins et al. 2022).

Figure 22. Energy Innovation projection of IRA emissions impact



Source: Mahajan et al. (2022).

These projections provide a strong foundation for interpreting the potential impacts of the IRA. They are far from deterministic, however, and the results of the law will be fluid and depend on the effectiveness of its provisions. A core premise of the IRA—beyond the broad political palatability of incentives versus constraints—is that the roughly decadal time horizon of many of its provisions will enable clean energy to scale across the US energy system and reduce emissions in the near term while also setting the foundation for long-term reductions toward net-zero. As such, the strategies and structures underpinning the IRA's constituent parts and programs will evolve and require timely analysis, including that which feeds private sector actors seeking to take advantage of IRA opportunities.

While these projections reveal the promise of the IRA, they assume a degree of linearity between incentives provided, capital invested, ensuing cost curves, and emissions impacts that obscures significant uncertainty. Constraints in supply chain developments, human capital progress, degrees of public acceptance for large solar and wind expansions, broader permitting challenges and long lead times, and beyond will all affect the impacts of IRA provisions. These effects must be continuously analyzed—including at the subnational level.

The State Policy Landscape

The absence of durable and comprehensive federal drivers of energy transition and emissions control policies prior to the IRA led to states taking a range of actions. Thus far, 33 states have released climate action plans or are in the process of revising or developing them, which broadly include GHG reduction targets and actions planned or implemented for reaching them.[7] Twenty-four states plus the District of Columbia have specific GHG emissions targets, albeit from different baseline years and of varying degrees of ambition.

Carbon pricing and electricity portfolio standards cover a substantial portion of the US power production and emissions profiles via subnational cap-and-trade programs.[8] California's system has operated since 2013; covers power, fossil fuel distributors, and major industrial emitters; and is linked to its 2030 emissions reduction goal.[9] On the eastern seaboard, 12 states on the eastern seaboard participate in the Regional Greenhouse Gas Initiative (RGGI), a cap-and-trade program targeting electric power that went into effect in 2009 and is likewise tied to a 2030 emissions target.[10] Thirty states, three US territories, and the District of Columbia have mandated clean energy standards (CESs) or renewable portfolio standards (RPSs) requiring a minimum amount of electricity be generated by renewables, with 11 jurisdictions requiring that 100 percent of electricity ultimately come from eligible low-carbon sources.[11] There are signs that renewable heating fuel standards (RHFS)—which require sellers of natural gas to procure a growing proportion of their supply from qualifying fuels such as RNG and/or low-carbon hydrogen—may be in the offing to

[7] Of these, 23 states have released plans, 8 states are updating plans, and 1 state is developing a plan (Center for Climate and Energy Solutions, n.d.).

[8] For a summary of all carbon pricing instruments operating in the United States see: World Bank, *State and Trends of Carbon Pricing 2021, (Washington, DC: World Bank, 2021), p. 71* https://openknowledge.worldbank.org/handle/10986/35620.

[9] This goal is a 40% reduction in GHGs below 1990 by 2030.

[10] RGGI states are Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, Virginia, Vermont, and, as of April 2022, Pennsylvania.

[11] The jurisdictions with 100% clean energy standards are California, Colorado, the District of Columbia, Hawaii, Massachusetts, New Mexico, New York, Oregon, Puerto Rico, Virginia, and Washington.

drive the expansion of RNG and hydrogen supply chains along with their integration as heating sources.[12]

Transportation has likewise proven to be a space for state-level mitigation action, as well as an additional battleground for interpreting the Clean Air Act. Forty-five states and the District of Columbia offer incentives for EVs and/or hybrids, including rebates, tax credits, and favorable electricity rate treatment (Igleheart 2022). The incentives range from tax credits or rebates for fleet acquisition goals, exemptions from emissions testing, or favorable electricity rate treatment. Seven states have some version of a low-carbon or alternative fuel standard, and 13 states are applying a RGGI-type model to the transportation sector via the Transportation and Climate Initiative. Beginning in 2009, California set standards—in collaboration with the federal government—on fuel efficiency and emissions across multiple vehicle categories, as well as requirements that auto manufacturers increase the number of zero-emissions vehicles sold in the state (California Air Resources Board, n.d). These policies became mired in federal disputes, with the Trump administration–era EPA curtailing California's right to set vehicle emissions standards stronger than those at national levels, which was later restored by the Biden administration in March 2022 (Office of Governor Gavin Newsom 2022). Such discontinuity could readily resurface.

Policy Landscape Implications

The IRA and BIL provide an important foundation for investments in soft and hard energy transition infrastructure. For the US to reach its climate goals, these federal government investments will need to galvanize a multiplicative effect of private and subnational investments—along with construction of infrastructure and deployment of new technology—at an unprecedented scope, scale, and pace. At present these investments appear promising for fostering such effects in the core sectors of clean electricity, vehicle electrification, industrial decarbonization, and advanced technologies, but uncertainties abound. Scaled-up private sector efforts are needed to both to drive their own energy transition operations and those of their sector peers, along with effectively advocating for more regulatory certainty and energy transition prioritization from governments at multiple levels.

CONCLUSION: CHALLENGES AND OPPORTUNITIES FOR US NET-ZERO EMISSIONS AND NEXT STEPS FOR ENERGY PATHWAYS USA

The BIL and IRA created a dynamic shift in the US policy landscape. The impact of this shift is still being assessed and will ultimately depend on unknown implementation efficacy and engagement on challenges that are outside statutory frames at federal and state levels. Critically, the IRA and BIL provide an important foundation for investments in soft and hard energy transition infrastructure, but do not address all components of an equitable transition. For the US to reach its climate goals, these federal investments will need to galvanize a multiplicative effect of private and subnational investments—along with construction of infrastructure and deployment of new technology—at an unprecedented scope, scale, and pace. At present these investments appear

[12] This includes a RHFS that was introduced in Massachusetts through legislation in 2021. See: https://malegislature.gov/Bills/192/H4081.

promising for fostering such effects in the core sectors of clean electricity, vehicle electrification, industrial decarbonization, and advanced technologies, but uncertainties abound. Scaled-up private sector efforts are needed to both to drive their own energy transition operations and those of their sector peers, along with effectively advocating for more regulatory certainty and energy transition prioritization from governments at multiple levels.

The provisions of the current federal policy mix are indicators of this administration's assessment of key challenges and prioritization of policy levers to accelerate the energy transition. Of note is the BIL and IRA focus on financial policy incentives for clean technology deployment. As noted previously, some barriers to such deployment are not addressed and will need additional policy tools to accelerate deployment. For example, infrastructure siting and build-out is a long-recognized barrier to an accelerated electricity transition. The Council on Environmental Quality found that, across all federal agencies, the average Environmental Impact Statement completion time (from notice of intent to record of decision) was 4.5 years; the median was 3.6 years (CEQ 2020). Multiple intersecting challenges, including land availability and competition, species and ecosystem prioritization, and social resistance to siting decisions can all decelerate US net-zero progress. These considerations have myriad direct and indirect consequences, including the potential future preferencing of less land-intensive energy resources such as geothermal, nuclear, and fossil fuel with CCUS as compared to wind and solar; site selection for wind, which has highly variable space requirements per gigawatt-hour; and decisions on transmission infrastructure and grid integration. They also impact national efforts to mine for needed clean energy materials domestically—which influences their costs, availability, supply chain reliability—and the ability of projects to receive tax credits based on domestic content requirements. The IRA and BIL provisions bring national attention to a suite of priorities that are essential for the energy transition, each of which has associated challenges.

Key areas for accelerating the US energy transition include the following:

- Accelerated deployment of clean electricity and the electrification of vehicles
- Accelerated energy efficiency and the electrification of buildings
- Development and deployment of advanced energy technologies, including hydrogen, CCUS, DAC, zero-carbon liquid fuels, and advanced nuclear and geothermal energy sources
- Reduced industrial-sector emissions through electrification, efficiency upgrades, the deployment of advanced energy technologies, and low- or zero-carbon fuels
- Reductions in methane emissions in oil and gas exploration and development
- Enhanced conservation and sequestration in forest and agricultural lands
- Accelerated state and regional coordination and efforts
- Ensured equitability for the energy transition
- Increased domestic supply chain sourcing to support all aspects of the transition

Forward progress in any of these key areas will impact efforts in others, creating synergies or unanticipated hurdles and deceleration. While this report is not designed to deeply assess each of these areas, we highlight the following as areas of future focus for Energy Pathways USA. Future work will build on these core areas and will include overarching attention on ensuring the energy transition is both equitable and aligned with ambitious net-zero targets.

Issue Areas

Clean Electricity Deployment and Electrification

Accelerating the deployment of clean electricity and the electrification of vehicles, including siting, transmission incentives, utility-scale energy storage, and the transportation and storage of CO_2, is the foundation for economy-wide decarbonization. The IRA provides $760 million through 2026 for DOE grants to facilitate and accelerate the siting and permitting of interstate transmission projects, $350 million through 2026 for the Environmental Review Improvement Fund, and funding for capacity enhancements throughout review agencies. These and other provisions are intended to shrink administrative burdens and reduce permitting times and are necessary, but not sufficient in and of themselves, to catalyze the acceleration of siting and permitting required to meet decarbonization goals. Both national and site-specific work is needed to further elucidate siting and licensing barriers and develop solutions that can supplement and help inform these government-driven efforts. Near-term analysis will therefore focus on issues, challenges, and opportunities relating to siting and permitting, supply chain development and management, and interjurisdictional and interfirm coordination—focusing on how these variables affect clean electricity deployment and electrification and industrial decarbonization, and policy options for addressing them.

Subnational Coordination

A longstanding difficulty with achieving consensus on climate policy is the uneven distribution of energy consumption, energy production, and manufacturing within US states. States with the smallest populations—and potentially higher transport needs resulting from dispersed population centers—have the highest per capita energy use. Residential and commercial use roughly follows weather patterns measured by heating degree days, with colder states using more energy for heating purposes. Industrial use follows roughly the same distribution of energy use in other sectors where the central states have much higher energy use per person than those on the coasts. These physical realities combine with a wide range of energy and emissions regulation policies and instruments and the presence of multiple regional and state grids, RTOs, and ISOs.

Net-zero efforts necessitate further integration of energy transmission, storage systems, markets, preferential dispatch connections, demand management measures, and more across currently siloed systems. In lieu of more uniform federal policies that are unlikely to emerge, there is a need for creative analysis that offers both broad principles for subnational cooperation across systems and bespoke solutions that target specific state and regional actors. Moreover, it will be important to assess how relevant federal policies, even if not uniform, can incentivize or otherwise affect the development of cooperative subnational efforts.

Strengthening Supply Chains

The IRA takes key initial steps to address supply chain challenges and bolster technology component production in North America and builds on other federal efforts to create a resilient supply chain. For example, it creates a $7,500 tax credit for battery components that requires 100% to be produced in North America by 2029. The ultimate impact of these and other incentives created by the IRA will depend not only upon the supply chain investments they spur over the course of this decade, but also the extent to which the demand they create is sustained over the longer term, which in turn may depend on future policies. DOE's 2022 report assessing supply chain challenges, proposing a strategy for ensuring that key elements of the supply chain are available and insisting that the supply chain will not decelerate the policy efforts made in other areas, shows prioritization around this issue (DOE 2022a). However, permitting, siting, and jurisdictional issues that challenge the other clean energy infrastructure systems discussed previously also pertain to raw materials. Cost-competitiveness is more complex in these spaces because of often sprawling international supply chains for clean energy inputs—particularly for solar and batteries. Further analysis and engagement are needed to move domestic supply chain enhancement goals to practical realities.

Industrial Decarbonization and Advanced Technologies

The US industrial sector is considered difficult to decarbonize largely because of the diverse energy inputs that feed into a varied array of industrial processes and operations (DOE 2022b; NAS 2021). Decarbonizing the US industrial sector requires combining established and advanced technologies and practices, namely improving energy efficiency; industrial electrification; low-carbon fuels, feedstocks, and energy sources; and CCUS. Vitally, these components of industrial decarbonization must work in concert, and cross-cutting issues that connect them require further analysis. These intersectional issues include the need for improved thermal operations and material efficiency, material substitution, and end-of-life material feed-ins to low-carbon feedstocks (DOE 2022b). Such intersections expand into the need for broader systems-level analysis of circular-economy approaches that integrated emerging biobased options, CCUS, material efficiency gains through product lifecycles, and interactions between multiple technological pathways.

Work Plan Components

Energy Pathways USA is uniquely configured to identify, analyze, and develop strategies that address cross-sectoral interdependencies and operational synergies and barriers among these issue areas. Energy Pathways USA will work to accelerate an equitable energy transition through exploring and analyzing current and proposed federal, state, and regional policy incentives and the broad range of their potential impacts, including on emissions, costs, technology, and consumer behavior. These efforts will include advancing technical and economic modeling of decarbonization pathways, beginning with advances in clean electricity and electrification and building to industrial sectors, and leveraging private sector and knowledge partner expertise to identify and develop solutions to the challenges in all of the key areas. Energy Pathways USA's model of working has the following three components.

Exploring Federal and State Policy Development and Implementation

While the IRA and BIL represent a policy landscape pivot, policy challenges and barriers remain that have the potential to slow US progress toward net-zero goals. By and large, the quantitatively focused studies explored in this report do not develop in-depth policy recommendations. NAS did recommend first setting a net-zero emissions goal for 2050, along with putting a price on carbon. NAS also recommended adopting CESs for electricity (75% by 2030) and transitioning to EVs (50% of sales by 2030). Each of the studies also identified the need to invest in key technologies to reduce costs and increase adoption after 2030, and several highlighted the need to improve the efficiency of planning and permitted of transmission and future CO_2 pipelines, along with other key areas already identified. Additional work is needed to understand implementation bottlenecks and explore alternate policy pathways in an iterative fashion that mobilizes analysis as state and federal decision makers take the next steps for an equitable energy transition. For example, sector-relevant analysis on the IRA deployment options could highlight synergies and barriers presented by the financial incentive structure of the law. The IRA law authorizes substantial federal loan capital and loan guarantees (~$369 billion in total) for energy and transportation projects and businesses. This capital is managed by the DOE and is additional tax and other incentives present elsewhere in the law. This loan capital and risk defrayment could enable future technologies and scale emerging ones that otherwise would struggle to develop. The DOE was reviewing 77 applications for $80 billion in loans sought before the IRA was signed, and the pool of capital will now grow substantially. It is vital that these projects galvanize meaningful acceleration toward net-zero and avoid stranded assets and waste wherever possible while still keeping a risk appetite that enables occasional high and unforeseen rewards. This is a difficult balance to find, and work that enhances principles for loan deployment across specific high-impact clean electricity and electrification sectors could help prioritize and inform the use of both capital and guarantee measures.

Parallel state policy efforts to accelerate the energy transition can also create synergies or barriers. As discussed previously, states are differently situated based on energy resources, consumption, and technology deployment. An accelerated energy transitions requires an analysis of state and regional coordination and implementation of diverse energy policies, including the role of RTO/ISO coordination, interstate transmission infrastructure and transportation corridors, and innovative deployment for advanced energy technology. For example, 31 states and the District of Columbia have either an RPS or CES. Thirteen power companies signed a letter to the Biden administration in April 2021 calling for a national CES. Over 38% of emissions from energy are priced in the US through subnational instruments (OECD 2021). However, definitions of clean energy, uses for renewable energy credits and solar renewable energy credits, levels and coverage of carbon pricing, and the broad intentions of different policy instruments relative to emissions reductions vary widely across different regulatory systems. These realities and developments create the chance to evaluate the current effects of CES, RPS, and carbon pricing instruments on US net-zero efforts. Analysis could extend to evaluate potential effects under scenarios of plausible changes and expansions to these instruments in federal and select subnational forms.

Finally, the IRA funds several environmental and climate justice initiatives that enhance the equity dimension of mitigating GHG emissions, legacy air pollution, and access to affordable clean energy. Key provisions include $27 billion to the Greenhouse Gas Reduction Fund, which is intended to increase access to low-cost finance for clean energy projects, that prioritizes $7 billion in the first funding stream to low-income and marginalized communities to benefit from zero-emission technologies and $3 billion in climate justice block grants for community-led projects to address legacy air pollution. While these initiatives are significant, deeper analysis is necessary to explore how different transition pathways could affect vulnerable populations.

Advancing Modeling for Clean Electricity and Electrification

All existing net-zero analyses suggest that the transition to clean electricity generation is a critical building block for both lowering emissions from generation itself and for providing the energy needed to electrify the rest of the economy. Such electrification is needed given that other approaches to substituting away from fossil fuels and reducing emissions are less available and/or less cost effective. There is therefore the need to continually improve modeling approaches for clean electricity and electrification that recognize relationships more fully across actors, sectors, and policies, and reveal opportunities to accelerate US decarbonization trends.

Three essential areas form the foundation of further developing the net-zero options for US electricity generation and corresponding electrification.

First, more robust definitions of clean energy generation are needed to facilitate effective comparisons across policy instruments and emission-reduction pathways. Wind and solar are uncontroversial inclusions, though siting issues for make their wider social, environmental and equity implications more varied and complex. Conventional and advanced modular nuclear creates questions on how long existing units will operate and what the prospects are for future infrastructure. Future hydroelectric dams could be included based on their emissions footprint or prohibited because of wider ecological and social concerns. Biomass creates questions both about its carbon content and the how demand for biomass feedstocks competes with that for liquid biofuels. Battery storage and new, closed loop pumped hydro storage both may ultimately warrant further modeling attention vis-à-vis clean electricity trends and possibilities. So too might natural gas and/or coal use with CCUS, which creates questions about capture rates, costs, transport, and storage. The future of hydrogen as a clean fuel depends in part on how much can be used to cofire either turbines or combined-cycle units, new hydrogen-burning turbines, retrofits of existing plants, constraints on using excess renewable generation to electrolyze water, and broader assumptions on methane leakage from natural gas (which are also relevant beyond hydrogen).

Second, the pace and scale of the electricity sector's transition to net-zero emissions will depend on economic, policy, and technology factors. A deep assessment of pathways for the electricity transition should incorporate a policy framework that includes possible subsidies and tax credits (such as those in the IRA legislation), emissions targets by year, potential CO_2 prices, CESs, RPSs, and any new regional policies across states. Expanded modeling is also needed to advance understanding of potential demand increases associated with electrification; capital costs for renewables, nuclear and CCUS; natural gas prices; contributions of renewables and fossil fuels to system reliability; amounts of renewables by state; costs of connecting renewables to existing grids and of developing additional transmission (including long-distance); land-use restrictions; stranded asset costs; material costs for new construction; storage capacities; and consumer responses to energy price changes. End-use considerations likewise abound, including, for example, how growing heat pump and electric resistance heating deployment will affect electricity supply and demand considerations. Broadly, there is need to assess the levels of incentive needed over long time horizons to reach a zero-carbon electricity sector by a given year (e.g., 2040, 2045, 2050). Conversely, there is also the potential to explore high-cost and/or constrained fossil fuel supply scenarios that could better illuminate the risks with continued reliance on coal and gas.

Third, given that there is unlikely to be a single correct forecast of EV adoption (and other electrified sectors), the best option for any analysis may be to evaluate a range of possible outcomes as a component of net-zero policies. This approach allows additional information such as policy decisions and/or financial support for charging stations to influence EV sales trends—not typically part of a cost-optimization modeling framework such as those used to forecast electricity sector behavior. Other trends can also be considered through modeling, such as different estimates of vehicle costs or sales forecasts from vehicle manufacturers.

Leveraging Cross-Sectoral Expertise from Leading Private Sector and Knowledge Partner Voices to Accelerate the Energy Transition

Energy Pathways USA is designed to bring together a range of organizations and sectors, including energy producers, carbon-constrained industries, technology providers, finance, transportation, and electric utilities, all of whom play significant roles in the energy transition and have critical insights into energy system constraints and synergies. This diversity of perspective and partners' deep expertise informs our work through in-depth exchanges on the full energy system and enables the analyses to reflect the multiplicity of energy system acceleration paths. Knowledge partners and contributors are committed to help accelerate the energy transition to net-zero carbon emissions by 2050. By engaging in dialogue founded on robust policy, technology, and modeling analyses, partners are stress-testing energy transition pathways to build a systems-level fluency and operational reality into developed energy transition pathways.

Next Steps

The Energy Pathways USA partnership will build on the findings and plans outlined in this report to provide a series of future knowledge products geared toward accelerating net-zero progress in the United States. Working with members throughout to create these products, the Energy Pathways USA team will seek traction for their findings in public and private spheres. This continuous process of cocreation will build on the momentum of current net-zero efforts in the US, and lead to outcomes both intended and unforeseen. Only through such collaborations can net-zero goals that are decades in the future drive the urgent change that is needed now.

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APPENDIX: GLOBAL NET-ZERO ANALYSES AND PROJECTIONS

IPCC

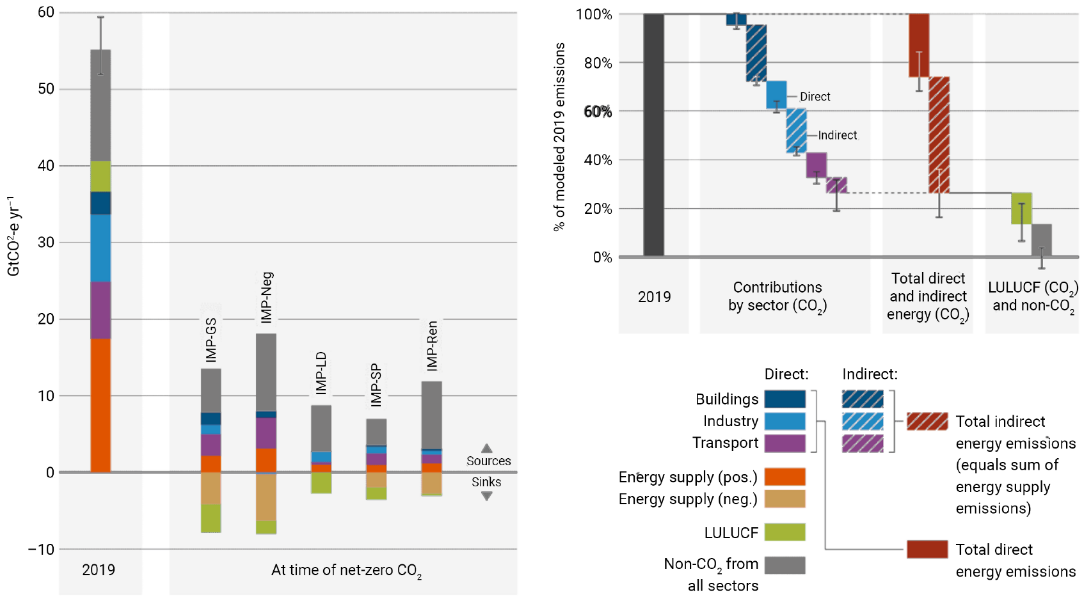
The IPCC recently released their Sixth Assessment Report: *Climate Change 2022: Mitigation of Climate Change*, which examines the literature from a wide range of disciplines on different aspects of climate change mitigation (IPCC 2022). The report's integrated-assessment modeling looked at eight groups of emissions scenarios to evaluate potential likelihood of exceeding stated goals for global warming levels (both peak and by 2100)—only three of which result in warming of 2°C or less in the year. All three of these categories are expected to involve rapid and significant reductions in GHG emissions across the global economies, in most cases implying that global GHG emissions have to peak by 2025. Neither currently proposed policies nor potential modest actions come close to containing global temperatures. Any successful strategies are likely to require net-negative emissions globally by 2100, if not before.

Within IPCC's broad categories of potential emissions trends, several Illustrative Mitigation Pathways (IMP) were examined to see how different combinations of sectoral mitigation strategies might affect how and where the emissions reductions would occur. In Figure A1, "CurPol" is current policies, "ModAct" is moderate action, "IMP-GS" is gradual strengthening, "IMP-Neg" is net-negative emissions in energy and industry through CCUS, "IMP-LD" is low energy demand, "IMP-Ren" is heavy use of renewables, and "IMP-SP" is inclusion of sustainable development goals. The figure contrasts global GHG emissions in 2019 to the remaining sectoral contributions when net-zero CO_2 emissions is reached. It distinguishes between direct energy emissions and indirect emissions. In most of the IMG scenarios, non-CO_2 emissions are still relatively high across the approaches. Aside from the scenario with heavy use of renewables, carbon sinks are essential in reaching net-zero, as is also likely the case for some net negative emissions across energy industries. Harder-to-abate components of the industrial and transport sectors continue to be among the largest likely emissions sources.

The literature used in the IPCC Sixth Assessment Report, however, is more optimistic on the costs of emissions reductions than the likelihood of achieving them. Figure A2 presents estimates of GHG reduction opportunities for a detailed list of sources and categorizes them by costs. Many reductions have net lifetime costs that are lower than those of the alternative technologies being used in the reference case trends. Wind and solar energy are estimated to be particularly cost-effective compared to fossil generation currently in use. Other areas in lighting, energy efficiency, and LDVs also have the potential for significant low/negative cost emissions reductions. Industrial sources and agriculture/land use are on the opposite end of the spectrum, with potentially much higher abatement costs per ton.

Taking these costs into consideration, IPCC finds that mitigation pathways likely to limit warming to 2°C have global GDP losses of 1.3% to 2.7% in 2050 (CO_2 prices of around \$90/ton in 2030 and \$210/ton in 2050, with substantial variability around these central estimates). Limiting warming to 1.5°C with limited/no overshoot of temperatures is associated with GDP losses of 2.6% to 4.2% in 2050 (central CO_2 prices of around \$220/ton in 2030 and \$630/ton in 2050). However, IPCC estimates that—if the economic impacts of 2°C of warming are on the moderate to high end of the potential range—the global benefits of the emissions reductions pathways will exceed the global mitigation costs over the twenty-first century (even without accounting for the benefits from sustainable development, nonmarket damages of climate change, or any improvements in human

Figure A1. GHG emissions by sector at net-zero CO_2 (and relative contributions)



Source: IPCC (2022), Figure SPM.5(ef).

health). These costs and benefits vary widely by region, depending on policy implementation and international cooperation.

Energy Transitions Commission

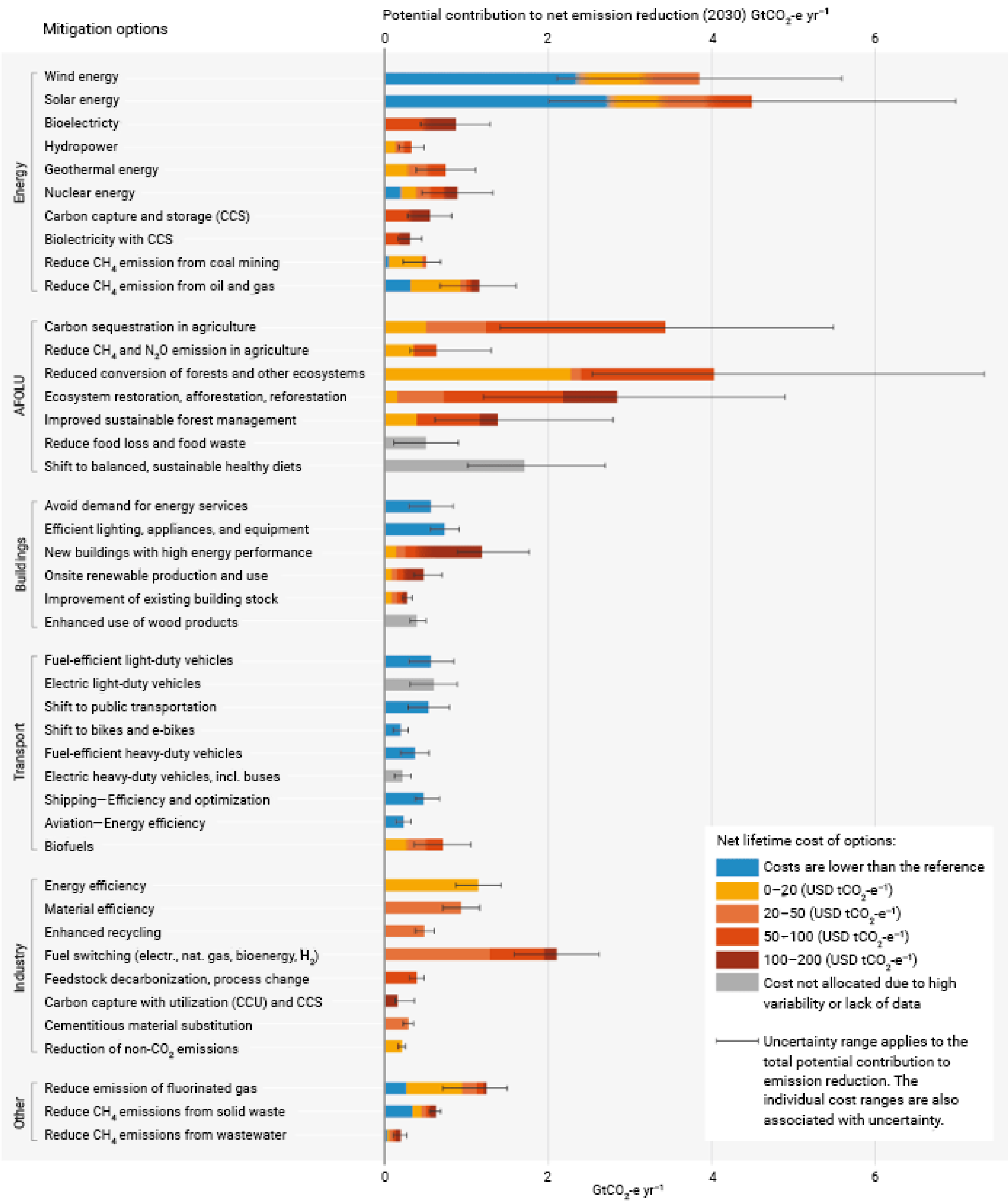
As part of a series of reports, the Energy Transitions Commission released *Making Mission Possible: Delivering a Net-Zero Economy* (ETC 2020), which examined challenges to lowering emissions in hard-to-abate sectors of the economy including cement, steel, plastics, heavy road transport, shipping, and aviation. This global analysis concluded that the technologies needed to decarbonize hard-to-abate sectors are either known or in development, and it estimated that full decarbonization of the world's economies would cost less than 0.5% of global GDP.

Three keys to transforming the energy system by 2050 are identified: (1) massive clean electrification that results in 70% of final energy use being fulfilled by zero-carbon electricity; (2) transition to a hydrogen economy where electrification is less suitable, leading to hydrogen supplying more than 10% of energy needs; and (3) carbon capture and storage or use (CCS/U) for bioenergy and any remaining fossil fuels.

As in other reports, a critical component of their recommended approach is improving efficiency in energy (e.g., improved heating, vehicles, and industry), materials (recycling and improved materials), and services (better utilization of services, demand reductions, and behavioral changes). The report estimates that it is possible to lower energy demands by 30% in 2050 through these measures.

In this global analysis by the Energy Transitions Commission, sea and air transport consume much of the liquid fuels, while surface transportation is mostly electrified aside from some heavy transport that uses hydrogen. Most industrial uses are electrified, but heavy energy-intensive

Figure A2. Emissions abatement costs and quantities available by sector in 2030



Source: IPCC (2022) Figure SPM.7.

industries use much of the available hydrogen while some manufacturing sectors would make use of carbon capture in their processes. Building space heat and other operations such as space cooling, water heating, and cooking are largely electrified by 2050.

IEA Net Zero by 2050

IEA analyzed one potential global pathway for meeting net-zero CO_2 emissions goals by 2050, consistent with limiting warming to 1.5°C in their report *Net Zero by 2050: A Roadmap for the Global Energy Sector* (IEA 2021). Broadly, its conclusion was that the pathway is narrow and that success would depend on unprecedented adoption of clean technologies by 2030. The focus of the report was on CO_2 emissions from the energy sector—no offsets outside of energy industries were allowed because of concerns about permanence and offset availability under a global approach. The report's pathway also has comparatively limited reliance on negative emissions technologies to lower GHG, relative to other reports (IEA has 1.9 gigatons of CO_2 capture from bioenergy with carbon capture and storage and direct air carbon capture and storage in 2050, compared with IPCC scenarios that range between 3.5–15 gigatons by 2050).

The biggest technology opportunities identified were in advanced batteries, hydrogen electrolyzers, and DAC. Emissions savings from behavioral changes averaged around 5% of total reductions; however, these savings came in some potentially hard-to-abate sectors such as aviation. Key uncertainties identified in the net-zero pathway were the availability and use of bioenergy, CCUS, and the potential extent of behavioral changes.

A summary of the main IEA conclusions is as follows:

- Behavioral changes offset one-third of the growth in energy demand between 2020–2050.
- The largest and earliest opportunities are in wind and solar generation. By 2050, these sources supply more than one-third of all energy consumed.
- EVs are also important and early contributors to emissions reductions.
- Hydrogen plays an important role between 2030 and 2050.
- Efficiency contributions are significant, but don't increase much after 2035.
- Modern bioenergy represents 20% of all energy supplies by 2050. Bioenergy (coupled with CCUS where possible) expands land use from 330 million hectares in 2020 to 410 million hectares by 2050.
- There is no assumed expansion of cropland for bioenergy.
- There are no bioenergy crops allowed on currently forested land.
- Biofuel use in transportation is 50% of the size of EVs' contribution to transportation.
- CCUS grows rapidly after 2030, particularly from natural gas. By 2050, almost one-half of the 7.6 gigatons of CO_2 captured is from fossil fuels, compared with 20% from industrial sources and 30% from bioenergy use. Limiting the use of CCUS would require significant additional expansion in wind and solar generation, combined with electrolyzer capacity.
- The remaining unabated fossil emissions (1.7 gigatons CO_2 in 2050) are more than fully offset by BECCS and DACCS.

IEA lays out a set of key milestones to be achieved on the path toward net-zero emissions by 2050. The report does not provide country-specific actions, but generally assumes that "advanced economies" (including the United States) have the technology and resources to move more aggressively than other nations. Among the highlights relevant for the United States between 2030 and 2050 are:

- **2030**
  - Emissions reductions come from: behavioral changes (5%), current technologies (80%), and technologies under development (15%)
  - Coal plants without carbon capture have been phased out (advanced economies)
  - Large expansion of annual wind and solar installations (1,020 GW globally)
  - 60% of car sales are EVs (globally; presumably the US is higher)
  - All new buildings are zero-carbon-ready
  - Expansion of low-carbon hydrogen (150 megatons globally from 850 GW of electrolyzers)
- **2035**
  - Net-zero emissions from electricity generation (advanced economies)
  - No new sales of internal combustion engine cars (globally)
  - 50% of heavy truck sales are electric (globally)
- **2040**
  - 50% of aviation fuels are low emissions (globally)
  - Global net-zero emissions from electricity generation (including developing countries)
  - 2,400 GW of electrolyzer capacity (globally)
  - 50% of existing buildings are retrofit to be zero-carbon-ready (globally)
- **2050**
  - Emissions reductions come from: behavioral changes (5%), current technologies (50%), and technologies under development (45%)
  - More than 90% of heavy industry production is low-emissions (globally)
  - 520 megatons of low-carbon hydrogen annually, compared to total supply of 87 megatons in 2020
  - 7.6 gigatons of CO_2 are captured annually (globally)
  - The final energy mix for low-emissions sources in 2050 is around 20% fossil fuels with carbon capture, some increase in nuclear and hydroelectric, and the balance (>60%) in renewables

IEA chiefly concentrates on one possible pathway to net-zero emissions, though there is some limited discussion of key alternatives and uncertainties. The report's net-zero emissions trends were estimated with the IEA World Energy Model, a large-scale simulation model within the IEA's annual World Energy Outlook forecasts. The modeling focused on net-zero CO_2 energy-related and industrial process emissions by 2050 and had some consideration of methane emissions from the energy sector, but no detail on other emissions sources or types of GHG. The modeling assumes all countries cooperate to reach net-zero globally, based on economic development and equity concerns. The scenario approach is designed to aim for an orderly transition that minimizes stranded assets and volatility in energy markets.

Evaluation of the modeling results and assumptions that drive them is complicated for several reasons. First, detailed growth assumptions and results for energy supply, demand, and electricity generation are only available at a global level. More challenging is the fact that much of the analysis is driven by externally imposed conditions, which makes it hard to understand key issues from a modeling perspective. Among these imposed (and not always well-specified) assumptions are as follows:

- No new coal, oil, or gas development (thus, fuel prices decline with operating costs of existing fields)
- Any potential demand increase for fossil fuels from low prices is prevented by other policies
- CO_2 prices are assumed globally
    - Developed countries start at $75/ton in 2025 and rise to $250/ton by 2050
    - Some midtier countries start at $45/ton in 2025 and rise to $200/ton by 2050
    - Other emerging markets start at $3/ton in 2025 and rise to $55/ton by 2050
- A "broad range" of other policies are also mandated to reduce emissions (levels are not specified)
    - Renewable fuel mandates
    - Efficiency standards
    - R&D supports, market reforms, elimination of fossil-fuel subsidies
- Many other conditions are also imposed (e.g., restrictions on sales of internal combustion engine vehicles and mandates for liquid biofuels/synfuels in aviation)

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Energy Pathways USA, an autonomous regional initiative of the global Energy Transitions Commission, works with leading private sector companies, public bodies, nongovernmental organizations, and thought leaders to advance the US net-zero agenda. Convened by the Nicholas Institute for Energy, Environment & Sustainability at Duke University, Energy Pathways USA brings together experts from diverse sectors and organizations to explore and analyze current and proposed federal, state, and regional policy incentives and the broad range of their potential impacts, including on emissions, costs, technology, and consumer behavior. By advancing cross-sectoral dialogue based on robust policy, technology, and modeling analyses, this partnership aims to develop actionable pathways to accelerate an equitable energy transition.