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Chapter 5

Achieving a Net Zero Carbon Dioxide Emissions Economy in the United States

Climate change poses a significant threat to human well-being in the United States and around the world (CEA 2023; Jay et al. 2023). To ensure that continued economic progress can coincide with a safe and stable climate, the Biden-Harris Administration has set a target of achieving net zero greenhouse gas (GHG) emissions in the United States by 2050 (White House 2021a) and signed into law the most significant pieces of climate legislation in American history.

This chapter reviews the economics of achieving net zero emissions of carbon dioxide (CO_2), one of the main GHGs driving climate change.[1] In the United States, CO_2 represents 80 percent of total GHG emissions (EPA 2024a). Emissions of GHGs, including CO_2, are a classic negative externality. When a firm or individual emits CO_2 into the atmosphere, the costs are borne by everyone, leaving few economic incentives for abatement actions to reduce emissions.[2]

A fundamental role of government is to address externalities through policies that alter incentives, and current Biden-Harris Administration efforts are helping to fundamentally change the country's carbon emissions trajectory. This chapter will highlight the progress already made and discuss how to build on it to push all the way to net zero.

[1] Due to space constraints, this chapter does not discuss GHGs other than CO_2. The economics of reducing non-CO_2 emissions can differ significantly from those reviewed here. The Long-Term Strategy of the United States (White House 2021b) discusses paths to achieve net zero, including strategies related to other GHGs.

[2] Activities that generate CO_2, such as the burning of fossil fuels, often result in additional negative externalities via the release of hazardous air pollutants like sulfur dioxide, nitrogen oxides, and volatile organic compounds that affect humans and natural ecosystems.

Cost-effective policies incentivize the lowest-cost abatement actions, a concept known in environmental economics as the equimarginal principle.[3] Policies that prioritize the lowest-hanging fruit will lead to different levels of decarbonization in different economic sectors, because each sector faces unique decarbonization costs and challenges. In addition, the most cost-effective way to reduce CO_2 emissions need not lead to zero CO_2 emissions from every sector, because it can be more cost effective to achieve *net* zero by allowing emissions from some sectors and engaging in separate activities that remove CO_2 from the atmosphere to offset those emissions.

This chapter considers four distinct components of moving to net zero CO_2 emissions. It begins by discussing how to achieve zero CO_2 emissions in U.S. electricity production, broadly considered both technologically possible and inexpensive relative to abatement options in other sectors (Davis et al. 2023). The chapter then discusses the potential for reducing emissions by powering more economic activity with clean electricity instead of fossil fuels, a process known as electrification. Next, it discusses how to decarbonize economic activities that may be harder to electrify, including using cleaner fuels and improving energy efficiency. The chapter concludes by discussing the use of negative emissions technologies (NETs) to capture and store emitted carbon that would be comparatively more costly to eliminate.

Achieving net zero will involve a collection of policies for two reasons. First, there are many ways to address the central negative externality from CO_2 emissions. Economists most commonly advocate for economy-wide carbon taxes or cap-and-trade systems, which are designed to address the negative externality in all sectors simultaneously and incentivize each sector to respond in the lowest-cost way (EPA 2024b). An alternate approach is to

[3] Formally, the equimarginal principle says that, to achieve a given amount of abatement, the marginal cost of abatement should be equal across all sectors and firms. Otherwise, it is more cost effective to reallocate effort toward abatement activities with lower costs. Properly measured, the cost of abatement should reflect all costs and benefits, even those unrelated to CO_2 abatement, and include both short- and long-term costs.

address emissions with a series of sector-specific policies, as in the historic legislation passed during the Biden-Harris Administration.

Second, the negative externality from emissions is not the only market failure relevant to achieving net zero. Another critical market failure is that, due to positive externalities from knowledge spillovers, firms do not have private incentives to conduct sufficient research and development (R&D) into the new technologies needed to make progress in achieving carbon pollution-free electricity, expanding electrification, decarbonizing unelectrified activities, and deploying NETs. These knowledge spillovers also occur when firms initiate and scale up production, implying the need for government to support demonstration and deployment of new technologies. In other cases, such as developing a network of electric vehicle (EV) charging stations or building long-distance electricity transmission infrastructure, the government can help solve coordination problems that prevent the private market from making sufficient investments in deploying new technologies.

Understanding the Past, Looking to the Future

The Biden-Harris Administration has set targets of achieving a carbon pollution-free power sector by 2035 and a net zero GHG emissions economy by 2050 (White House 2023). The United States has also set a target of reducing its net GHG emissions by 50–52 percent below 2005 levels in 2030 as its Nationally Determined Contribution to the Paris Agreement, an international treaty intended to limit the increase in global average temperature to less than 1.5–2 degrees Celsius from the pre-industrial level (UNFCCC 2021a). This Nationally Determined Contribution reflects a focus on limiting cumulative emissions along the path to net zero.

Three historic pieces of legislation advance these goals: the CHIPS and Science Act, the Bipartisan Infrastructure Law (BIL), and the Inflation Reduction Act (IRA). These laws have funded hundreds of programs to decarbonize the American economy, including the selected major initiatives listed in table 5-1. Among many others, the programs include investment and production tax credits for clean energy and NETs, new tax incentives that make switching to clean energy technologies like EVs and heat pumps more affordable, and research, development, and deployment funding for new and emerging technologies (DOE 2023a; IRS 2024; Ambrose, Jacobs,

Table 5-1. Selected Biden-Harris Administration Climate Commitments and Major Policies

Climate Commitments

- On day one of taking office, the Administration rejoined the international Paris Climate Accords, which intends to limit global temperature increases to below 1.5–2°C above pre-industrial levels. The Administration set a target of reducing greenhouse gas (GHG) emissions by 50–52 percent by 2030 from 2005 levels and achieving a net zero GHG emissions U.S. economy by 2050.

Expanded Role of Federal Climate Leadership

- The Administration established the first White House Office of Domestic Climate Policy and elevated the role of Special Presidential Envoy for Climate to prioritize domestic and international decarbonization efforts and engagements.
- Historic federal actions and nationwide climate strategies across sectors include the U.S. National Blueprint for Transportation Decarbonization, the Administration's efforts to achieve 100 percent clean electricity by 2035, the U.S. Industrial Decarbonization Roadmap, the U.S. Buildings Decarbonization Blueprint, the Administration's climate-smart agriculture efforts and Nature-Based Solutions Roadmap, the U.S. Methane Emissions Reduction Action Plan, the National Climate Resilience Framework, and more.

Clean Energy Tax Credits

- Under the IRA, production tax credits can be claimed for renewable and clean electricity, zero-emissions nuclear power, advanced manufacturing, clean fuel, and hydrogen.
- Additionally, consumers can claim tax credits for energy efficiency home improvements such as heat pump purchases as well as qualifying electric vehicle (EV) purchases and electric and alternative fueling infrastructure under the IRA.
- Investment tax credits can also be claimed for investment in a variety of clean energy projects. As of October 2024, announced private investment in clean energy manufacturing and infrastructure, clean power, and EVs and batteries under the Administration has totaled over $400 billion.

Clean Energy Demonstrations and Deployment

- Through IRA, BIL, and CHIPS, over $100 billion has been invested directly in accelerating the deployment of clean energy, clean buildings, and clean manufacturing as well as making communities more resilient to climate change and providing clean water across the United States.
- The Department of Energy has taken steps to speed up the commercialization of emerging energy technologies through a $25 billion fund for clean energy demonstrations and increased project financing by the Loan Programs Office.

Buy Clean Initiative

- The Administration prioritized the procurement of American-made, lower-carbon construction materials in federally funded projects.

Grid Enhancement and Expansion

- The Administration has taken a number of steps to improve the reliability of the grid through measures that speed up the buildout of new transmission and increase the efficiency of existing infrastructure. This includes administering over $10 billion to modernize the grid through the Grid Resilience and Innovation Partnerships Program and improving the process for environmental reviews under the National Environmental Policy Act.

Greenhouse Gas Standards and Reduction Efforts

- Under the Administration, the Environmental Protection Agency (EPA) has finalized rules and standards to reduce GHG emissions from fossil fuel-fired power plants and vehicles. Additionally, the EPA implemented a first-of-its-kind fee for methane emissions.

and Tham 2022). The Administration has also taken significant regulatory action to reduce emissions from fossil fuel-fired power plants (EPA 2024c).

Although emissions reduction is the primary focus of this chapter, the Biden-Harris Administration's clean energy industrial policies also aim to deliver additional economic and community benefits. Since 2021, nearly 900 new or expanded clean energy manufacturing facilities have been announced, many since the passage of the BIL and IRA (DOE 2024a). Further, as a result of the IRA, more private clean energy funding is now going to economically disadvantaged communities (Van Nostrand and Ashenfarb 2023).

Historical Energy-related CO_2 Emissions Trends

U.S. CO_2 emissions from energy use peaked in 2007, then began to fall slowly (EIA 2024a). However, the trend in aggregate emissions masks important differences by sector—electric power, transportation, industrial (including agriculture), residential and commercial buildings—each of which face distinct economic challenges to decarbonization.

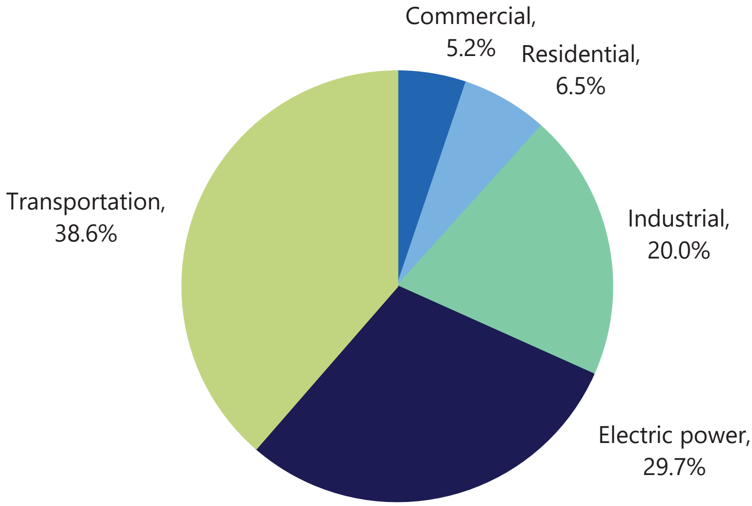
Figure 5-1a presents energy-related CO_2 emissions by sector. In 2023, transportation accounted for 39 percent of energy-related emissions, followed by the electric power sector at 30 percent and the industrial sector at 20 percent. Finally, the residential and commercial sectors together made up 12 percent of total energy-related emissions. When emissions from the electric power sector are distributed to the other sectors according to their electricity use, transportation contributed 39 percent, industrial contributed 28 percent, and residential and commercial buildings together contributed 33 percent of CO_2 emissions (EIA 2024b).

Figure 5-1b shows a notable decrease in emissions from the electric power sector, in part because the United States has produced more electricity from carbon-free sources, including wind and solar, since 2010 and in part because of a switch from coal to natural gas fossil fuel use (EIA 2024a). Emissions per kilowatt-hour of electricity generated have fallen by roughly one third since 1990 (see figure 5-2).

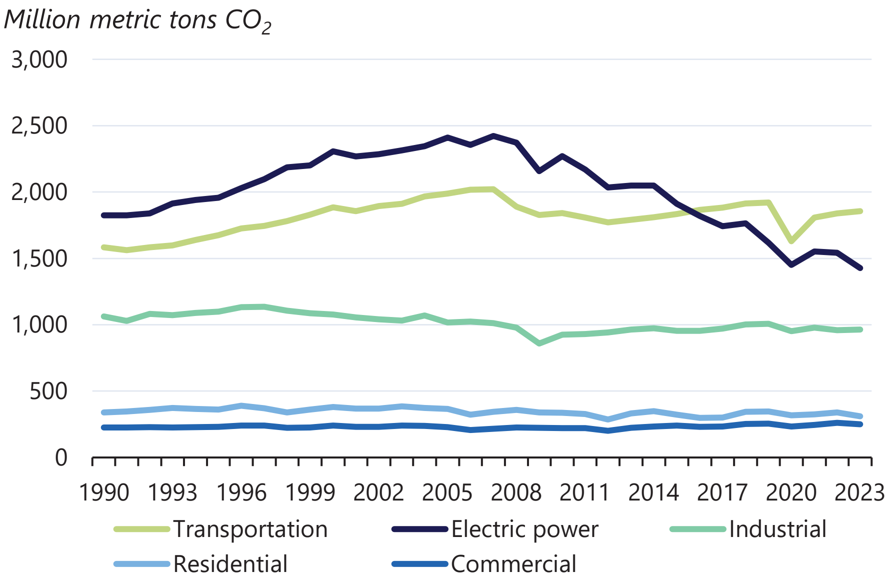
Figure 5-3 shows the extent of electrification by sector from 1949–2023. Electrification increased rapidly in both residential and commercial buildings from the 1950s to the 2000s, then slowed. In contrast, electrification has increased only slightly in the industrial sector. The flat transportation trend shown in figure 5-3 underestimates electrification because the data do not include at-home EV charging, which is measured as residential energy use. Still, it is difficult to electrify certain forms of transportation, such as heavy trucking, aviation, and international maritime shipping (Jaramillo et al. 2023). On average, electrification has increased gradually throughout the economy, from less than 5 percent of end-use energy in 1949 to nearly 20 percent in 2023.

Figure 5-1. Energy-related CO_2 Emissions

A. Share of 2023 Emissions



B. Emissions by Sector, 1990–2023



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Sources: Energy Information Administration; CEA calculations.

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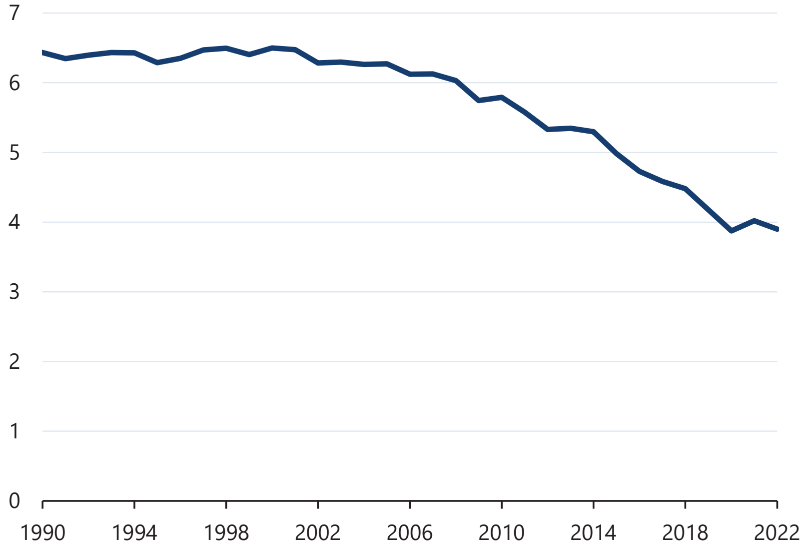
Figure 5-2. CO_2 Emissions per Kilowatt-hour, 1990–2022

Ten-thousandths of a metric ton of CO_2 emissions per kilowatt-hour



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Sources: Energy Information Administration; CEA calculations.

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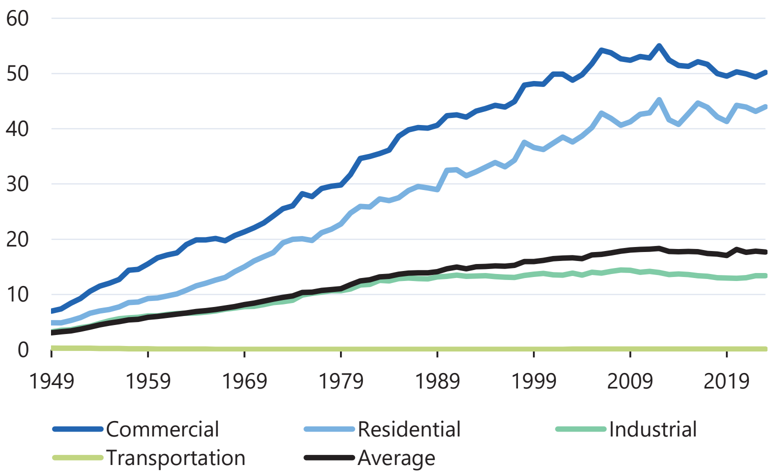
Figure 5-3. Electrification by Sector, 1949–2023

Percent of end-use energy coming from electricity



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Sources: Energy Information Administration; CEA calculations.

Note: Values are calculated as electricity sales to ultimate customers in the end-use sector (Btu) divided by end-use energy consumed by the end-use sector (Btu). Home electric vehicle charging is not included in the transportation values.

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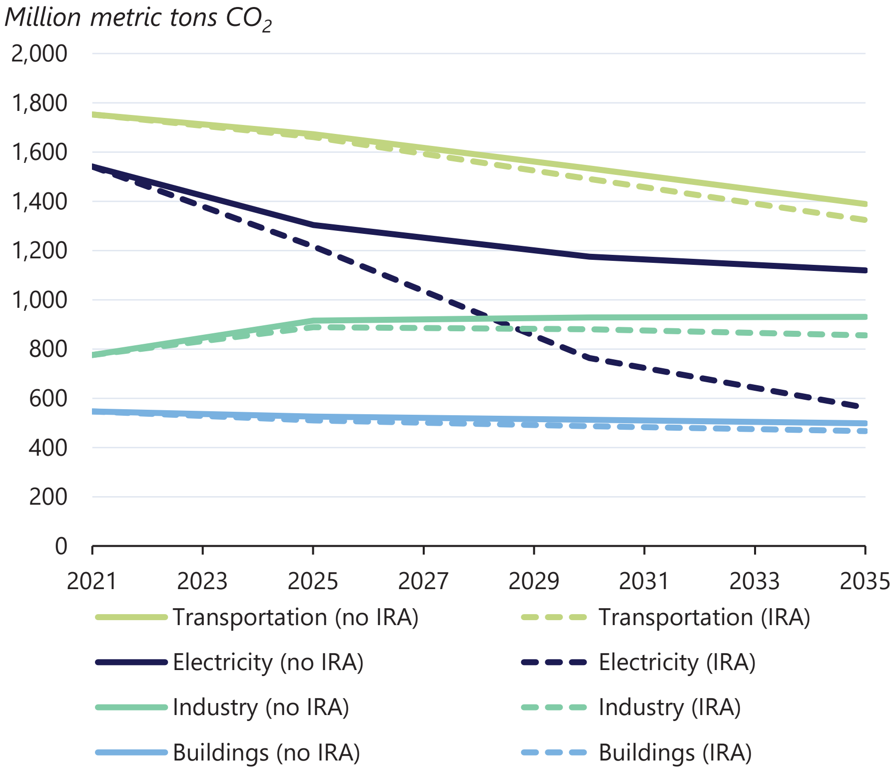
Future Impacts of Recent Mitigation Policy

Recent policy advances will drive ongoing progress toward net zero. Figure 5-4 compares projections of future emissions with IRA policies (shown as dashed lines) and without (shown as solid lines) for 2021–2035. The projections come from a recent study conducted by the EPA (2023) and represent averages across several different models that include a partial list of policies enacted during the Administration.[4]

Figure 5-4. CO_2 Emissions by Sector, with and without the IRA



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Sources: Environmental Protection Agency (EPA); CEA calculations.
Note: Projections are based on averages of all models included in the EPA's IRA report. IRA refers to the Inflation Reduction Act. Projections begin after 2021.
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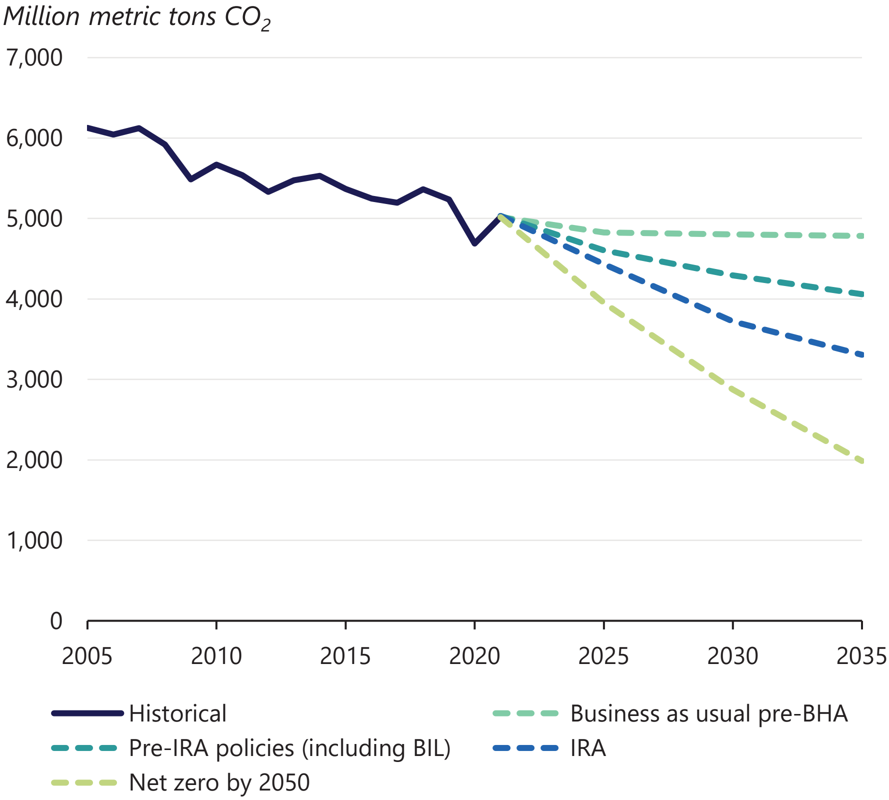
[4] The 14 models covered in the EPA analysis vary significantly by which IRA provisions they incorporate. No model covers all provisions, but all models include some. Some models, like GCAM-CGS and REGEN-EPRI, offer optimistic, moderate, and pessimistic scenarios of emissions reductions. For these models, the EPA analysis includes the moderate scenarios. The models do not account for the EPA’s 2024 GHG standards for fossil fuel-fired power plants (EPA 2024d), which may further decrease emissions. The values represent the mean of the models.

The projections show a near two-thirds reduction in emissions from the electric power sector by 2035, reflecting IRA subsidies for solar and wind production, as well as tax credits for carbon capture and storage in the power sector. In other sectors, the impact on CO_2 emissions from activities other than electricity use is smaller.

Paths to a Net Zero Economy

Figure 5-5 shows projected paths of future emissions in several scenarios, including the following: (i) a scenario without Biden-Harris Administration

Figure 5-5. CO_2 Emissions Under Different Scenarios



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Sources: Environmental Protection Agency (EPA); United States' 7th National Communication to the United Nations Framework Convention on Climate Change; CEA calculations.
Note: EPA projections for policy scenarios are based on an average of the 11 out of 14 models in EPA (2023) that include BIL in their 2022 policy scenario. EPA (2023) uses models collected by Bistline et al. (2023). Net zero line is based on a logarithmic extrapolation of 2021 data to 2050. IRA refers to the Inflation Reduction Act. BIL refers to the Bipartisan Infrastructure Law. BHA refers to the Biden-Harris Administration.
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policies, (ii) a scenario with the Administration policies enacted through 2022, (iii) a scenario also including the IRA-driven changes, and (iv) a path to net zero.[5] Uncertainty exists in any projection, but the broad patterns shown are robust and consistent across modelling efforts (EPA 2023; Bistline et al. 2023). As in figure 5-4, the simulations show that Biden-Harris Administration policies will drive significant emissions reductions relative to a no-policy scenario. At the same time, further policy intervention will likely be necessary to reach net zero.

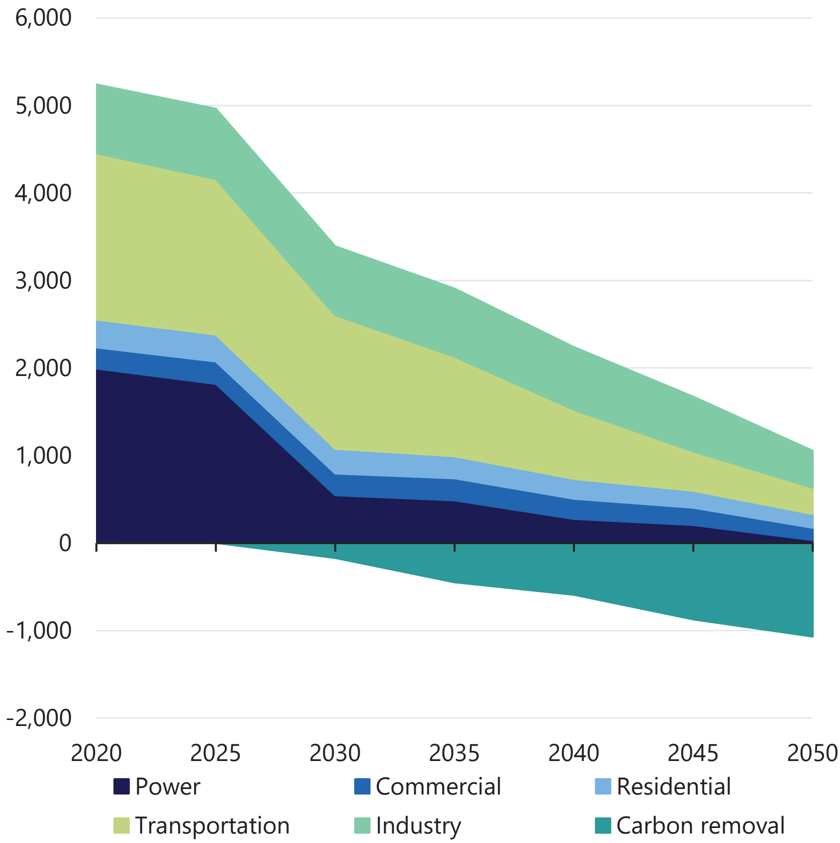
Figure 5-6 decomposes one possible path to net zero by sector based on a model from Huppman et al. (2023).[6] In the model, electricity is fully decarbonized, but heavy industry and some forms of transportation still require fossil fuel use. To offset these continuing fossil fuel emissions, as well as past emissions, NETs are used to remove CO_2 from the atmosphere. These NETs can be biological, like afforestation and farming practices which increase CO_2 uptake in the soil and biomass, or technological, like direct air capture and storage which uses chemical reactions to pull CO_2 from the air. The U.S. economy does not currently make sufficient use of NETs. As decarbonization advances into harder-to-decarbonize sectors, NETs are likely to become more cost effective.

[5] There are many different projections for CO_2 emissions in each of these scenarios. The CEA's goal is to highlight the general patterns behind such projections, not to endorse a specific result. The first scenario comes from the United States' 7th National Communication to the United Nations Framework Convention on Climate Change (2021b), the two Biden-Harris Administration policy scenarios come from EPA (2023), and the net zero scenario is an illustrative logarithmic extrapolation from 2021 levels to zero CO_2 emissions in 2050. The Long-Term Strategy of the United States (White House 2021b) models several alternative pathways to net zero that include all GHGs.

[6] This study is part of the Energy Modeling Forum, an ongoing collaboration between several groups, and provides thorough coverage of sector-level and independent NETs. The model used in figure 5-6 is the US-REGEN model from the Electric Power Research Institute (2021).

Figure 5-6. CO_2 Emissions by Sector, Net Zero Scenario

Million metric tons CO_2 per year



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Sources: Huppman et al. (2023); CEA calculations.

Note: Projections are based on the REGEN model developed by the Electric Power Research Institute. Sector emissions are net of sector-level carbon capture and storage (CCS). Carbon removal includes bioenergy with carbon capture and storage (BECCS), direct air capture and storage (DACS), and biological processes such as plant growth.

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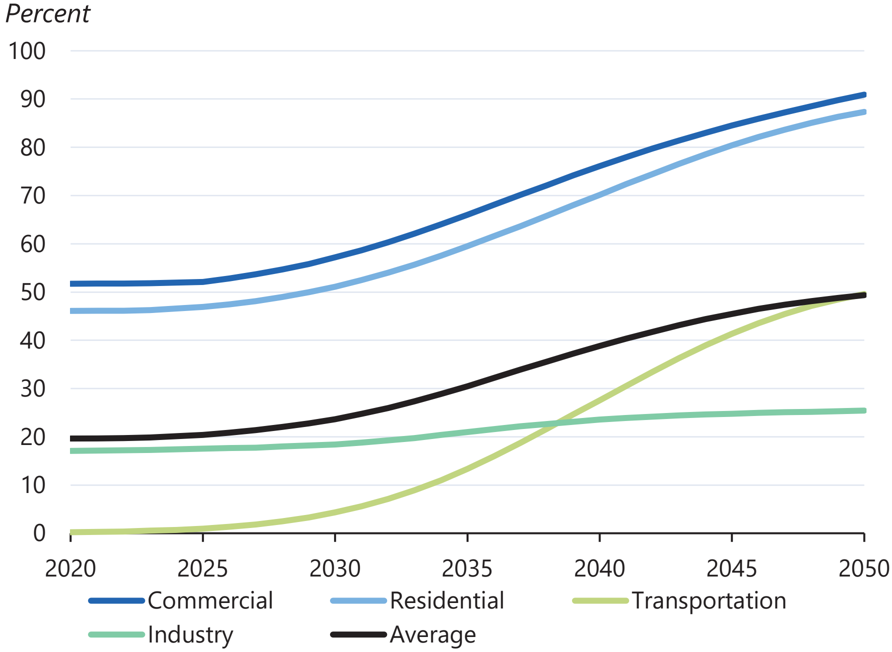
Electricity

Achieving complete decarbonization in electricity production is considered both technologically possible and inexpensive relative to abatement options in other sectors (Davis et al. 2023). This section discusses how to achieve net zero CO_2 emissions in electricity production and how electrifying other sectors can help achieve net zero economy-wide. Figure 5-7 shows one

Figure 5-7. Electrification by Sector for Net Zero CO_2 by 2050



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Sources: Williams et al. (2021); CEA calculations.
Note: Electrification is measured as electricity sales to ultimate customers in the end-use sector (EJ) divided by end-use energy consumed by the end-use sector (EJ).
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projection of how the share of electricity in final energy demand within each sector could evolve to achieve a net zero economy in 2050.

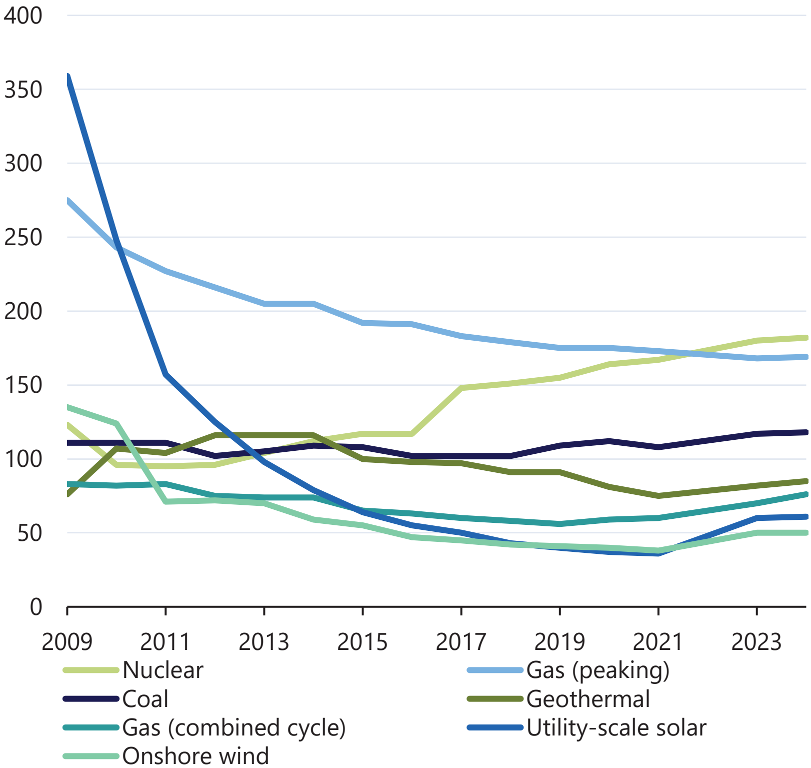
Decarbonizing Electricity

The carbon intensity of electricity production has dropped over the last two decades, driven in part by the falling price of renewables and in part by the switch from coal to natural gas fossil fuel use. Figure 5-8 shows the average cost per megawatt-hour of generating electricity over the lifetime of the production infrastructure (i.e., the levelized cost of electricity) for several different energy sources.[7] The cost of wind and solar has decreased dramatically. Indeed, solar went from being the most expensive energy source in 2009 to

[7] The levelized cost of electricity is a measure of the net present cost of electricity generation for a given generator over its lifetime. Often used to plan investments or compare costs of generation methods, it is calculated as the sum of total costs over the lifetime of a plant divided by total electricity produced. However, levelized costs may not account for all relevant characteristics of an energy project (Joskow 2011).

Figure 5-8. Levelized Cost of Electricity

Dollars per megawatt-hour



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Source: Lazard (2024).

Note: Data for 2022 are missing; the values in this year are linearly interpolated. Data are calculated by taking the midpoint of the high and low marginal costs of facilities across the United States. Subsidies are not included in the numbers used in the figure.

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one of the cheapest in 2023, second only to wind. These price decreases have helped drive out some fossil fuel-powered electricity by displacing some production and accelerating plant retirements.[8] However, continuing drops in solar and wind prices alone will not lead to full decarbonization of the electricity grid because of the need for complementary resources, permitting new clean energy projects, and expanding transmission.[9]

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[8] It can be less expensive to continue running some existing fossil fuel-fired plants until the end of their lifetimes than to replace them early with new solar and wind generation (Davis, Holladay, and Sims 2022).

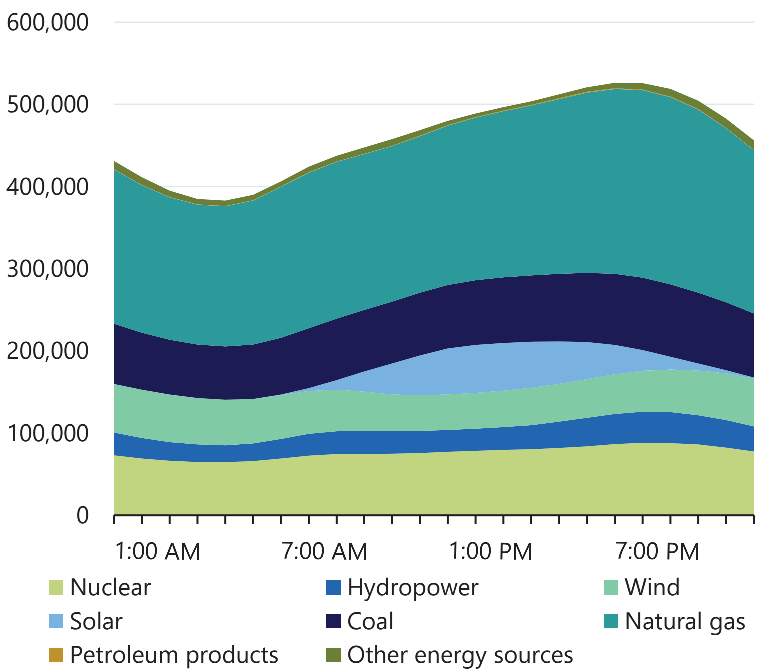
[9] Additional challenges, including workforce development and supply chain constraints for critical minerals needed for battery production, also play a major role but are beyond the scope of this chapter.

Wind and Solar Energy

Modeling studies widely agree that achieving net zero emissions requires the rapid acceleration of wind and solar deployment and that the grid can accommodate significantly more wind and solar energy than is currently deployed (Kroposki 2018). However, wind and solar are not always available. As an illustration, figure 5-9 shows variation in average electricity generation by source over the course of the day in the continental United States. While patterns vary across regions, total electricity use currently peaks in the early evening, just as solar energy becomes unavailable. Although wind power has the potential to meet demand at any time of the day, it is not always available.

Figure 5-9. Hourly Power Generation by Energy Source

Megawatt-hours



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Sources: Energy Information Administration; CEA calculations.

Note: Hourly data are averages from November 2023 through October 2024 that are converted to Eastern Daylight Time for the continental United States. Hour labels correspond to the end of hourly reporting periods.

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To provide reliable electricity, variable wind and solar energy are paired with complementary technologies that can provide electricity when they become unavailable. These complementary sources of electricity—"dispatchable" resources—include nuclear power, energy storage, some types of hydropower, and fossil fuels.[10] For example, because they have low fixed costs and high variable costs, natural gas "peaker" plants can be profitable even if they only run when less expensive, variable renewable sources are not available. Achieving a carbon pollution-free electric power sector also requires eliminating emissions from these complementary technologies.

Batteries and Storage Technology

Grid-scale batteries are an important technology for storing wind and solar energy in the United States so that it can be used whenever it is most needed.[11] Use of short duration grid-scale batteries, especially lithium-ion batteries, is rapidly increasing (EIA 2024c). The use of longer-duration batteries is more nascent, and many technologies are still in a demonstration phase (DOE 2023b). Pumped storage hydro is another key storage technology.[12] Although it has physical requirements that mean it cannot be installed everywhere, the U.S. Department of Energy (DOE) estimates that significantly more pumped storage capacity could be added by 2050 (DOE 2024c).[13]

While falling renewable energy and natural gas prices have driven decarbonization over the last two decades, achieving net zero will likely require the combination of variable renewables and effective storage to be cheaper than the alternative combination of variable renewables and natural gas (MIT 2022; Butters, Dorsey, and Gowrisankaran 2024). Figure 5-10 shows that the current price per megawatt-hour of renewables backed up by natural gas is lower than the price per megawatt-hour of renewables backed up by batteries. Figure 5-11 shows the projected decline in the cost of utility-scale battery storage per kilowatt through 2050. The fall in the cost for long-duration batteries, which last at least 10 hours, will allow daytime

[10] Natural gas availability can also be disrupted due to supply chain issues (Gilbert, Bazilian, and Gross 2021) as well as disruptions caused by extreme weather (DOE 2024b). Disruptions in natural gas availability have posed issues during several recent storms (DOE 2024b).

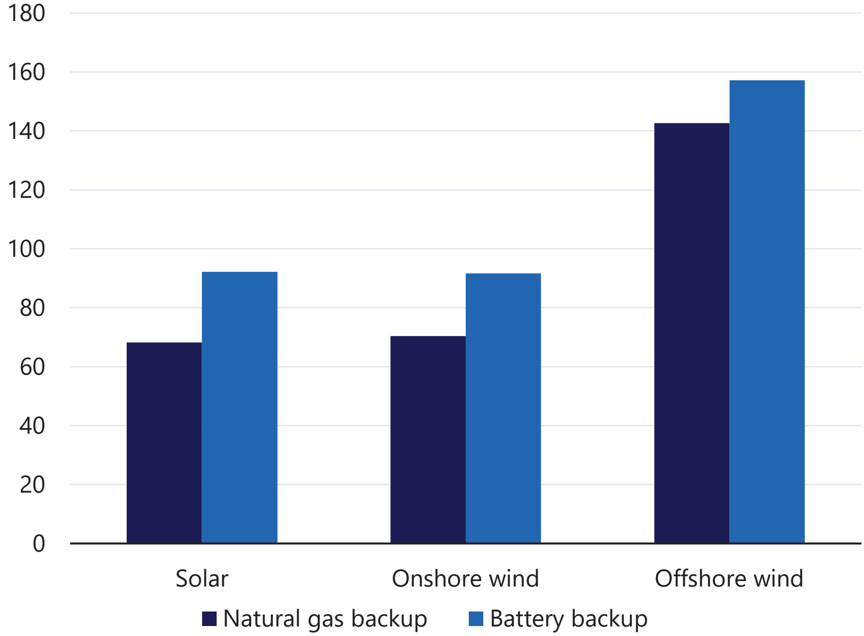
[11] Non-battery storage options also exist, including pumped hydro, compressed air, liquid air, and gravity-based energy storage technologies. Each option has different requirements for land and infrastructure that may make them more or less efficient in different situations (Shine 2023). As of 2022, pumped storage hydropower accounted for 96 percent of all U.S. utility-scale energy storage (DOE 2023c).

[12] When electricity demand is high, water is released from a high-elevation reservoir and generates electricity as it flows into a lower-elevation reservoir through a system of turbines. When electricity demand is low, excess electricity from wind and solar generation can be used to pump the water back up into the higher reservoir.

[13] Other forms of long-duration energy storage can store energy over days, weeks, or seasons (DOE 2023b), though further policy intervention is needed to make them commercially viable in many instances.

Figure 5-10. Levelized Costs of Variable Energy Sources, Spring 2023

Dollars per megawatt-hour



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Sources: Greenstone (2024); Energy Information Administration; CEA calculations.

Note: Backup energy sources ramp up during peak hours. Data are in 2023 U.S. dollars and do not account for subsidies.

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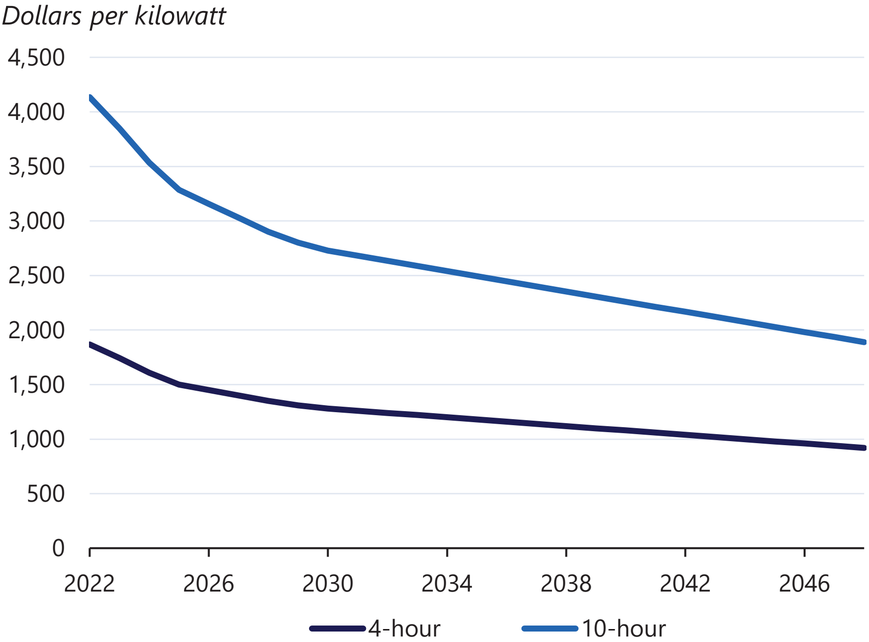
solar energy generation to satisfy nighttime demand and make wind energy available regardless of when the wind is blowing. In addition to supporting renewables and reducing emissions, adding storage to the grid improves resilience and reliability (DOE 2024b).

Governments can reduce energy storage costs by addressing externalities commonly associated with technological improvement. R&D externalities occur because new technological knowledge often benefits all firms working in a sector, not just those that undertake the research (Jones 2005). Learning-by-doing externalities occur because the process of producing a good teaches a firm how to reduce costs, and other firms can follow suit via spillovers (Gillingham and Stock 2018). This externality is especially important for nascent and emerging technologies, like some long-duration storage options, where demonstrating economic feasibility provides valuable information to other firms (Armitage, Bakhtian, and Jaffe 2024). Because the value of engaging in these activities for an individual firm is

Figure 5-11. Utility-scale Battery Storage Projected Costs



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Sources: Cole and Karmakar (2023); National Renewable Energy Laboratory; CEA calculations.

Note: Data are centered three-year moving averages of median projected values from 16 different studies, given in 2022 dollars. Data include energy and power costs but do not account for subsidies.

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less than the value to society, there will be an under-provision of technological improvement absent government intervention.

Policy can address these positive externalities by subsidizing R&D, production, and the demonstration of new technologies. To date, the Biden-Harris Administration has invested more than $300 million in long-duration energy storage technologies via the BIL and created the Advanced Manufacturing Production Credit for domestic production of clean technologies, including batteries. The DOE has set the goal of reducing the cost of long-duration energy storage, including batteries, by 90 percent by 2030 (DOE 2023d) and analyzed how near-term government support can lead these technologies to commercial viability (DOE 2023b).

Other Zero CO_2-emissions Options for Electricity Generation

Hydroelectric, nuclear, and geothermal power can also provide zero-CO_2 emissions electricity, and unlike wind and solar, some types of these resources are dispatchable. Hydropower plants, which convert kinetic energy from dammed water into electricity, provided 6 percent of electricity generation in 2023 (EIA 2024d). Hydropower is renewable, and it can be operated to provide stable generation or flexibly to complement wind and solar (DOE 2024c). While its potential to scale up is limited by natural resources (Fendt and Parsons 2021), the DOE estimates that significant new hydropower generation could be added by 2050 through upgrades to existing plants, adding capacity at existing dams and canals, and limited development of new stream-reaches, in addition to the potential for new pumped storage capacity already discussed (DOE 2024c).

Nuclear energy provides roughly 20 percent of current electricity generation in the United States. Nuclear plants have high fixed costs and low variable costs, making them well-suited for stable production. Most U.S. nuclear plants are large light-water reactors, which can offer low marginal costs per megawatt-hour due to economies of scale (DOE 2024d). In addition, investments in small modular reactors (SMRs), which have a smaller geographic footprint than traditional reactors and can be partially prefabricated offsite, can potentially allow for faster, cheaper construction in areas unsuitable for standard nuclear facilities. While SMRs may cost more per megawatt-hour than large reactors, they may be more suitable for replacing smaller retiring coal plants or industrial processes requiring high heat, and they may be more attainable for investors with limited land, labor, and capital (DOE 2024d). Recent technological advancements have improved their suitability for flexible production as well (Renteria, Schwartz, and Jenkins 2024), implying that nuclear could be used as a replacement for natural gas plants in complementing variable renewables.

Concerns about rare disasters and the challenges of storing nuclear waste have given rise to safety regulations that drive up the cost of nuclear energy (Lovering, Yip, and Nordhaus 2016), likely contributing to the decline in the construction of new plants since the 1980s (Makarin, Qian, and Wang 2024). However, nuclear plants can be safely built and operated at economically viable costs (Ritchie 2020). For example, France opened its first nuclear plant in the 1960s and produces the majority of its electricity using nuclear power today (EIA 2023). Scaling up U.S. nuclear power would require catalyzing private sector investments by streamlining regulation and investing in innovation, demonstration, and deployment (DOE 2024d; White House 2024a). The IRA provides tax credits for nuclear energy production and investment, and the Biden-Harris Administration funds a number of demonstration and research programs, offers low-cost loans for deployment of commercial technologies, and signed the ADVANCE Act to increase licensing efficiency (DOE 2024d).

Paths to net zero that prioritize geothermal energy will likely require further R&D investment (DOE 2024e). Geothermal contributed less than 1 percent of electricity generation in 2023 in part due to the geographic distribution of natural thermal resources (EIA 2024e). However, new technologies, such as enhanced geothermal, can help extract geothermal energy from a much wider range of natural environments (DOE 2024e). Some analyses project that geothermal will contribute more than 10 percent of electricity generation by 2050 (Augustine et al. 2023). The Biden-Harris Administration supports demonstration projects with BIL funding (DOE 2024f) and is working to streamline geothermal resource exploration on federal lands (DOI 2024).

Long-distance Transmission

The National Transmission Planning Study finds that the United States will need to more than double its 2020 electricity transmission capacity by 2050 to meet demand growth (DOE 2024g). This will require both new transmission lines and increased capacity on existing transmission lines (DOE 2024h; DOE 2024g). Increased transmission also increases the reliability of the grid, especially after natural disasters that hamper electricity generation in some locations (NERC 2023), and promotes the use of carbon-free energy sources.

The United States has three main power grids, or “interconnections:” the Eastern, Western, and Texas grids (DOE n.d.a). Regional transmission refers to sending electricity across long distances within each grid on powerful, high-voltage transmission lines. Electricity could also be transmitted inter-regionally across interconnections, but the grids are currently not closely connected.

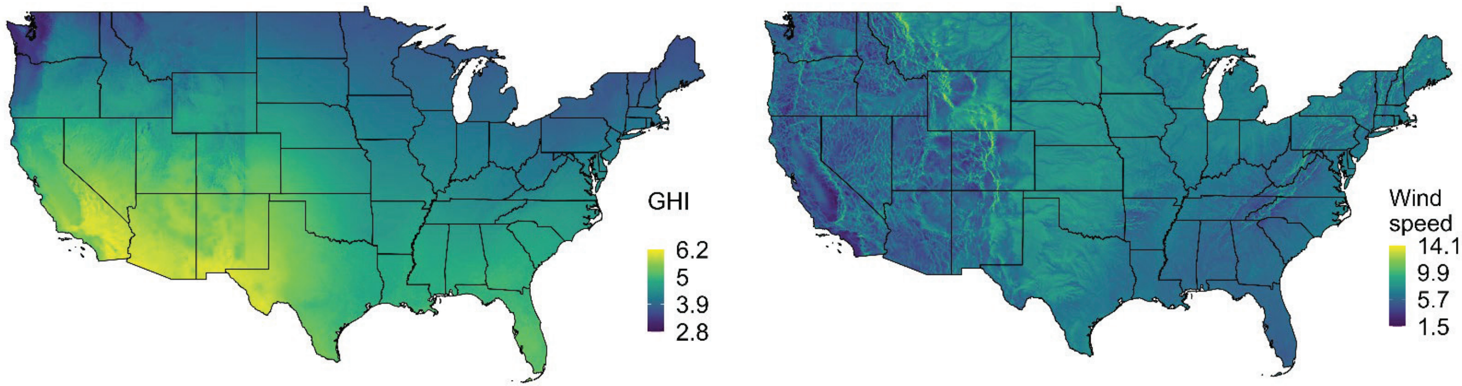
Transmission across regions and interconnections can help deal with the variability of wind and solar by reallocating renewable energy across space, complementing the ability of batteries to reallocate renewable energy across time. For example, many of the best locations for wind-based electricity production are in the center of the country, while most electricity demand occurs on the coasts (Joskow 2021). In addition, wind speeds are not constant even in windy locations. Figure 5-12 shows the uneven distribution of wind speed and solar irradiation across the country.

The grid system is not currently set up to optimally redistribute clean energy resources over long distances (Simeone and Rose 2024). In the extreme, places with high renewable energy potential may have negative electricity prices, because more electricity can be cheaply generated than is demanded within the regional grid. At the same time, prices may remain high in other regions, with demand exceeding renewable energy potential (Davis, Hausman, and Rose 2023). This price discrepancy implies that electricity produced inexpensively cannot be effectively routed to where it is

Figure 5-12. Distribution of Continental U.S. Solar and Wind Potential

A. Solar Irradiation

B. Wind Speed



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Sources: National Renewable Energy Laboratory; Census Bureau; CEA calculations.

Note: Solar irradiation is measured as average Global Horizontal Irradiation (kWh/m^2/day). Wind speed is measured as the average wind speed at 100m above surface level (m/s).

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needed. If renewables could be transmitted to locations with higher demand, they could push out higher-cost fossil fuel production, leading to cheaper electricity and fewer emissions in the receiving area. The financial benefits of transmission across interconnections have been estimated to be as high as almost three times greater than their cost on average (Bloom et al. 2020).

Planning for long-distance transmission is particularly difficult because the lines must pass through many states, Tribal lands, and privately owned properties. Moreover, the United States does not have a planning authority to coordinate inter-grid transmission projects (Joskow 2021). This inability to coordinate stakeholders when a project's benefits are widely distributed is a classic market failure (Coase 1960). There is also considerable scope to upgrade transmission capacity without building new lines (O'Boyle, Baker, and Solomon 2024), including reconductoring lines with high performance conductors and deploying grid-enhancing technologies. Such investments are not subject to the same coordination problems and can provide faster and more cost-effective routes to upgrading the grid.

Increased transmission would cause wholesale prices to rise in some regions and fall in others (Davis, Hausman, and Rose 2023). Locations sending electricity over long distances would tend to see prices increase, while receiving locations would see prices decrease. Thus, some power producers in receiving regions have incentives to block new transmission projects (Hausman 2024; Davis, Hausman, and Rose 2023).

The Biden-Harris Administration has taken steps to address the costs and coordination challenges that impede new transmission projects. The Administration funds large-scale interregional transmission projects through the $2.5 billion Transmission Facilitation Program and grid resilience through the $10.5 billion Grid Resilience and Innovation Partnerships Program (GRIP), both introduced under the BIL (DOE 2023e; DOE 2024i; DOE n.d.b). The Administration has also created the Coordinated Interagency Transmission Authorizations and Permits Program, which aims to speed up the federal permitting process for transmission projects, and the National Interest Electric Transmission Corridor Designation Process to expedite key projects (DOE n.d.c; DOE 2023f). The Federal Government also supports state-level actions through programs like the Federal-State Grid Modernization Initiative, technical assistance from the National Labs, and low-cost financing through the DOE Loan Programs Office (White House 2024b; Lawrence Berkeley National Lab n.d.; DOE 2024j). Additionally, the independent Federal Energy Regulatory Commission (FERC) has introduced new rules to expedite regional transmission projects (FERC 2024a).

Permitting for Energy Generation

Infrastructure projects, including clean energy and transmission projects, may be subject to a variety of state and local requirements, such as land use and zoning laws, as well as federal statutes including the National Environmental Policy Act (NEPA). NEPA requires agencies to consider the reasonably foreseeable environmental effects of major federal actions, which can be done through an environmental impact statement (EIS), environmental assessment (EA), or categorical exclusion. NEPA reviews often serve as a vehicle for projects to address compliance with substantive federal environmental laws, including the Endangered Species Act, the National Historic Preservation Act, the Clean Air Act, the Clean Water Act, and more (Luther 2011). EISs require the most thorough agency reviews and have historically taken several years, on average, for agencies to complete, which can delay the buildout of clean energy infrastructure (Morales and Rigby 2023).

Permitting requirements change the economic incentives to undertake clean energy projects by creating deterrents to investment. The financial return on a project is determined by the present discounted value of future profits, which depends on the size of future profits, how long firms must wait to receive them, the interest rate, and the certainty with which profits will be received. Permitting affects the present discounted value through two channels. First, delays in permitting processes can delay projects and push profits further into the future. Second, permitting can increase uncertainty about whether projects will come to fruition. Both effects decrease the risk-adjusted return to financial capital tied up in a project, creating additional barriers to new clean energy generation unrelated to the cost of generation.

The Biden-Harris Administration has taken steps to improve the efficiency of the federal permitting process. First, the IRA allocated $1 billion to hire experts and invest in new technologies to expedite review (White House 2024c). Additionally, amendments made to NEPA in the Fiscal Responsibility Act of 2023 and implemented by the Council on Environmental Quality's Bipartisan Permitting Reform Implementation Rule now require that an EIS must not exceed 150 pages (or 300 pages for a proposal of extraordinary complexity) and must be completed within two years, while an EA must not exceed 75 pages and must be completed within one year (White House 2024c; CEQ 2024). These reforms will further the progress the Biden-Harris Administration has already made in cutting six months off the median time it takes for agencies to complete EISs, while protecting the environment and communities (White House 2024d).

Interconnection Queues

Before new energy generation projects can be connected to the grid, transmission operators must ensure that the grid can handle the increase in load. Historically, projects have been evaluated in the order they are submitted. Each additional project in the queue then imposes a cost on future projects by increasing wait times, which can delay the return on investment and dissuade investors from undertaking otherwise-profitable clean energy generation projects (Johnston, Liu, and Yang 2023). Because these costs do not enter into firms' decisions to join the queue, this creates a negative externality that can lead to inefficient project selection, and government intervention to decrease wait times can increase completions. If the grid is at capacity, new applicants must also pay to upgrade transmission infrastructure, providing positive spillovers to other projects that can free-ride on their investment (Johnston, Liu, and Yang 2023). Using BIL funds, the DOE has analyzed solutions for reducing interconnection queues (DOE 2024k) and invested in interconnection infrastructure, including through the $10.5 billion GRIP and Title 17 Clean Energy Financing Program (DOE 2024j). FERC Order 2023 also aims to reduce interconnection queues by guiding transmission providers to conduct batch studies of multiple projects at once, as well as incentivizing faster completion (FERC 2024b; DOE 2024j).

Demand Response

Variability in renewable energy availability can also be addressed by adjusting demand, much like congestion pricing for traffic. Most retail consumers, including households and small businesses, do not pay retail rates that fully reflect changes in the cost of producing electricity (Borenstein, Bushnell, and Mansur 2023). This means that many customers have no incentive to adjust their consumption patterns to match the availability of cheap, renewable energy. Allowing electricity prices to reflect fluctuations in demand or supply (e.g., after sudden increases in heat or drops in the availability of wind power) could help consumers time their electricity consumption for when renewables are available (Joskow and Wolfram 2012).

New technologies, such as digital meters and advanced sensors, make it easier for consumers to adjust electricity demand in response to changes in electricity prices (DOE n.d.d). They can help consumers respond to changes in electricity prices without having to take additional action or even be aware of the rate changes (Bollinger and Hartmann 2019). Recent evidence suggests that time-varying prices with caps to limit consumer spending can improve the timing of energy demand (Hinchberger et al. 2024). Demand response can also be used by environmentally conscious consumers to reallocate demand in the absence of time-varying electricity prices. The Biden-Harris Administration has promoted demand response programs as part of a wider effort to promote the use of automation technologies to better balance electricity supply and demand (DOE 2023g).

Carbon Capture and Storage

Many efforts to decarbonize electricity focus on ensuring that new clean generation displaces fossil fuels. Another approach is to alter the process of fossil fuel combustion to reduce CO_2 emissions. Carbon capture and storage, or CCS, is a term for a suite of technologies that aim to capture CO_2 from process exhaust and prevent it from reaching the atmosphere.[14] The equimarginal principle implies that CCS should be used at power plants to reduce emissions when it is less expensive than using a combination of renewables and storage, other generation technologies, or adjusting demand. As a result, CCS can be used to ensure that the economy achieves net zero CO_2 emissions as quickly as possible and can be phased out when zero-carbon energy sources become lower cost alternatives to supply all electricity. Knowledge gained from R&D and deployment of CCS in the power sector will spill over to other sectors that make use of CCS.

The EPA has found that CCS is a cost-effective way to reduce emissions, and its recent regulations adopted under section 111 of the Clean Air Act will require all long-term coal-fired plants and some new gas-fired plants to control 90 percent of their CO_2 emissions (EPA 2024d). This regulatory design requires firms to limit emissions without mandating use of a specific technology, incentivizing them to do so in the least expensive way possible. CCS is a cost-effective way to comply in part due to tax credits that were increased and extended by the IRA, highlighting the interaction of recent legislation and regulatory efforts in propelling the economy toward net zero.

Electrification

Given the potential for rapidly decarbonizing the electricity sector, further electrification of the economy is crucial for reaching net zero. This section discusses the economics of electrification in each sector of the economy.

The Transportation Sector

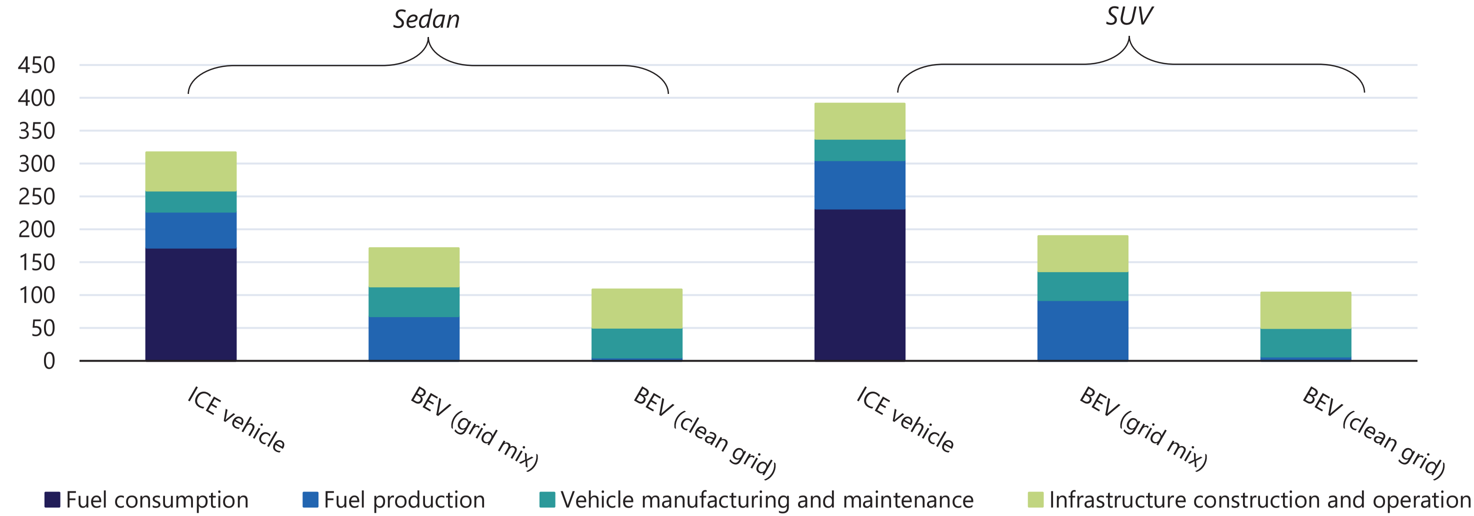
In 2023, transportation contributed nearly 40 percent of energy-related CO_2 emissions (see figure 5-1). Electrification offers significant opportunities for reducing emissions not only from fuel consumption, but also from fuel production, vehicle manufacturing and maintenance, and infrastructure.

Personal vehicles. Replacing internal combustion engine (ICE) with EVs is central to achieving net zero in the transportation sector. More than 90 percent of American households have at least one car (Census 2022), and tailpipe CO_2 emissions from passenger vehicles and light trucks made up 18 percent of total U.S. CO_2 emissions in 2022 (EPA 2024e). Figure 5-13 compares lifecycle emissions from ICE vehicles and EVs. Replacing all ICE vehicles with EVs would reduce emissions per passenger mile traveled (PMT) by 46 percent with the mix of electricity generation sources projected

[14] CCS in the power sector prevents emissions from fossil fuel use but does not pull CO_2 from the atmosphere. For this reason, it is not considered to be a NET.

Figure 5-13. Emissions per Passenger Mile from Personal Vehicles

Grams CO_2-e per passenger mile traveled



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Sources: International Council on Clean Transportation; CEA calculations.

Note: ICE vehicle refers to vehicles with internal combustion engines and BEV refers to battery electric vehicles. Calculations are made for vehicles registered in the United States in 2021 using the GREET model from Argonne National Laboratory. Grid mix refers to electricity generated from both fossil fuel and renewable sources projected for 2021–2038. Clean grid refers to electricity produced with zero emissions. CO_2-e is a measure of total greenhouse gas emissions that converts non-CO_2 gases into their equivalent quantity of CO_2 in terms of warming potential.

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to be used from 2021–2038 and by 66 percent with a zero-carbon emissions grid.

The Biden-Harris Administration has set the target that 50 percent of new passenger cars and light trucks should be zero- or low-emissions vehicles, including battery electric, plug-in hybrid electric, and fuel cell electric vehicles, by 2030 (White House 2021c). As of the second quarter of 2024, low-emissions vehicles made up 9 percent of new vehicle sales, up from less than 1 percent in 2014, and battery EVs alone made up 7 percent (EIA 2024f). As older ICE vehicles are retired, the share of EVs on the road will increase.

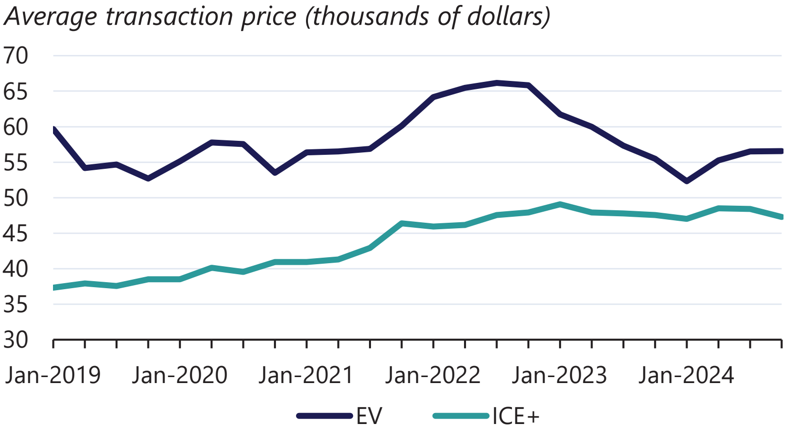
There are two main challenges to increasing EV adoption, both of which the Biden-Harris Administration has taken action to address. First, EVs have historically been more expensive than ICE vehicles in the United States, although the market prices are converging (see figure 5-14a) in part thanks to government support for R&D (White House 2024e) and critical mineral supply chains (White House 2022). In addition, the IRA funds EV tax credits that lower the price for many consumers below the trend shown in figure 5-14a, and EVs often have lower operating costs (Treasury 2024; Orvis 2022). Second, consumers have concerns about EVs' range and ease of travel. ICE vehicles have historically been able to travel farther than EVs before refueling (although EV and ICE vehicle ranges are converging, as shown in figure 5-14b), charging typically takes longer than filling a gas tank, and charging stations are not as common as gas stations.

To make EVs better substitutes for ICE vehicles, complementary investments are needed to extend battery range and build charging stations (Rapson and Bushnell 2024). Without government intervention, investment in charging stations would be insufficient because of a coordination problem: Investments in charging stations are not profitable unless many people drive EVs, and fewer consumers will buy an EV if charging stations are not available along long-distance routes (Gillingham and Stock 2018). In response, investments from the BIL and IRA are working to reduce EV prices, increase range, and expand charging networks, which have contributed to the quadrupling of EV purchases and the doubling of the number of publicly available chargers since the Biden-Harris Administration took office (White House 2024e; DOT 2024). More than $25 billion of investment in the U.S. EV charging network has been announced to date, including over $10 billion from the private sector (White House 2024e). The investments may need to be adjusted over time to keep adoption on track. These investments will also encourage adoption of electric medium-duty vehicles such as delivery vans.

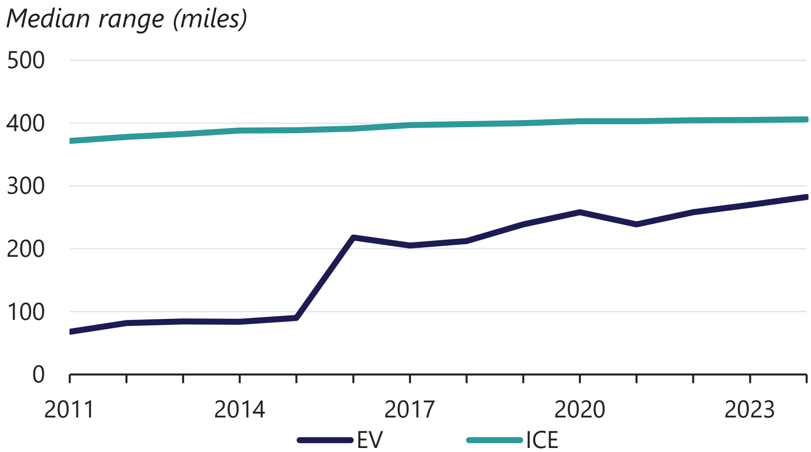
Shared transit. Shared transit addresses congestion and emissions externalities, which means that government intervention to increase its availability can increase wellbeing. Increasing ridership can also reduce emissions. Figure 5-15 shows emissions per PMT for an average bus occupancy

Figure 5-14. Range and Transaction Price for New Light-duty Vehicles

A. Transaction Price



B. Range



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Sources: Department of Energy; Cox Automotive; CEA calculations.

Note: Average transaction price is calculated as a three-month moving average and is based on all transacted models, thus reflecting differences in the composition of model categories. Median range is based on all available model configurations certified by the Environmental Protection Agency (EPA) in a given year and does not represent sales- or production-weighted data. Range for electric vehicles is based on EPA estimates; range for ICE vehicles is based on tank size and combined city/highway fuel economy. The ICE model category includes gasoline vehicles, while the ICE+ model category includes all internal combustion engine vehicles as well as hybrid vehicles.

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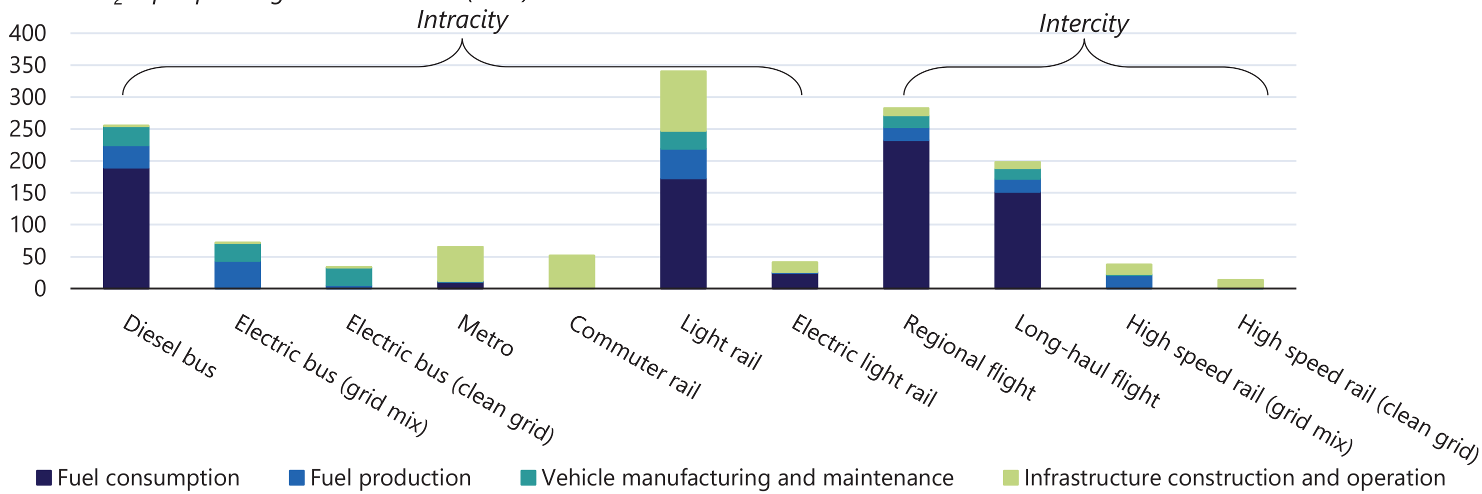
Figure 5-15. Emissions per Passenger Mile from Mass Transit

Grams CO_2-e per passenger mile traveled (PMT)



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Sources: Transportation Life-Cycle Assessment Passenger Database; Fuels Institute; Federal Highway Administration; CEA calculations.

Note: Metro, commuter rail, and light rail with an energy mix (20 percent renewable energy) are calculated for the San Francisco systems; electric light rail is calculated for Los Angeles. Grid mix refers to electricity generated from both fossil fuel and renewable sources; assumptions about the shares are described in each source. Clean grid refers to electricity generated with zero emissions. Bus PMT are calculated for 11 passengers, the average occupancy in 2018. CO_2-e is a measure of total greenhouse gas emissions that converts non-CO_2 gases into their equivalent quantity of CO_2 in terms of warming potential.

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of 11 people (Federal Highway Administration 2018), though most buses can transport 50–70 passengers at a time (Transportation Research Board 2013). While both private and public EVs have low marginal operating emissions, displacing private vehicles with shared transit helps decrease life-cycle emissions via reduced vehicle production, maintenance, infrastructure investments, and vehicle end-of-life.

Increasing public transit ridership will require government action to build new networks, connect long-distance transit with last-mile travel modes, reduce trip times, and set optimal prices considering environmental externalities. A recent study finds that optimal fares for public transit can be as low as $0.16 and optimal service is more frequent when emissions and congestion are taken into account (Almagro et al. 2023). The benefits of expanding the use of a fully electric, zero-emissions public transit fleet would be greater.

Federal, state, and local governments can act to make a rapid transition to an electrified public transit system. For example, the EPA's Clean School Bus Program buys electric school buses with funding from the BIL (EPA 2024f). Federal funding and incentives for the electrification of rail can help fund the replacement of older, high-emissions locomotives with new electric locomotives (Federal Railroad Administration 2024). As shown in figure 5-15, meeting demand for new regional transportation by building new high-speed rail can also help reduce emissions.

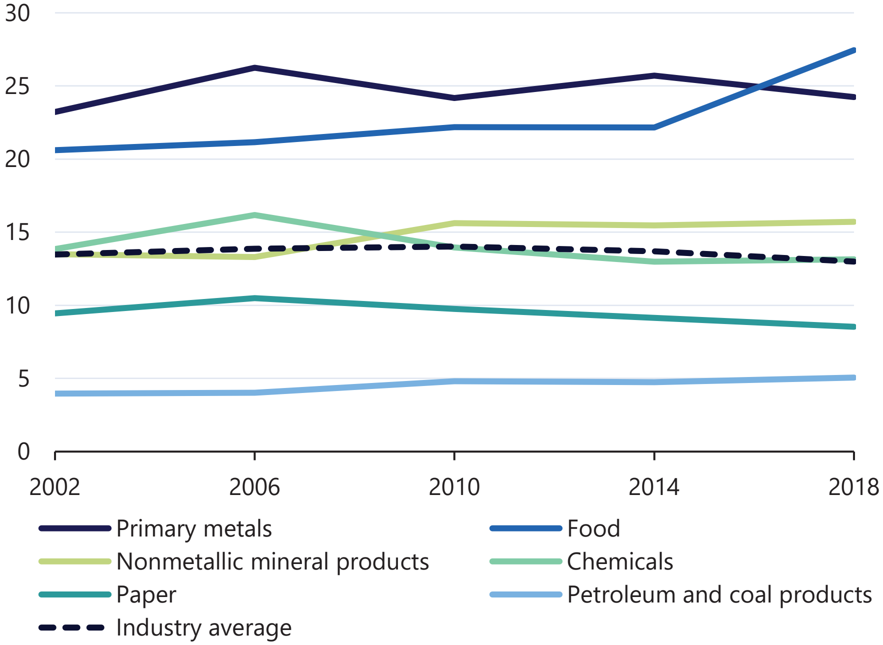
Freight. Freight is transported by container ship, rail, air, and heavy-duty vehicles. While inexpensive batteries could enable the electrification of heavy-duty vehicles (Ledna et al. 2024) and shorter-distance, interregional container shipping (Kersey, Popovich, and Phadke 2022), decarbonizing global shipping and aviation will likely make use of other technologies that will be discussed later.

The Residential and Commercial Building Sectors

Direct emissions from buildings comprise 12 percent of annual U.S. CO_2 emissions (EIA 2024a). Electrifying heating and cooling, water heating, and cooking will deliver increasing emissions reductions over time as the grid decarbonizes (Leung 2018). Because buildings are durable, retrofits will play a major role in building electrification: 75 percent of homes and 51 percent of commercial space projected to exist in 2050 have already been built (DOE 2024l). However, retrofits tend to be costly, and without subsidies, many households and businesses will continue to use existing technologies until they must be replaced. The Biden-Harris Administration supports electrification through IRA tax credits and home energy rebates (White House 2024f). While building codes are set at the state and local level, the Federal Government can participate in model code development and offer incentives

Figure 5-16. Electrification by Industry Subsector

Percent of end-use energy coming from electricity



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Sources: Energy Information Administration; CEA calculations.

Note: The subsectors included are the six most energy-intensive subsectors in 2018. Primary metals includes steel and aluminum. Nonmetallic mineral products includes cement and glass. Chemicals includes fertilizer. Values are calculated as electricity sales to ultimate customers in the end-use subsector (Btu) divided by end-use energy consumed by the end-use subsector (Btu). The average value represents the average across all industry subsectors, not just those shown.

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and support for local jurisdictions to require new construction to be electric ready (DOE 2024l).

Because buildings already consume 75 percent of electricity production, decreasing demand for electricity in buildings through improved energy efficiency will tend to lower electricity prices (O'Shaughnessy et al. 2022). This decrease in prices will then promote electrification throughout the rest of the economy.

The Industrial Sector

The decarbonization of industry will rely on a combination of electrification, energy efficiency, low-carbon fuels, and CCS, among other solutions (DOE 2022a). Because of the wide range of industrial processes, optimal measures will depend on the industrial subsector. For example, in sectors that use low and medium temperature heat, electrification can be cost effective with existing technologies, which generally means using industrial heat pumps to replace natural gas boilers (Rissman 2022). This process of electrification will be spurred by policies that lower the cost of electricity relative to natural gas, including subsidies for clean energy generation and batteries. For applications where higher temperatures are required, such as producing steel, cement, and glass, heat electrification is unlikely to be economical soon. For many energy-intensive subsectors, electrification is still nascent (figure 5-16). The Biden-Harris Administration has funded a wide range of R&D and demonstration projects to promote electrification and other forms of industrial decarbonization, which will be discussed in the following sections (DOE 2024m; DOE 2020; DOE 2024n).

Beyond Electricity

This section discusses the economics of decarbonization for un-electrified parts of the economy and the use of NETs to remove emissions that are difficult to eliminate.

Decarbonization Beyond Electrification

While grid decarbonization plays a critical role in economy-wide decarbonization, it is still possible to decarbonize portions of the economy that do not rely on electricity.

Sustainable Fuels

When full electrification is not cost effective, using fuels that have fewer emissions on a lifecycle basis can be an effective way to reduce emissions. These fuels are likely to play a large role in decarbonizing both high-heat industrial processes and freight transportation (Lu et al. 2023). Powering aviation and cargo ships with electricity is not efficient with current technology, because batteries with the capacity to handle long-distance ranges are very heavy and take up considerable cargo space (Kennedy and Feldman 2023). The United States is investing in alternative energy-dense sustainable aviation fuels derived from biomass, wastes, or captured CO_2 and hydrogen as part of its target to reduce aviation emissions by 20 percent by 2030 (White House 2021d; DOE 2024o).

Hydrogen can also be used as an alternative to fossil fuels in ICE vehicles, fuel cells, and heavy industry. However, there is a tradeoff between emissions intensity and cost across the available production technologies. Without subsidies and given current grid conditions, it is currently cheapest to produce liquid hydrogen using fossil fuels in a manner that produces CO_2 and other GHG emissions, rather than using electricity (Schelling 2023). In 2020, 95 percent of hydrogen production used natural gas as an input (DOE 2020). Due to uncertainty about the future economic viability of low carbon fuels like clean hydrogen (Davis et al. 2023), subsidies for R&D and production—such as the IRA's Clean Hydrogen Production Tax Credit—are likely to be important. The BIL funds the establishment of Regional Clean Hydrogen Hubs (DOE 2024p) in addition to other projects promoting research, development, demonstration, and deployment of clean fuels (DOE 2023h).

Increasing Energy Efficiency

Energy efficiency has been the driving force behind past decarbonization of the U.S. economy. CO_2 emissions per dollar of gross domestic product fell 55 percent from 1990–2022, largely due to increases in economy-wide energy efficiency (i.e., decreases in primary energy use per dollar of real GDP). While improvements in energy efficiency will never be sufficient to achieve complete decarbonization on their own while fossil fuel energy sources are in use, the equimarginal principle suggests they are likely to be an important component of reaching net zero carbon emissions, especially in economic activities that are not completely electrified.

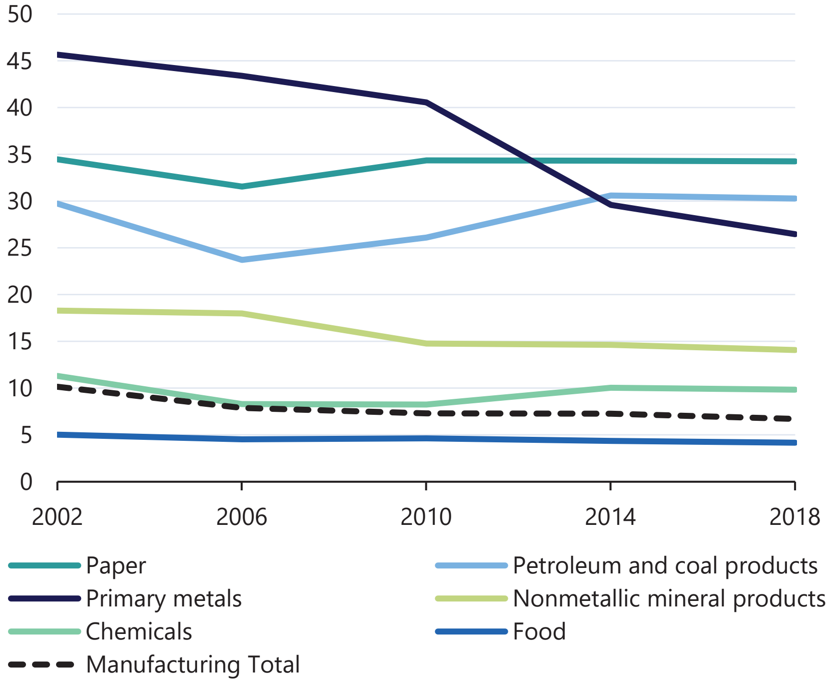
Energy efficiency is a central component of industrial decarbonization, with specific applications differing by subsector. Figure 5-17 shows that energy efficiency improved from 2002–2018 even within subsectors that did not experience significant electrification. The Industrial Decarbonization Liftoff report outlines how the Biden-Harris Administration has promoted energy efficiency with tools including R&D and demonstration projects (DOE 2023i).

Energy efficiency can also play a key role in decarbonizing freight transportation and global shipping (Lu et al. 2023). Improvements in the design of trucks, ships, planes, and engines as well as new innovations in the use of sails to capture wind for maritime freight can all reduce CO_2 emissions per ton-mile (Kennedy and Feldmann 2023). The Biden-Harris Administration issued the U.S. National Blueprint for Transportation Decarbonization, which discusses how to increase energy efficiency within transportation modes and incentivize switching activity to more energy efficient modes, such as shared transit, when possible (DOE 2023j).

Increasing energy efficiency is also crucial to decarbonizing the building sector. Buildings can be made more energy efficient through investments in insulation, air sealing, envelope requirements, and energy efficient appliances and lighting (DOE 2024l). The Biden-Harris Administration supports these efforts with IRA tax credits and home energy rebates (White House 2024f), energy efficiency standards for appliances and commercial and industrial equipment as directed by Congress (DOE 2024q), energy code

Figure 5-17. Energy Use per Real Dollar of Value Added by Industry Subsector

1,000 Btu per chained 2017 dollar



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Sources: Bureau of Economic Analysis; Energy Information Administration; CEA calculations.

Note: The subsectors included are the six most energy-intensive subsectors in 2018. Primary metals includes steel and aluminum. Primary metals includes steel and aluminum. Nonmetallic mineral products includes cement and glass. Chemicals includes fertilizer. Values are calculated by dividing total energy use (Btu) by gross real value added for each industry subsector. The average value represents the average across all industry subsectors, not just those shown.

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requirements for federal programs, and $1.2 billion in IRA and BIL funding to support local jurisdictions in adopting new energy codes (DOE 2023k).

Where buildings are located also affects energy use through the impact of weather on energy demand for heating and cooling, emissions from commuting (Lyubich 2024; Almagro et al. 2024; DOE 2023j), and land use (Hong et al. 2021). Indeed, place effects account for 14–23 percent of heterogeneity in household energy use (Lyubich 2024). In 2021, 14 percent of building emissions were estimated to come from embodied carbon in material manufacturing, transport, construction, and disposal (DOE 2024l), suggesting that switching to less carbon-intensive building materials and practices and reducing the frequency of repairs and rebuilding can lower CO_2 emissions per year of use. As a result, rezoning to encourage dense construction in low disaster-risk, transit-rich areas, combined with updating building codes for energy efficiency and climate resilience, can ensure that housing construction and emissions reduction goals advance together (Schuetz 2022). The Biden-Harris Administration emphasizes the role of land-use planning and transit-oriented development in reducing emissions in its Blueprint for Transportation Decarbonization (DOE 2023j).

CCS in Industry and Transportation

As in the electric power sector, CCS could play an important role in decarbonizing heavy industries like steel and cement production, as well as the production of low-carbon fuels used for transportation. CCS is more likely to be both a short- and long-term solution in these sectors, unlike in the power sector where it is likely to be a short-term tool for speeding up the transition (Browning et al. 2023).

Negative Emissions Technologies

Reaching net zero will require offsetting emissions from sectors where cost-effective mitigation is not feasible (DOE 2022b). In other words, there is a need for NETs, which can allow the economy to reach net zero even when carbon emissions still occur in some sectors.

Biological NETs are any biological process pulling CO_2 from the atmosphere, usually through plant growth, to maintain or enhance natural carbon sinks. In particular, forest growth consumes significant CO_2, and some farming practices can increase the carbon uptake of soil.

Technological NETs are engineered systems that remove CO_2 from the atmosphere. The simplest technological NET is direct air capture and storage (DACS). DACS pulls CO_2 from the atmosphere using chemical reactions (IEA 2024a). DACS requires an external source of energy that may itself be produced with either fossil fuels or carbon-free energy sources. As a result, the net cost of using DACS to remove emissions depends on both the technology for capturing and storing emissions and the technology for generating the energy inputs.

Bioenergy with carbon capture and storage (BECCS) is a hybrid NET that involves growing, harvesting, and converting plants into electricity or biofuel (IEA 2024b).[15] In the conversion process, CCS is applied to capture and store emissions. Unlike CCS used to decarbonize fossil fuel electricity generation, BECCS can result in net negative emissions because plant growth pulls CO_2 from the atmosphere.

The ability of DACS and BECCS to yield net negative emissions, rather than simply preventing new emissions, makes them potentially important tools for meeting international targets to limit global temperature change, like the 1.5–2 degrees Celsius goal in the Paris Agreement. While the Biden-Harris Administration's targets are expressed in terms of flow emissions, long-run climate targets depend on the stock of carbon in the atmosphere. As highlighted by the United Nation's Intergovernmental Panel on Climate Change (IPCC), negative emissions can play an important role by offsetting positive emissions that occur during the transition to net zero and legacy emissions from before the transition in order to keep total warming from exceeding the target (IPCC 2018).

Recent analyses show great potential for NETs to contribute significantly to achieving net zero by 2050 (Pett-Ridge et al. 2023; IPCC 2018). However, due in part to the early stage of development and significant technology uncertainties, a wide range of costs for technological NETs have been reported.[16] DACS is currently considered too expensive to be widely deployed. Producing electricity with BECCS is less expensive than using DACS, but still costs more than other abatement options. Certain biological NETs, such as afforestation/reforestation, are much less expensive but may be less permanent, since, for example, the carbon stored in a forest would be released if it were burned or cleared (NASEM 2019; Cook-Patton et al. 2020; Fuss et al. 2018).

The equimarginal principle suggests there is no need to undertake an action that reduces emissions at a higher cost than it takes to remove a ton of emissions through NETs. For this reason, technological NETs are often referred to as the "backstop technology" (Heal 2009). As technology improves and the price of this backstop technology comes down, the upper limit of the cost of reaching net zero will also decrease.

R&D is expected to reduce the costs of DACS and BECCS meaningfully (DOE n.d.e). For example, a survey of technical experts found an expected decrease from the 2020 cost of DACS of over 50 percent by 2050 (Abegg et al. 2024). Achieving such cost reductions will require government policy to address externalities related to R&D spillovers and learning-by-doing (Jones et al. 2024). Higher tax credits for CCS—which also apply to DACS and BECCS—in the IRA will potentially help spur learning-by-doing.

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[15] BECCS is part of a broader category of NETs known as Biomass Carbon Removal and Storage (BiCRS) that includes any process that stores CO_2 captured by plants and algae (DOE 2022b).

[16] See, for example, Fuss et al. (2018), NASEM (2019), Cook-Patton et al. (2020), Abegg et al. (2024), Homsy et al. (2024), and DOE (n.d.e).

In addition, the Biden-Harris Administration is funding four Regional Direct Air Capture Hubs and the Carbon Capture Demonstration Project to harness learning-by-doing externalities and accelerate the demonstration and deployment of DACS (DOE 2024r; DOE 2024s). Regional hubs also help address coordination externalities by ensuring that carbon capture facilities and carbon transportation infrastructure are co-located (Armitage, Bakhtian, and Jaffe 2024). Government support to create market incentives for NETs is particularly important, because NETs do not always yield a marketable product (Jones et al. 2024).

The Path Ahead

The Biden-Harris Administration has made the transition to net zero GHG emissions a policy priority, setting out targets for a carbon pollution-free electricity sector by 2035 and net zero GHG emissions by 2050. The Administration signed into law the most significant climate legislation in U.S. history, including the IRA, BIL, and CHIPS and Science Act. These historic achievements have made significant and unprecedented progress in pushing the economy toward the Administration's targets.

Achieving these goals will require transformation across all sectors of the economy, implying that the equimarginal principle will play an important role in climate policy. Net zero can be accomplished most cost effectively with a combination of (i) a fully decarbonized electric power sector, (ii) significant electrification across other sectors, (iii) the use of clean fuels, energy efficiency, and CCS to decarbonize un-electrified activities, and (iv) NETs to offset remaining emissions.

The central goal of climate policy is to address the negative externality of GHG emissions, including CO_2. The Biden-Harris Administration's efforts are projected to fundamentally alter the country's emissions trajectory. Future administrations can build on this progress in several ways, including using carbon pricing to address this externality simultaneously throughout the economy or continuing the current strategy of addressing the externality separately with different policies aimed at different economic activities.

Achieving net zero will also require policy to address a set of additional market failures beyond the CO_2 emissions externality, such as promoting R&D and demonstrating the economic feasibility of nascent technologies. Through historic investments in the advancement and deployment of clean energy technology, the Biden-Harris Administration has taken the first necessary steps to address the market failures and achieve the transition to a net zero economy.