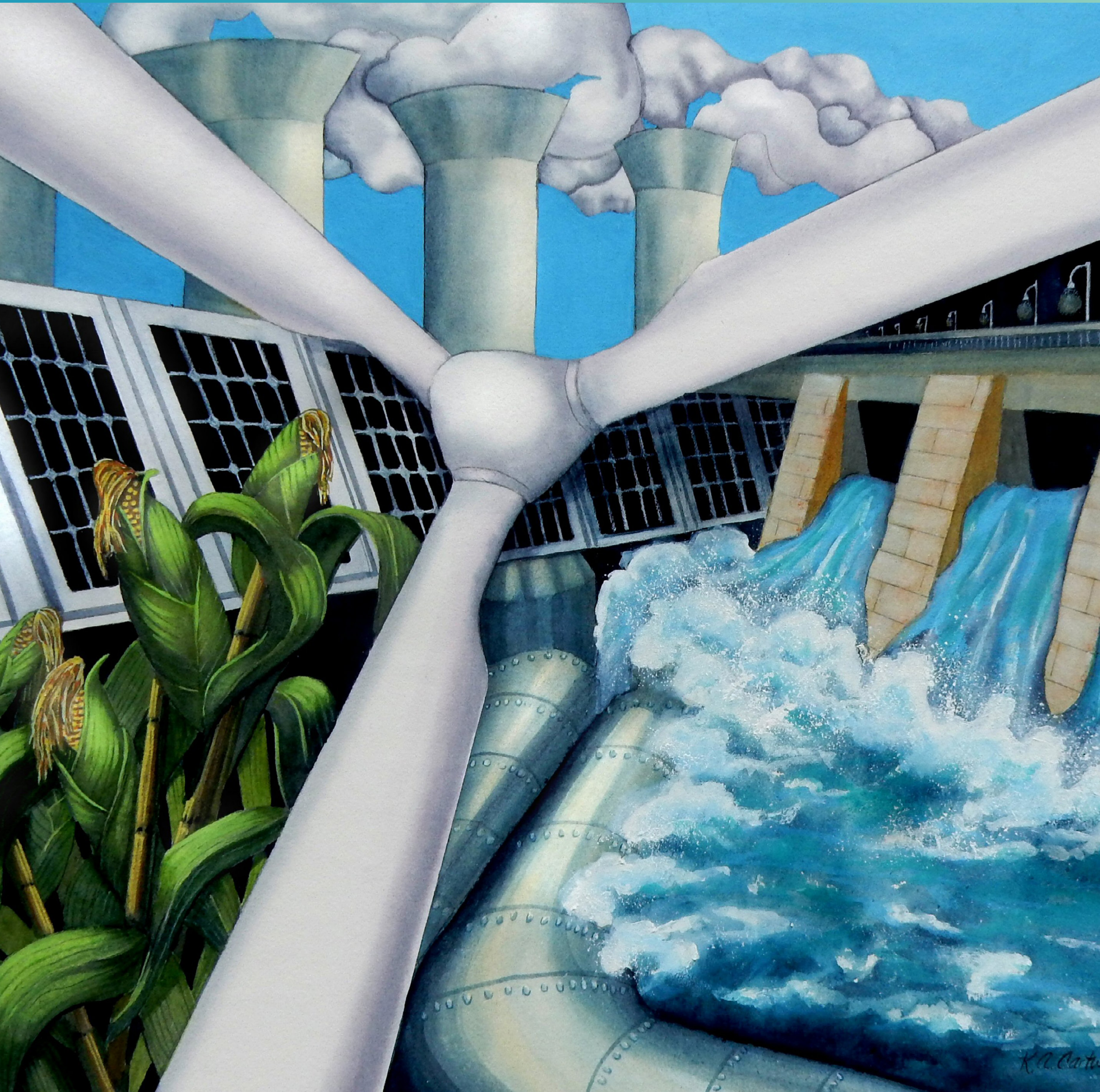
Fifth National Climate Assessment: Chapter 32

Mitigation



Chapter 32. Mitigation

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Introduction

Mitigation refers to efforts to reduce emissions or to remove carbon from the atmosphere with the goal of avoiding or reducing the effects of climate change, which is different from adapting systems and activities to a changed climate (Ch. 31). To meet international climate goals, global carbon dioxide (CO_2) emissions would need to reach net zero by around 2050 (KM 32.1).[1]

Mitigation is the most cost-effective response to climate change, with potentially large benefits to economies (Ch. 19), social and economic equity (Ch. 12), human health (Chs. 13, 14, 15), food security (Ch. 6), and ecosystems (Chs. 7, 8). Modeling studies agree that large near-term decreases in greenhouse gases (GHGs) in the United States are feasible by improving energy efficiency, electrifying end uses of energy, and generating electricity from non-emitting energy sources such as solar and wind (KM 32.2). However, the optimal mix of technologies to reach net-zero emissions is not yet clear, and further research and development is needed to determine the best options for long-duration energy storage, non-emitting and dispatchable (sometimes called firm) sources of electricity, and net-zero options for aviation and long-distance freight transport, as well as carbon dioxide removal (KM 32.3). Actions to immediately and substantially reduce emissions are available, and can be supported by individual choices and decisions by multiple stakeholders (KM 32.5). Further, racial, economic, demographic, and geographic inequities and injustices are embedded within existing infrastructure and social systems, and mitigation will both influence and be influenced by equity, environmental, and economic factors (KM 32.4).

Key Message 32.1

Successful Mitigation Means Reaching Net-Zero Emissions

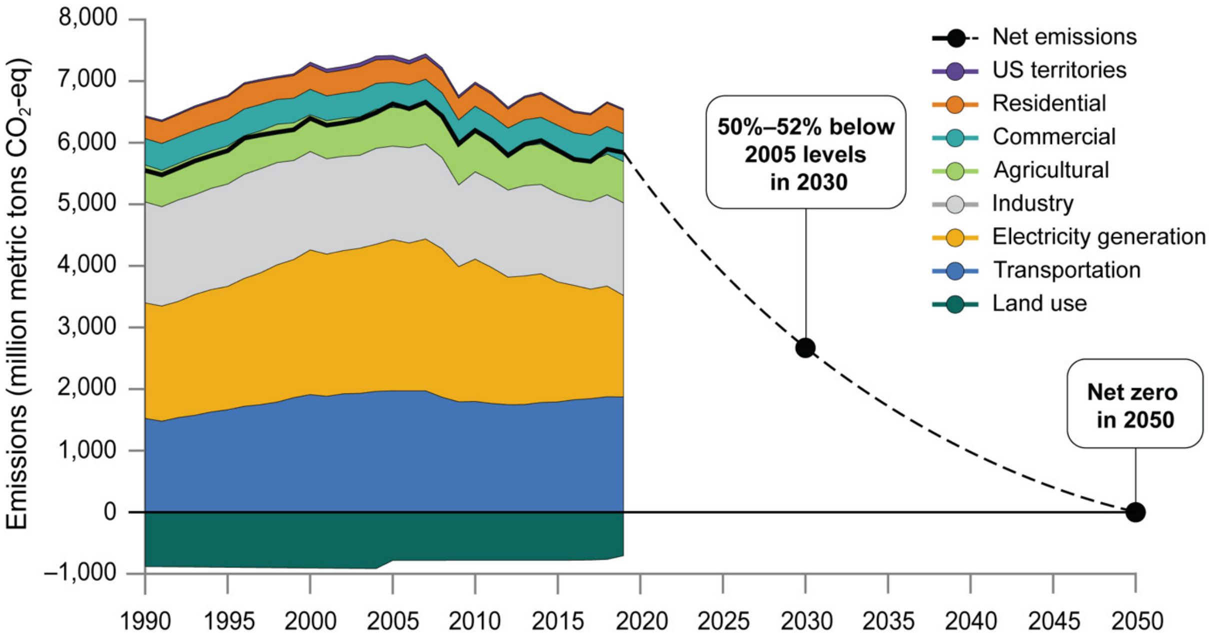
Greenhouse gas emissions in the United States decreased by 12% between 2005 and 2019, mostly due to replacing coal-fired electricity generation with natural gas–fired and renewable generation (*very high confidence*). However, US net greenhouse gas emissions remain substantial and would have to decline by more than 6% per year on average, reaching net zero around midcentury, to meet current national climate targets and international temperature goals (*very high confidence*).

Mitigation Goals

To achieve the Paris Agreement (an international treaty on climate change) goal of limiting global warming to well below 2°C above preindustrial levels and pursuing efforts to limit global warming to 1.5°C above preindustrial levels, global CO_2 emissions need to reach net zero around 2050 and remain net zero or net negative afterward.[2] Thus, US CO_2 emissions reaching net zero around midcentury would be consistent with Paris goals, although a wide range of trajectories is possible based on considerations of international equity, burden-sharing, costs, and policy assumptions.[3,4,5] This chapter addresses pathways and options for mitigation of US emissions from all sectors consistent with national and international climate goals.

As part of the Paris Agreement, countries communicate nationally determined contributions (NDCs)—emissions-reduction targets that they intend to achieve. The latest NDC communicated by the United States to the United Nations Framework Convention on Climate Change (UNFCCC) Secretariat sets an economy-wide target of reducing all its net GHG emissions (not only CO_2) by 50%–52% below 2005 levels in 2030, or roughly −6% per year beginning in 2022, putting the country on a path to achieve the goal of reaching net-zero GHG emissions by no later than 2050 (Figure 32.1).[6] In addition, 24 states and Washington, DC, have their own reduction targets (KM 32.5).

US Greenhouse Gas Emissions by Sector with 2030 and 2050 Goals Added



US emissions will need to decrease rapidly to reach levels consistent with international climate targets.

Figure 32.1. Figure shows US annual greenhouse gas emissions and sinks from 2005 to 2019, as well as future targets for achieving the US nationally determined contribution under the Paris Agreement. US territories—including American Sāmoa, Commonwealth of the Northern Mariana Islands, Federated States of Micronesia, Guam, Republic of the Marshall Islands, and Republic of Palau—contribute minor emissions (not visible) that are not broken down by sector. CO_2-eq = carbon dioxide equivalent. Adapted from DOS and EOP 2021.[6]

Major Trends

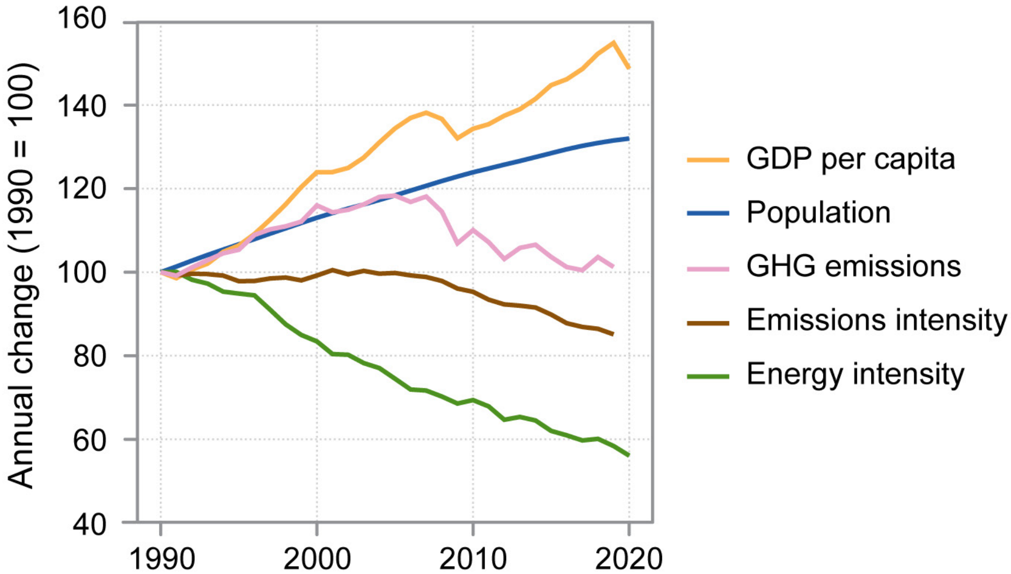
Between 1990 and 2019, US CO_2 and nitrous oxide (N_2O) emissions increased by approximately 3% in each case. Emissions of fluorinated gases increased by 86%, and methane (CH_4) emissions decreased by 15%.[7] Although the latest EPA inventory reports emissions through 2021,[8] this chapter focuses on trends in emissions to 2019 because the COVID-19 pandemic caused substantial but largely temporary changes in energy-related emissions worldwide (see, e.g., Davis et al. 2022;[9] Liu et al. 2020[10]). The EPA estimates that US carbon dioxide equivalent (CO_2-eq) GHG emissions were about 6.6 billion metric tons (or gigatons; Gt) in 2019, 2% more than in 1990.[7,11] The sources of these emissions are primarily electricity generation, transportation, and combustion of fuels in other sectors (i.e., commercial, residential, and industrial), with smaller contributions from agriculture, industrial processes, and waste (Figure 32.1). Major sinks were land-use change and especially forests, which resulted in net uptake of 0.7 Gt of CO_2 in 2019. Net GHG emissions from all sources and sinks were thus 5.8 Gt of CO_2-eq in 2019.[7,8,11]

Between 2005 and 2019, US GHG emissions decreased by 12%, mainly because of reductions in electricity generation emissions. Indeed, since 2017, the largest share of GHG emissions has come from the transportation sector (Figure 32.1). Estimates include emissions occurring within all US territories, as annually reported to the UNFCCC Secretariat by the EPA. Independent estimates by other scientific bodies and researchers are similar but not identical.[12,13,14,15]

Sector-Specific Trends and Drivers

Between 1990 and 2019, economic and population growth have acted to increase US energy-related emissions but have been counterbalanced by reductions in both the energy used per dollar of GDP (or "energy intensity of economic activity") and the CO_2 emissions per unit of energy used (or "emissions intensity of energy").[16] In particular, decreases in energy emissions since 2007 were driven by a steady and substantial fall in CO_2 emissions per unit of energy consumed from a maximum of 59 million metric tons (megatons; Mt) of CO_2 per exajoule (10^{18} joules) of energy consumed in 2007 to 51 Mt per exajoule in 2019 (Figure 32.2).

Changes in Drivers for Energy-Related Greenhouse Gas (GHG) Emissions



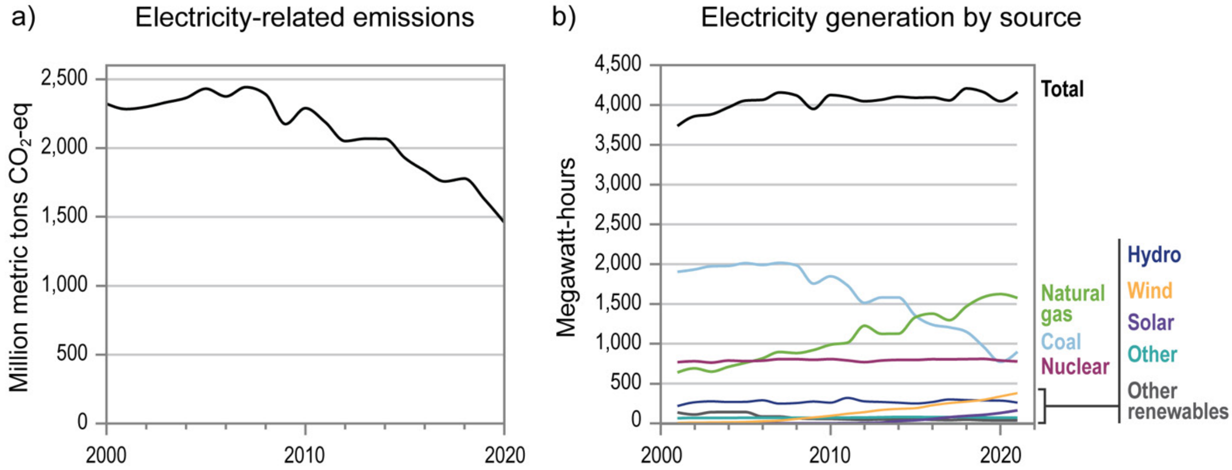
US greenhouse gas emissions have dropped even as population and economic activity (as measured by GDP) have climbed.

Figure 32.2. Energy-related greenhouse gas (GHG) emissions in the United States have declined since 2007 (pink) despite rising population (blue) and economic activity measured by the GDP (orange). Behind the decreasing trend are gradual reductions in energy use per dollar of GDP (energy intensity, green) and large decreases in GHG emissions per unit of energy produced (emissions intensity, brown). Figure credit: Stanford University.

Electricity Sector Emissions

GHG emissions from the electricity sector in 2019 were 1,629 Mt of CO_2-eq, or 30% of energy-related emissions.[7] Decreases in US energy-related emissions since 2007 mostly reflect changes in the electricity sector, especially the retirement and reduced use of coal-fired power plants and corresponding increases in lower-cost electricity from natural gas–fired power plants (and to a lesser extent renewable technologies; Figure 32.3b). US emissions from electricity generation in 2019 were roughly 40% below 2005 levels (Figure 32.3a).

Trends in Electricity Generation by Source and Related CO_2 Emissions



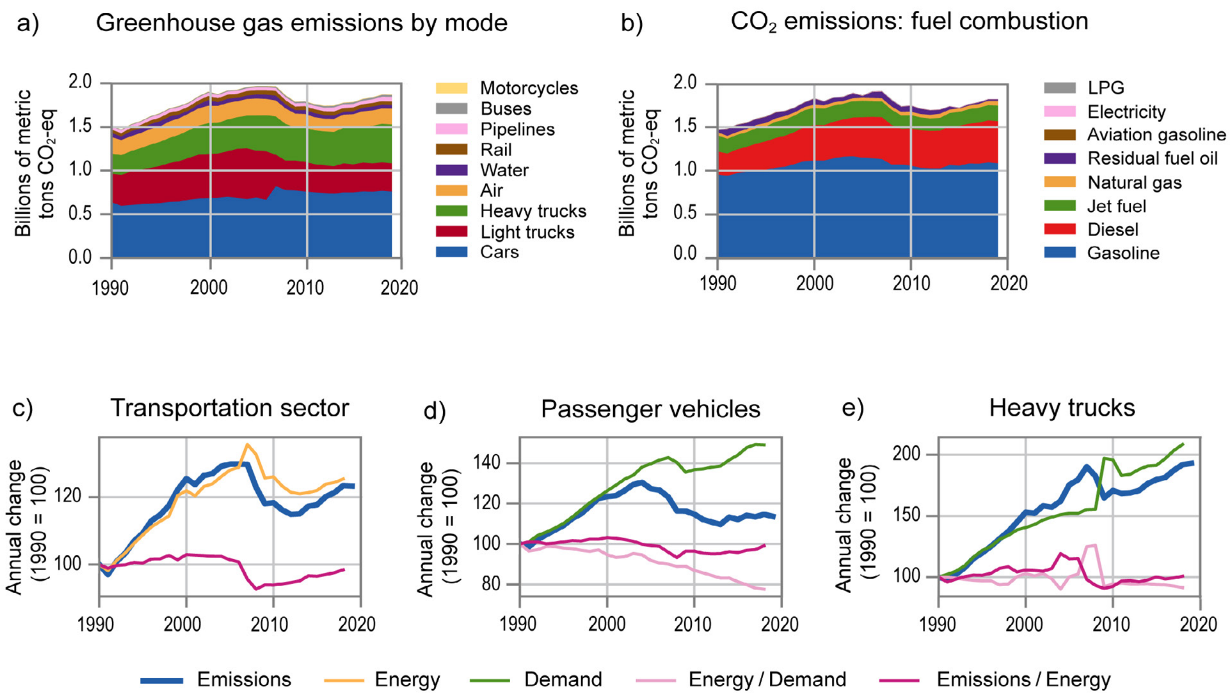
Carbon dioxide (CO_2) emissions from electricity generation decreased by almost 40% between 2005 and 2020.

Figure 32.3. The decrease in electricity-related emissions between 2000 and 2020 (**a**) can be explained by the decline in high-emitting coal generation and the growth in generation from lower-emitting (natural gas) and non-emitting (wind and solar) sources (**b**). CO_2-eq = carbon dioxide equivalent. Adapted from Scott Institute for Energy Innovation 2017[17] [CC BY-SA 4.0].

Transportation Sector Emissions

GHG emissions from the transportation sector in 2019 were 1,874 Mt of CO_2-eq.[7] Most transportation emissions are CO_2 emissions from combustion of gasoline (59.6%, mostly for light trucks and cars), diesel (26.4%, mostly for heavy trucks, buses, and trains), and jet fuel (9.8%; Figure 32.4). In contrast to electricity sector emissions, transportation emissions increased by 23% between 1990 and 2018, largely reflecting 49% growth in demand for passenger vehicle transport over the period (measured in passenger-kilometers, or the distance traveled in km multiplied by the number of passengers), which was partially offset by a 22% decrease in energy required per passenger-kilometer. Over the same 1990–2018 time period, demand for heavy trucks (measured in vehicle-kilometer, or the total distance traveled by the truck fleet) more than doubled, and improvements in energy per vehicle-kilometer were more modest (an 8.6% decrease in energy required per vehicle-kilometer).

Trends in Transportation Emissions and Underlying Drivers



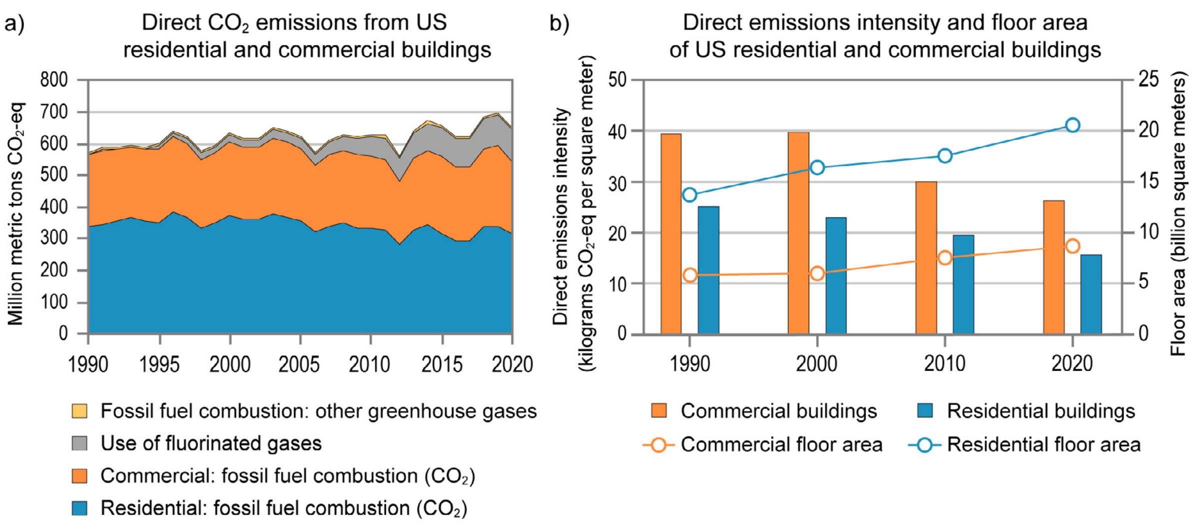
Transportations emissions fell from 2007–2012 but have climbed since then.

Figure 32.4. The figure shows US greenhouse gas emissions by transportation mode. Emissions from transportation decreased starting in 2007 (**a**), reflecting decreases in carbon dioxide (CO_2) emissions from fuel combustion (**b**), but both have increased again since 2012. The trend was consistent across different types of vehicles, driven by a drop in demand during a period of recession and high fuel prices (**c**, **d**, **e**). Passenger vehicles include cars, light trucks, and buses. LPG refers to liquified petroleum gas or propane; CO_2-eq = carbon dioxide equivalent. Figure credit: Stanford University.

Residential- and Commercial-Building Sector Emissions

Direct GHG emissions from residential and commercial buildings were 699 Mt CO_2-eq in 2019. Since 1990, direct emissions from US residential and commercial buildings (i.e., excluding electricity) have risen by roughly 14% (Figure 32.5a). The increase is primarily related to steady growth of fugitive emissions of fluorinated gases from building cooling systems.[8] Over the same period, energy efficiency improvements and increasing electrification have kept flat direct CO_2 emissions from onsite fuel combustion despite 50% increases in both residential and commercial building floor area (Figure 32.5b).[18,19]

Trends in Residential- and Commercial-Building Emissions and Intensities



Overall greenhouse gas emissions from buildings have climbed despite small declines in CO_2 emissions from onsite combustion of fossil fuels.

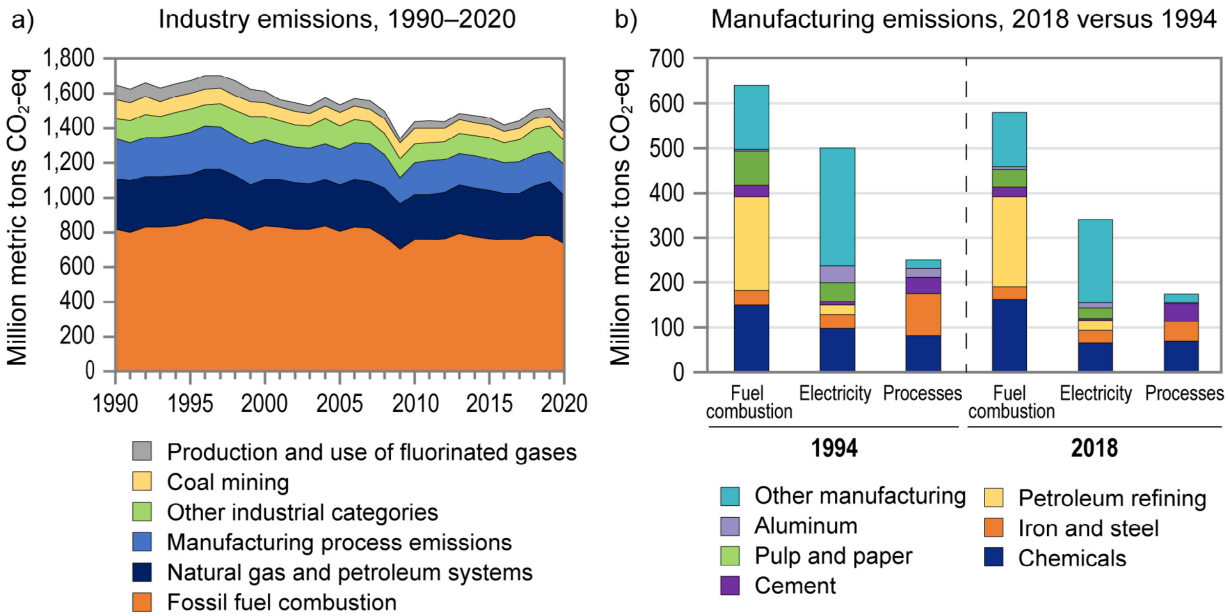
Figure 32.5. Carbon dioxide (CO_2) emissions from onsite fuel combustion in US buildings have decreased modestly since 2005 (**a**), driven by decreasing fuel-related emissions per building floor area (**b**), but overall related greenhouse gas emissions from buildings have increased over the same period due to both growth in the size of floor area (lines in panel b) and increasing levels of fluorinated gases escaping from building cooling systems (gray area in panel a). CO_2-eq = carbon dioxide equivalent. Figure credit: University of California, Santa Barbara.

Industrial Sector Emissions

GHG emissions from the industrial sector were 1,568 Mt of CO_2-eq in 2019.[8] Direct emissions from the industrial sector, including onsite fuel combustion as well as all process and fugitive GHG emissions (e.g., emissions from calcination of limestone in cement production and methane leakage from oil and gas infrastructure), decreased by 14% between 1990 and 2020, primarily due to decreases in total fossil fuel combustion, fluorinated gas production and use, and metals-related process emissions (Figure 32.6). The manufacturing sector (i.e., production of goods and materials) is the largest source of direct emissions within the overall industrial sector and accounts for substantial electricity sector emissions related to purchases of power and heat (Figure 32.6b). Six key manufacturing subsectors (petroleum refining, chemicals, cement, iron and steel, aluminum, and forest products) account for around 70% of all emissions attributable to the manufacturing sector (Figure 32.6b).

Between 1994 and 2018, electricity-related emissions from US manufacturing have decreased by about 32% due to improved process efficiencies, deployment of combined heat and power systems, and decarbonization of purchased electricity. However, direct emissions from onsite fossil fuel combustion have decreased by only 10% over the same period and now account for about three-quarters of direct manufacturing emissions (Figure 32.6b).

Trends in Industry Emissions



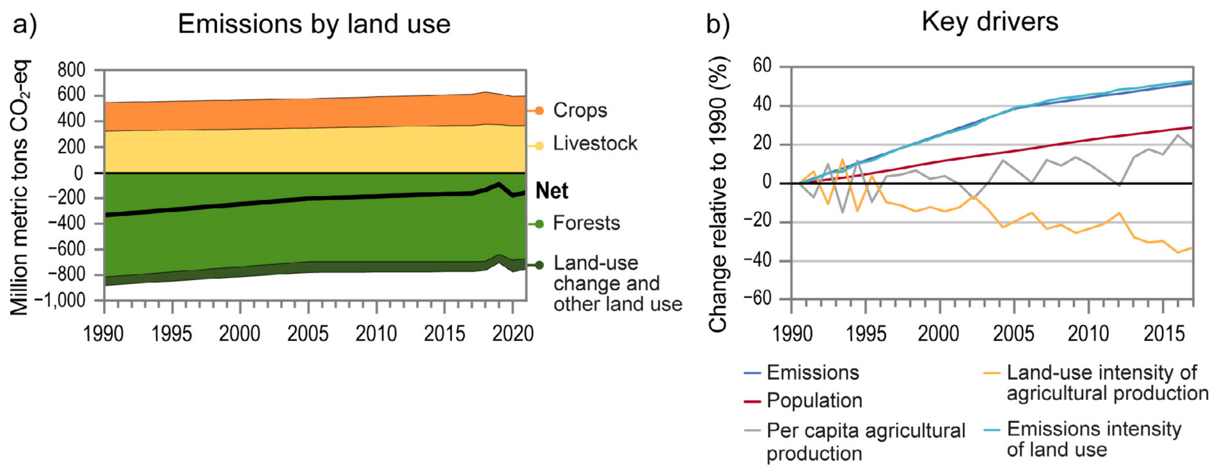
Greenhouse gas emissions from US industry, including manufacturing, have declined in recent decades.

Figure 32.6. Greenhouse gas emissions from US industry have declined modestly since 2005 across all sources (**a**). Panel **b** shows the breakdown of industry emissions in 1994 and 2018 by key manufacturing subsectors such as chemicals, iron and steel, pulp and paper, and aluminum. Data on intensity of industry emissions over time are not available. CO_2-eq = carbon dioxide equivalent. Figure credit: University of California, Santa Barbara.

Land-Related Emissions

Annual US GHG emissions related to land use in 2019 can be split into emissions of 615 Mt of CO_2-eq from agriculture and uptake of 704 Mt of CO_2-eq by other land use and land-use change (including forests; Figure 32.7). Thus in 2019, there was a net land-related uptake (i.e., negative emissions) of 90 Mt CO_2-eq. Forests take up carbon, but the amount of carbon sequestered by US forest land has decreased from 816 Mt CO_2 in 1990 to 638 Mt CO_2 in 2019[8] due to a combination of drought, wildfire, and disturbances by insects and disease (Box 7.2; KM 6.1).[20,21,22] Agricultural emissions (excluding fuel combustion) increased slightly from 548 Mt CO_2-eq in 1990 to 615 Mt CO_2-eq in 2019. The net uptake of 90 Mt CO_2-eq from US lands in 2019 represents a 73% decrease from the uptake of 333 Mt CO_2-eq in 1990.[8]

Trends in Land-Use Greenhouse Gas Emissions and Underlying Drivers



US forests sequester more carbon than is emitted by agriculture, but the forest sink has weakened in recent decades.

Figure 32.7. Net greenhouse gas emissions from US land use are negative, meaning the carbon taken up by forests is greater than agricultural emissions (**a**). However, this net sink has weakened since 2005, driven by increases in the emissions intensity of land use (light blue curve in panel **b**) and despite decreases in the land-use intensity of agricultural production (yellow curve in panel b). CO_2-eq = carbon dioxide equivalent. Figure credit: University of California, Irvine.

Key Message 32.2

We Know How to Drastically Reduce Emissions

A US energy system with net-zero emissions would rely on widespread improvements in energy efficiency, substantial electricity generation from solar and wind energy, and widespread electrification of transportation and heating (*high confidence*). Low-carbon fuels would still be needed for some transport and industry applications that are difficult to electrify (*high confidence*). Land-related emissions in the US could be reduced by increasing the efficiency of food systems and improving agricultural practices and by protecting and restoring natural lands (*high confidence*). Across all sectors, many of these options are economically feasible now (*high confidence*).

Established Opportunities to Reduce Energy-Related Emissions

In modeling studies, deeply decarbonized and net-zero-emissions energy systems share several common characteristics, but regional approaches may depend on differences in resources,[23,24] industrial bases,[25] existing infrastructure,[26,27] geography,[28] governance and politics,[29] public acceptance,[30] and broader policy priorities.[31]

Improve Energy Efficiency

Improving energy efficiency means supplying the same level of end-use services or output while using less energy. Efficiency of buildings and appliances can be improved by design or retrofits (e.g., better insulation),[32] as well as by optimizing control and management of devices (e.g., HVAC and lighting; KM 12.3;

Figure 5.5).[33] Further efficiency gains are available in the transportation sector: urban design can reduce travel demands;[34,35] public and active transportation modes can greatly reduce energy use per passenger-mile;[36,37] and advanced engines, electrification, reducing the weight of vehicles, and aerodynamic improvements can reduce energy use per passenger-mile (KM 13.3).[38,39,40] In model scenarios of energy systems that successfully reach net-zero CO_2 emissions, total US energy use often decreases relative to current levels, despite economic and population growth.[41,42]

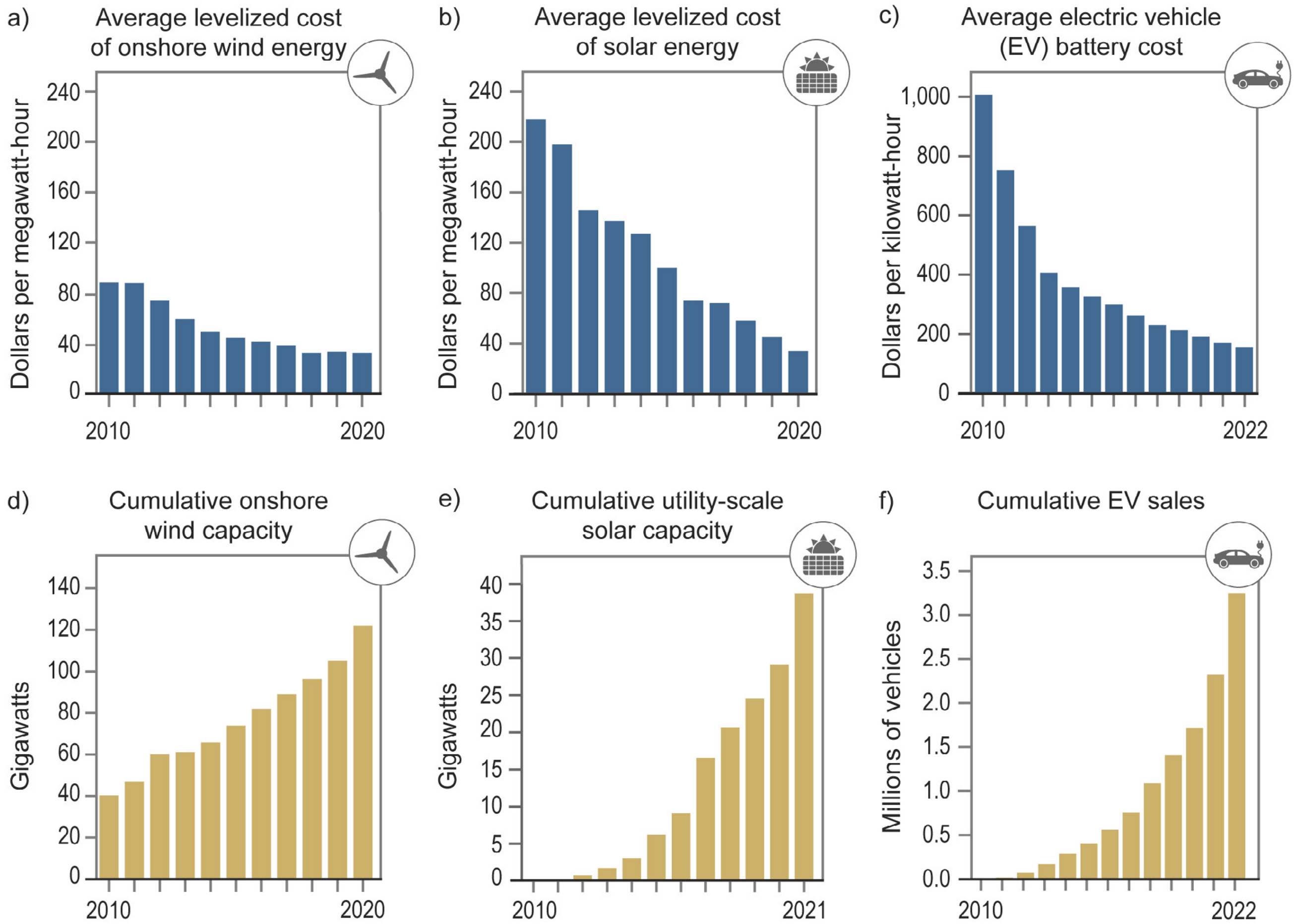
One of the concerns with energy efficiency is whether it can induce rebound effects of different types. Studies have shown that the direct rebound effect (i.e., use of more of a good or service as it becomes more affordable) is low in the context of energy goods and services, but there is more uncertainty regarding indirect rebound effects (i.e., how an increase in energy efficiency of a good or service may lead to a change in the use of other goods and services or changes in the overall economy).[43,44]

Decarbonize the Electricity Sector

Options for reducing electricity system emissions include variable renewables (e.g., solar and wind resources, which are not available on demand; KM 5.3), dispatchable or "firm" renewables (e.g., biomass, hydropower, and geothermal, which can be available on demand), and other low-emitting dispatchable resources (e.g., nuclear and carbon capture and storage [CCS]–equipped fossil-fired generators); energy storage technologies; improved transmission (both upgrading conductors and new rights-of-way); and demand management. The rate and scale at which these technologies may be deployed in the future depend on the uncertain trajectories of their costs and energy markets, as well as a host of non-economic factors (KM 32.4).[45,46,47,48,49,50,51,52,53]

However, given their plummeting costs (Figure 32.8a, b) and growing policy support (e.g., the Inflation Reduction Act of 2022[54]), variable renewable-energy resources—especially wind and photovoltaic solar generation—are expected to play central roles in decarbonizing electricity systems across the United States. Energy system models project that the capacity of wind and solar would need to increase 2 to 10 times faster each year than maximum historical rates (Figure 32.9b) to reach the 2030 target of halving economy-wide GHG emissions and midcentury net-zero targets (Figure 32.1).[41,42] In such scenarios, expansion of energy storage generally supports greater reliance on wind and solar (Figure 32.1).[41,42]

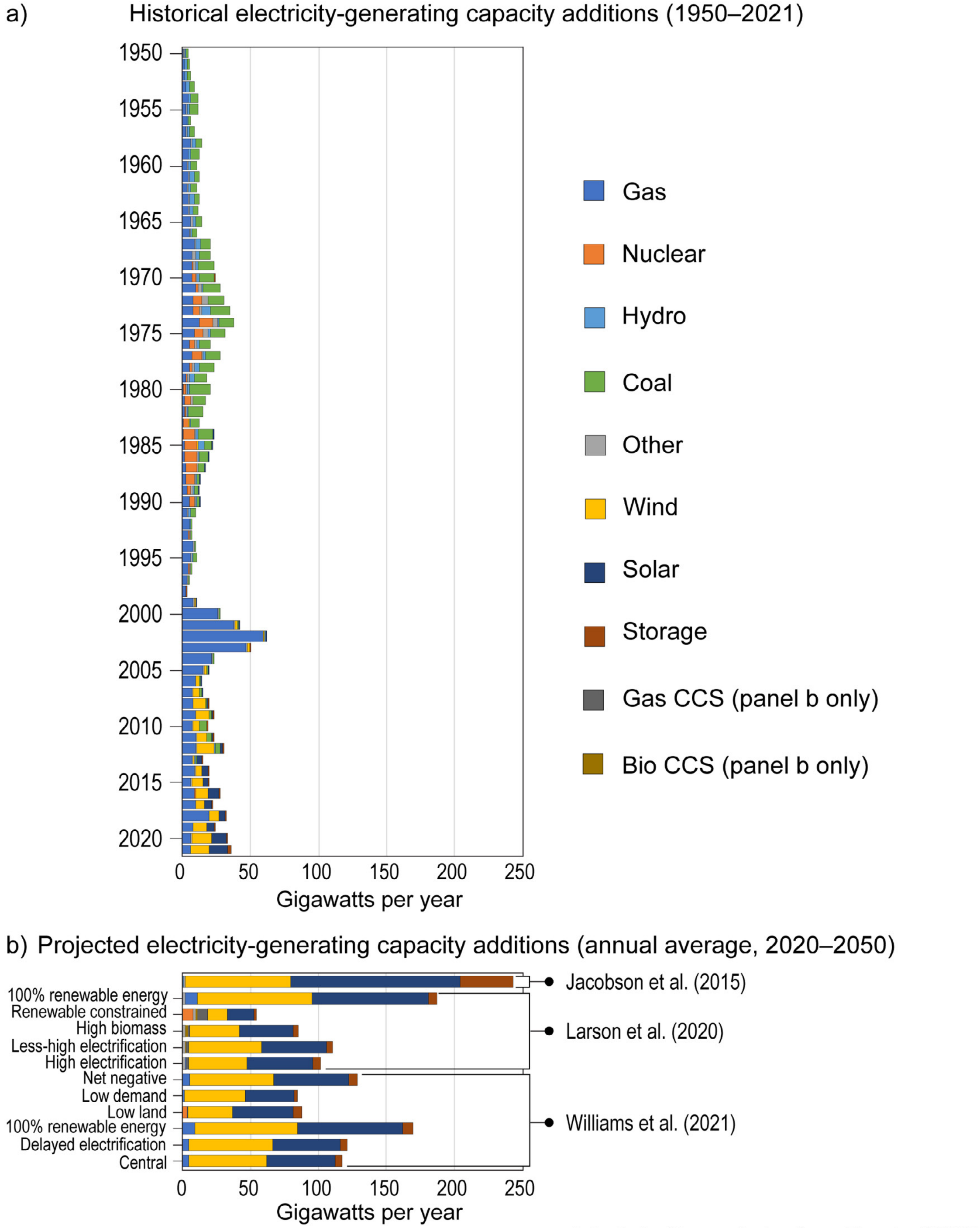
Historical Trends in Costs and Capacity of Low-Carbon Energy Technologies in the United States



Costs of renewable energy sources and electric vehicle batteries have declined as their cumulative deployment has increased.

Figure 32.8. Costs of onshore wind (**a**), solar photovoltaics (**b**), and electric vehicle (EV) batteries (**c**) have decreased sharply since 2000 (data shown here start in 2010), as the cumulative capacities of wind and solar generation (**d**, **e**) and the cumulative number of EVs sold (**f**) have increased. Figure credit: Electric Power Research Institute, National Renewable Energy Laboratory, NOAA NCEI, and CISESS NC.

Historical and Projected Net-Zero Annual Capacity Additions by Technology for the US Under Net-Zero Scenarios



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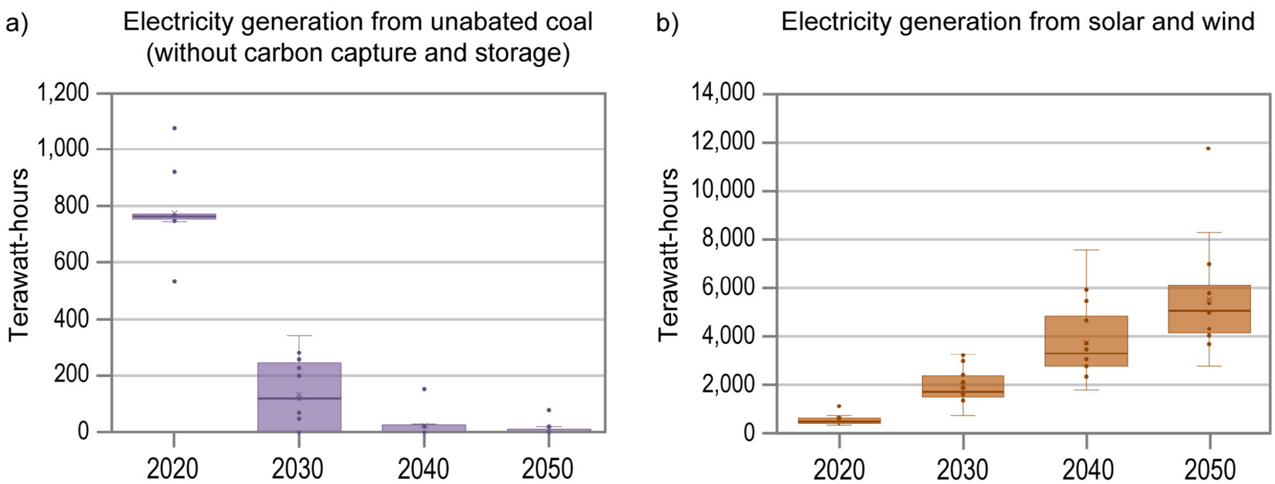
To reach net zero, the US will need to add more electricity-generating capacity in each of the next 30 years than we have added historically.

Figure 32.9. Since 1950, increases in US electricity-generating capacity have exceeded 50 gigawatts (GW) in only one year, 2002 (**a**). In comparison, scenarios of net-zero-emissions energy systems produced by models project average increases in electricity-generating capacity of more than 50 GW per year every year between 2020 and 2050 (**b**). CCS refers to carbon capture and storage. See Jacobson et al. 2015; Larson et al. 2020; and Williams et al. 2021.[49,52,59] Adapted from Bistline 2021[60] with permission from Elsevier (https://www.sciencedirect.com/journal/joule).

The same model scenarios consistently project the rapid decline of coal-fired electricity generation in decarbonized systems to near zero by 2030 (Figure 32.10).[41,42] In contrast, natural gas–fired electricity generation declines more slowly in most of these net-zero emissions scenarios, facilitating penetration of variable renewables but operating less frequently over time unless equipped with CCS.[52,55,56]

Projected Coal and Solar/Wind Electricity Generation



Models project a steep decline in coal-generated electricity and increases in renewables.

Figure 32.10. Across net-zero scenarios produced by models, median US coal electricity generation (thick horizontal lines) is expected to decrease sharply between 2020 and 2030 (**a**). Meanwhile, in the same scenarios, median solar and wind generation would increase steadily between 2020 and 2050 (**b**). Plots show individual scenarios as points, the 25th–75th percentile ranges as rectangles, and the 10th–90th percentile ranges as thin vertical lines. The mean of each set of scenarios is represented by an X. Figure credit: University of California, Irvine, and Electric Power Research Institute.

Finally, net-zero CO_2 emissions scenarios often maintain—but do not greatly expand—existing nuclear and hydropower capacity in the absence of significant cost declines (such as improved economics from small modular designs; KM 5.3) and/or constraints on the deployment of other technologies.[41,42,57] In contrast, both transmission infrastructure (i.e., power lines) and international and interregional transfers of electricity often increase in decarbonization scenarios, although the scale of such increases varies.[41,42,58]

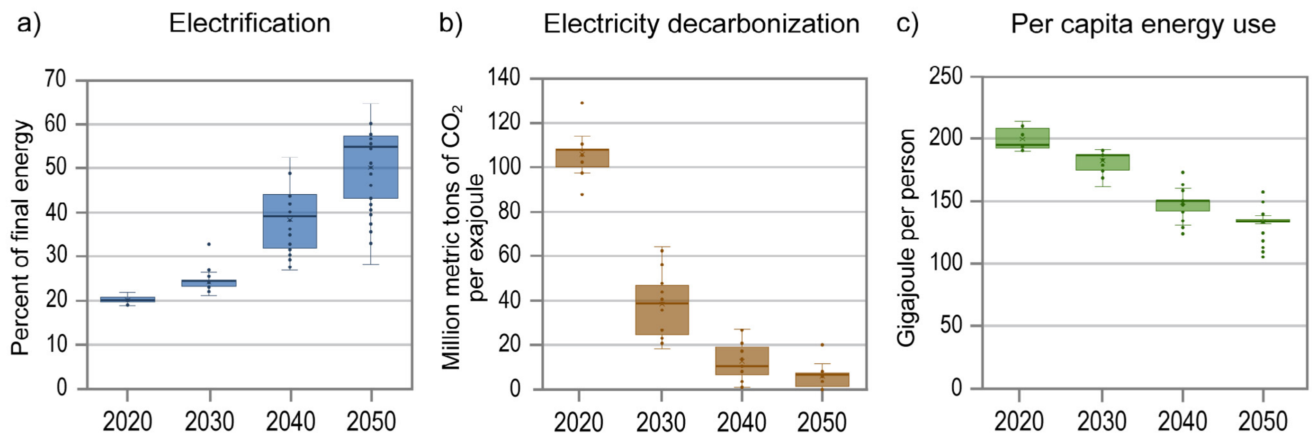
Electrify Energy End Uses

As electricity systems are decarbonized, energy model scenarios consistently project widespread electrification of energy end uses such as on-road transportation and heat for buildings and industry (KM 5.1).[41,42,49,51,52,53,61] Electricity may also be used to produce low-carbon fuels, such as hydrogen and e-fuels (liquid fuels produced by combining carbon captured from the atmosphere with hydrogen produced by electrolysis), for difficult-to-electrify applications (Box 32.1).[62] The share of US final energy demands (i.e., energy used) met by electricity in net-zero-emissions energy systems will depend on the costs of low-carbon alternatives such as biofuels and hydrogen, but estimates range from 30%–60% in 2050, up from about 20% today (Figure 32.11).[41,42]

In transportation, light-duty electric vehicles (EVs) have had policy support (e.g., tax refunds) at both the state and federal level for a long time, and new EV sales have increased in recent years (Figure 32.8).[63,64,65,66] The EV share of new light-duty vehicle sales in the US is expected to grow quickly,[66,67] which is the case in model scenarios that reach net-zero emissions by midcentury.[41,42] Many medium- and heavy-duty vehicles can also be electrified,[68] although some applications (e.g., long-distance trips) may present special challenges.[69,70,71,72,73] Decarbonization of the most difficult-to-electrify transportation sectors (e.g., aviation, international shipping) may require liquid biofuels or fuels synthesized using electrolytic hydrogen and carbon captured from the atmosphere.[74,75]

Insofar as electricity is generated from non-emitting sources, electrification of space and water heating would drastically reduce direct emissions from residential and commercial buildings in the United States (where these end uses account for the bulk of natural gas and oil consumption).[76,77,78] Similarly, most industrial energy demand could be electrified using existing technologies,[79] although achieving net-zero emissions in some industries may present special challenges[80,81,82,83]—particularly related to the costs of supplying high-temperature heat with electricity[84] and/or fundamental changes in processes such as switching to direct reduction of iron ore with electrolytic hydrogen or installing carbon capture and storage on thousands of cement kilns worldwide.[85]

Characteristics of US Energy Systems in Climate Mitigation Scenarios



Net-zero model scenarios show large increases in electrical energy, accompanied by decarbonization of electricity sources and modest decreases in overall energy use per person.

Figure 32.11. Across net-zero model scenarios, between 2020 and 2050 the median share of all energy used (thick horizontal lines) by end consumers that is electricity increases (**a**), the median carbon intensity of electricity decreases (**b**), and the median energy per capita decreases modestly (**c**). Plots show individual scenarios as points, the 25th–75th percentile ranges as rectangles, and the 10th–90th percentile ranges as thin vertical lines. The mean of each set of scenarios is represented by an X. CO_2 = carbon dioxide. Figure credit: University of California, Irvine; Electric Power Research Institute; and Evolved Energy Research.

Established Opportunities to Reduce Land-Related Emissions

Despite increasing demand for food and the headwinds of climate change impacts on agriculture, there are multiple options for decreasing land-use emissions and protecting and enhancing terrestrial carbon sinks (Ch. 11).

Use Most-Productive Land for Agriculture

Agriculture requires more land, by far, than any other human activity.[86] One way to reduce the land required to grow food is to continue farming the most productive lands (those that grow more crops per land area). Removing the most productive areas from cultivation would lead to an increase in the overall land area required for agriculture.[87] Loss of productive US farmland to sprawl or even restoration could thus lead to substantial land-use change and related GHG emissions elsewhere (e.g., if demanded agricultural goods are imported from other regions).[88,89] For these reasons, studies have suggested mitigation efforts should prioritize restoration of marginal (i.e., not the most productive) lands.[90]

Reduce Food Waste

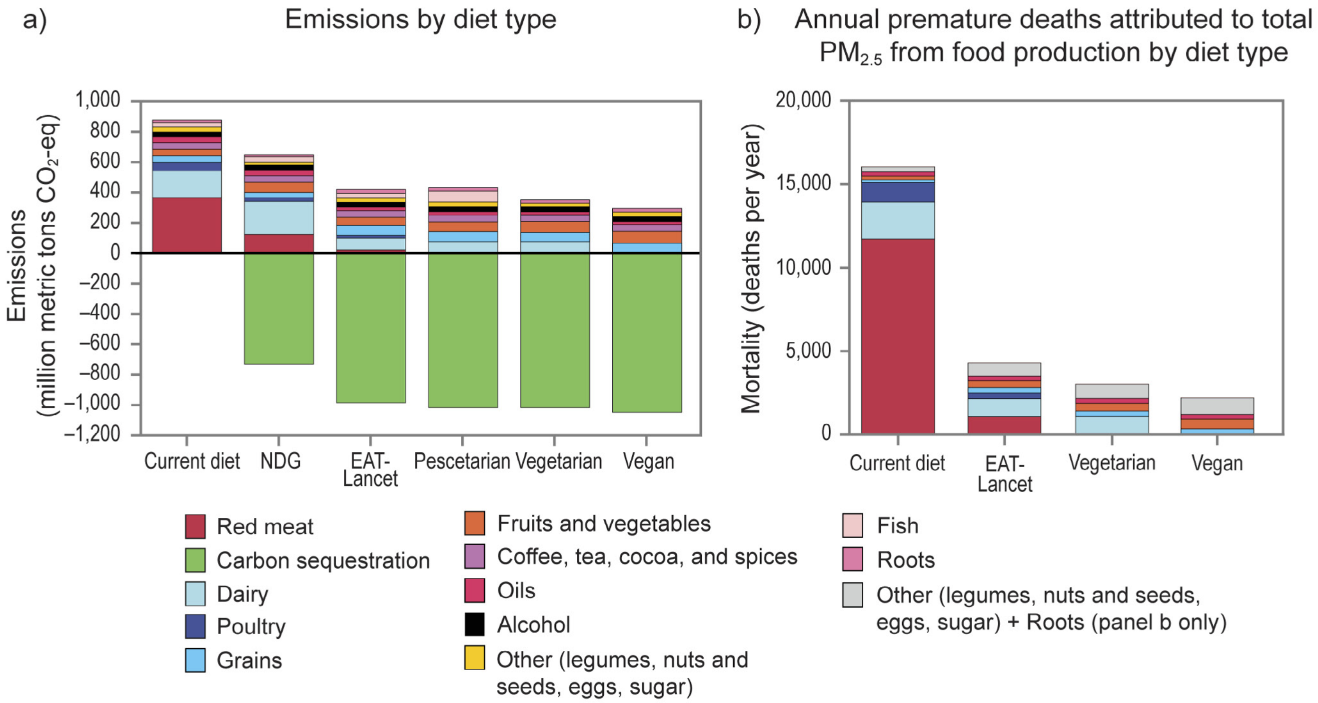
More than a third of all food in the US is currently wasted, more than 40% of which is food discarded by retailers and consumers (Box 11.2; Figure 11.12).[91,92] Multiyear campaigns (from 4 to 11 years long) in five other developed countries successfully reduced food waste per person by 8%–29% through public education and public and private initiatives.[91] Assuming similar reductions could be achieved, US agricultural land and land-related GHG emissions could be reduced by 4%–13%.

Shift Diets

GHG emissions produced during food production, distribution, transportation, and sale at retail or restaurants vary across different foods, so that different diets will entail different levels of life-cycle GHG emissions.[93,94,95,96] In particular, although meat is a good source of protein and micronutrients, it generally produces more emissions per calorie than plant-based foods because energy is lost at each trophic level.[93] Emissions related to meat production also vary: for example, ruminant animals usually produce much more GHG emissions per calorie of meat and per gram of protein than poultry (Figure 11.8).[97] By reducing demand for emissions-intensive food, shifts to pescatarian, vegetarian, vegan, Mediterranean, or “flexitarian” (less meat consumption but not strictly vegetarian) diets can reduce land-related GHG emissions while providing direct health benefits (Figure 32.12),[94,98,99,100] although analyses and models differ as to the level of future food demand related to such diets and other socioeconomic changes.[101] Shifting diets and associated changes in agricultural practices have implications for land-use change as well as supply chains, air pollution, and human health.[102] Consideration of energy and other inputs per unit of production and the resulting impacts on net GHG emissions is important for comparison of different dietary choices.

However, 10.4% of American households are food insecure (Box 11.1),[103] so any approach to reduce the consumption of higher-emissions foods that results in higher food prices could disproportionately harm these households. Instead, policies might encourage less emissions-intensive diets while also reducing food costs and increasing consumer choice by making a diversity of plant-based and other lower-emissions, nutritious, and affordable options more widely available.

Emissions Reductions and Related Health Benefits from Dietary Shifts



Changes in American diets could decrease US land-use greenhouse gas emissions, increase carbon sequestration, and reduce air pollution.

Figure 32.12. Studies have estimated potential reductions in greenhouse gas (GHG) emissions (**a**) and air pollution-related deaths (**b**) if the shares of foods in Americans' current (average) diet were to shift. Although the specific changes in diet vary across studies, all would reduce GHG and pollution emissions as well as enhance carbon sequestration relative to the current diet. EAT-Lancet refers to a "flexitarian" diet that is mostly plant-based but includes modest amounts of fish, meat, and dairy foods. NDG refers to government-endorsed national dietary guidelines. $PM_{2.5}$ refers to particulate matter 2.5 micrometers or smaller in diameter. CO_2-eq = carbon dioxide equivalent. Figure credits: (a) University of Minnesota, NOAA NCEI, and CISESS NC; (b) adapted from Domingo et al. 2021[102] [CC BY-NC-ND 4.0].

Improve Management of Croplands and Pasture

There are numerous opportunities to decrease the intensity of emissions (and/or increase sequestration; see Box 32.2) of croplands and pasture, including 1) improving soil health, 2) improving nitrogen fertilizer management, 3) increasing the number of trees and other perennials on the landscape (e.g., by agroforestry; see Ch. 11),[104,105,106] and 4) avoiding methane emissions. Soil health and carbon sequestration can also be improved by amendments (including biochar; Figure 11.5), cover crops, reduced tillage,[107] and diversification of crop rotations.[108] Careful and sustained implementation of these practices can increase not only soil carbon but also yields, resilience, and profitability.

Better aligning the timing and amount of fertilization with plants' needs can reduce fertilizer use[109,110] and thereby also reduce both nitrous oxide (N_2O) emissions from the soil and fossil fuel emissions from fertilizer production. Fertilizers with synthetic nitrification inhibitors can further reduce N_2O emissions.[111] Increased fertilizer efficiency and inhibition of nitrification processes in soil together can reduce N_2O emissions by roughly 50%.[112,113]

There are also feasible options for reducing agricultural (livestock and rice) and waste (landfill and wastewater) sources of methane emissions.[114] Methane is a relatively short-lived GHG that has contributed to at least 25% of climate warming to date.[115,116] Consequently, technically feasible near-term methane emissions reductions could slow global decadal warming by 30%, avoiding a quarter degree Celsius of warming by midcentury.[114] In addition to land-related sources of methane, there are large reductions possible from the oil and gas sector,[117] primarily by repairing leaks at little or no net cost[114] and ideally prioritizing disproportionately large sources (i.e., super-emitters).[118,119,120]

Avoid Conversion and Monitor Carbon Fluxes on Unmanaged Land

Between 50 and 150 Mt of annual CO_2 emissions could be avoided by stopping conversions of unmanaged land in the United States (i.e., natural forests, grasslands, wetlands, or other ecosystems where there has been no substantial human influence or intervention).[121] Strategies for stopping such conversions include densification of already-developed areas, zoning, and property tax incentives, as well as land protection such as conservation easements and public parks.[122,123,124,125] Related to this opportunity, the recent decrease in carbon sequestration by US forests (KM 32.1) is a concern. Further weakening of this carbon sink would make reaching net zero proportionally that much more difficult. Improved monitoring of forest carbon fluxes and their drivers is therefore important, including those on unmanaged land and in boreal Alaska (KM 7.2).[126,127,128]

Key Message 32.3

To Reach Net-Zero Emissions, Additional Mitigation Options Need to Be Explored

Although many mitigation options are currently available and cost-effective, the level and types of energy technologies and carbon management in net-zero-emissions energy systems depend on still-uncertain technological progress, public acceptance, consumer choice, and future developments in institutions, markets, and policies (*high confidence*). Attractive targets for further research, development, and demonstration include carbon capture, utilization, and storage; long-duration energy storage; low-carbon fuels and feedstocks; demand management; next-generation electricity transmission; carbon dioxide removal; modern foods; and interventions to reduce industry and agricultural emissions (*medium confidence*).

Potential Opportunities to Reduce Energy-Related Emissions

There are many uncertainties and outstanding questions related to mitigation of energy-related emissions. These uncertainties are reflected by the large differences in the scale and mix of energy sources and use as well as carbon management across modeled net-zero-emissions energy systems, which highlight potential mitigation opportunities.

The Mix of Electricity Sources in Net-Zero-Emissions Energy Systems

In recently modeled net-zero-emissions US energy systems, the share of electricity demand met by variable renewables—as opposed to firm sources—varied from 45%–89% depending on the availability of energy storage, transmission, and the mix of solar and wind.[41,42] Although grid managers are gaining experience planning and operating electricity systems with large amounts of solar and wind generation, questions persist as to the maximum share of these resources that should be included in reliable and resilient decarbonized systems[129] and the best approaches for dealing with their natural variability.[130] Large shares of variable renewables can be incorporated in electricity grids through the use of 1) batteries, hydrogen, and other types of energy storage; 2) transmission and interregional transfers of electricity; 3) firm low-carbon electricity sources; and 4) greater demand-side responses. The costs and effectiveness of these approaches for managing variability differ and are related to the spatial and temporal variability of solar and wind resources,[24,75,131,132,133,134,135,136] in addition to a host of non-cost factors (KM 32.4). Moreover, energy sources and technologies will interact in complex ways to fulfill the different functions in electricity systems (e.g., providing energy, capacity, and ancillary services over different timescales), depending on their relative costs and system benefits, policy stringency and design, geophysical resources and infrastructure, environmental co-benefits, and societal preferences.[55,56,137] Further research, development, and demonstration of technologies and approaches are needed to resolve uncertainties, identify key sensitivities, and clarify the most attractive options for providing reliable, resilient, and affordable electricity in net-zero-emissions energy systems (Figure 5.6).

Alternative Fuels for Difficult-to-Electrify Sectors

As with electricity, there is considerable uncertainty about the scale and mix of other energy carriers (e.g., hydrogen, bioenergy, e-fuels) that may be needed by difficult-to-electrify sectors such as long-distance transportation of freight, long-haul aviation, high-temperature industrial heating, and space heating in very cold climates.[75,84,138,139,140] Hydrogen, ammonia, alcohols, and carbon-based fuels (e.g., methane, petroleum, methanol) can all be produced with low and eventually net-zero CO_2 emissions (Box 32.1). However, it is not clear whether producing and burning these fuels would be lower in cost and more sustainable than continuing to use fossil fuels and managing the related emissions through CCS or carbon dioxide removal (CDR; removal of CO_2 from the atmosphere).[62] Here again, further research, development, and demonstration of technologies will help reveal critical dependencies and trade-offs and clarify the most sustainable and cost-effective pathways to net-zero-emissions fuels.

Box 32.1. Hydrogen

Hydrogen is an energy carrier that could link together multiple energy sectors (known as sector coupling) and facilitate high shares of variable wind and solar generation in electricity systems.[141,142] Multiple processes can produce hydrogen—including electrolysis, which uses electricity to split water into hydrogen gas (H_2) and oxygen gas (O_2). These processes represent potential links between the electricity sector, fuels for transportation and industry, and feedstock for chemical materials.

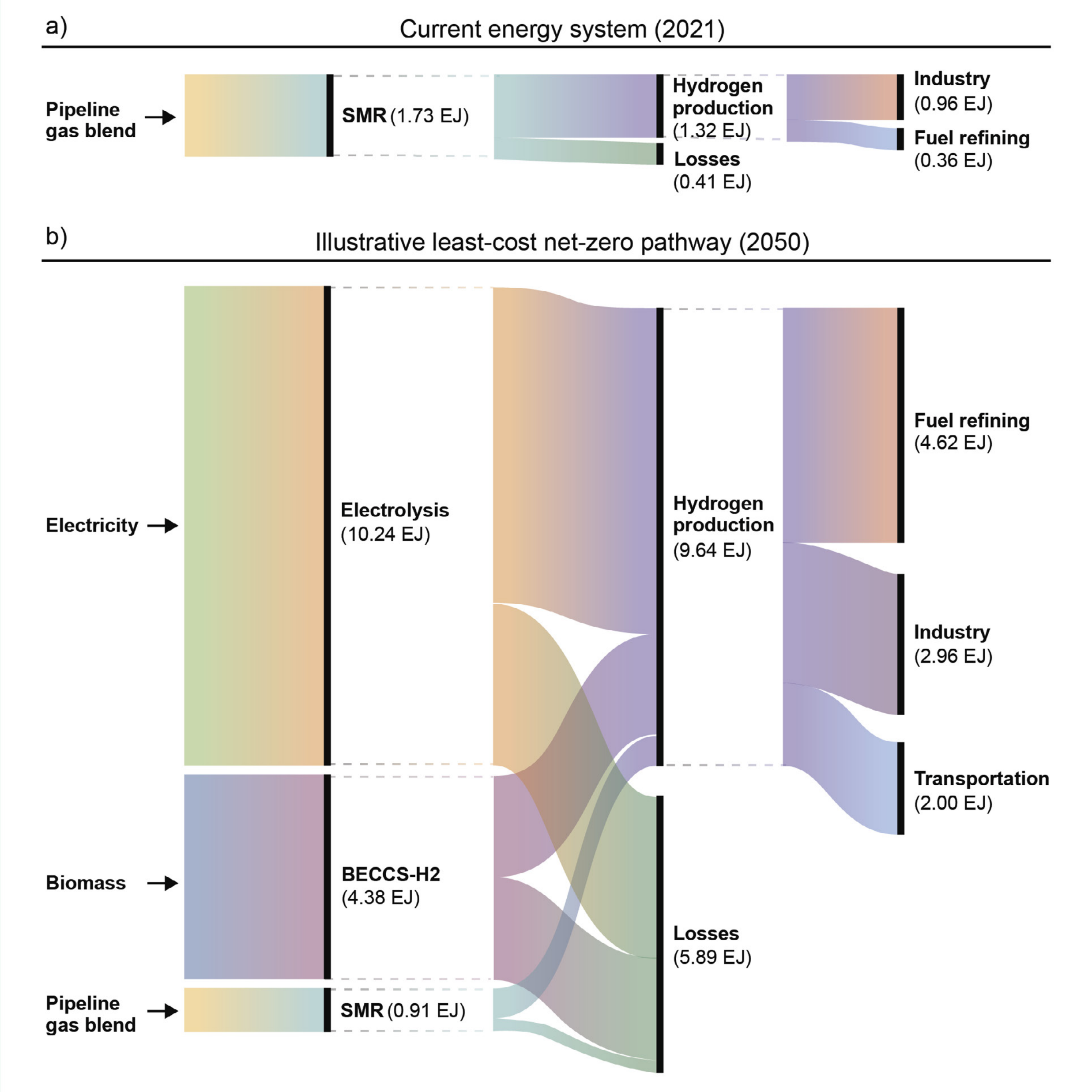
Some electrolyzers (e.g., proton exchange membrane) can also be ramped up and down in seconds[143,144] to help manage electricity demand in energy systems with variable electricity sources.[142,145] Other means of producing hydrogen with low or no CO_2 emissions, such as methane or biomass pyrolosis and steam methane reforming (SMR) with carbon capture, utilization, and storage (CCUS),[142,146,147] may also contribute to decarbonization if life-cycle GHG emissions can be kept low,[148,149] but these will not facilitate sector coupling or act as flexible electricity demand.

Global hydrogen demand was 90 Mt in 2020 and was supplied almost exclusively by fossil fuel feedstocks: 59% by natural gas without CCUS, 19% by coal, 21% from by-product processes that often contain a mixture of other gases, and less than 1% each of natural gas with CCUS, oil, and electricity (Figure 32.13).[150] Petrochemical processes were the largest sources of by-product hydrogen. Reflecting its fossil origin, hydrogen production in 2020 accounted for 900 Mt of CO_2 emissions.[150] Of all hydrogen produced in 2020, 44% was used in refineries, 37% in ammonia production, 14% in methanol production, and 6% in the direct reduction of iron, with other demands accounting for less than 1%.[150]

As noted in the discussion of alternative fuels (KM 32.3), hydrogen may help to decarbonize difficult-to-electrify end uses such as long-distance transport of freight and aviation, for which energy density is critical.[74,75] However, pressurizing or storing hydrogen in liquid phase for transport and storage adds additional costs and requires heavy storage tanks.[75,142] When used, hydrogen can either be oxidized in fuel cells or combusted in gas turbines[151,152] to produce electricity (or thrust) in a power-to-gas-to-power loop. Although substantial energy is lost in this loop, it allows shifting electricity in time from when it is readily available to when it is needed most.[131,134]

A key challenge is the current high cost of producing hydrogen from zero- or low-emitting processes. Hydrogen produced from carbon-emitting SMR can cost in the range of \$1–\$2.50/kg H_2, much lower than the more than \$4/kg H_2 achievable with current electrolysis technology and wind or solar power.[153,154] The US Department of Energy's Hydrogen Shot program has set a goal of achieving clean hydrogen production for \$1/kg H_2 within a decade by reducing both electrolyzer and wind- and solar-electricity costs (KM 5.3).[153] There are also challenges of leakage from and embrittlement of infrastructure not originally designed for hydrogen, such as natural gas pipelines, which create concerns about safety,[142,155] the potential for increases in air pollutants such as nitrogen oxides if hydrogen is combusted,[156,157] and the climate-warming influence of fugitive hydrogen.[158,159] However, at low concentrations, hydrogen can be safely injected into natural gas pipelines and used in conventional home appliances.[160,161,162,163,164]

Hydrogen Production by Source and End Uses in 2021 and 2050



Energy model scenarios show that the magnitude, sources, and uses of hydrogen will change substantially by 2050.

Figure 32.13. Curves in the figure show how hydrogen is produced (left), lost to waste (middle) and used (right) currently (**a**) and in an illustrative 2050 scenario (**b**). The thickness of the curves represents the amount of hydrogen in each category. Today, most hydrogen is produced by steam reforming of natural gas (SMR) and used by the chemical industry (especially for making fertilizer). In the depicted net-zero emissions scenario, by 2050 the largest source has become electricity, and fuel refining has become the largest use. BECCS-H2 refers to hydrogen produced from biomass feedstocks with carbon capture and storage; EJ = exajoule. Adapted with permission from Haley et al. 2022.[165]

Carbon Management

Most model scenarios that reach net-zero emissions in the United States entail substantial use of CDR technologies, not as a replacement for emissions reductions but instead to offset continuing emissions from the most difficult-to-decarbonize sectors and processes, such as aviation and cement making (sources of emissions that may be much more expensive to eliminate), to offset non-energy GHG emissions, and to reduce GHG concentrations in the atmosphere. The degree and form of CDR deployment, including the balance between industrial carbon capture and intentional enhancement of natural carbon sinks, remain highly uncertain, however, and depend on technological readiness, economics, public acceptance, and institutional and political considerations (Box 32.2).

Box 32.2. Carbon Dioxide Removal

The most recent modeling studies of net-zero emissions scenarios for the United States consistently project that some quantity of carbon dioxide removal (CDR) from the atmosphere will be needed to offset any residual greenhouse gas (GHG) emissions.[41,42] The scale of CDR called for in these scenarios ranges from 0.8–2.9 gigatons (Gt) of carbon dioxide (CO_2; median is 1.6 Gt) in scenarios that reach net-zero CO_2 emissions by 2050 (Figure 32.14).

CDR options fall into two categories according to whether they enhance uptake of atmospheric CO_2 by biological processes or by chemical processes, each of which can be further disaggregated depending on where the processes occur (e.g., on land, in the ocean, or in industrial facilities).[166,167] Different approaches have different biophysical and economic limits to scale,[168] as well as different concerns related to equity and environmental justice,[169,170] environmental impacts,[171] permanence or durability of removal (i.e., the timescale of sequestration and its reversibility),[172,173,174] and additionality (i.e., the removal would not have occurred without human intervention).[166,175]

Current energy models are relatively simplistic in their representation of CDR, typically including only 1) bioenergy with carbon capture and storage (BECCS), 2) afforestation/reforestation, and 3) industrial direct air capture (DAC). Among these methods, the on-land biological options (BECCS and afforestation/reforestation) are the most prevalent in net-zero emissions scenarios; BECCS dominates if underground carbon sequestration is allowed (Figure 32.14).

Most scenarios use DAC sparingly, owing to its cost and energy requirements (Figure 32.14), but recent studies have highlighted potential cost reductions.[176] Evaluations of natural climate solutions meanwhile suggest that reforestation represents the largest opportunity for land-based mitigation.[177] Up to 128 million acres of land in the US are reforestable and could sequester 200–500 million metric tons (Mt) of CO_2 per year[178,179] given substantial investments in the reforestation supply chain.[180]

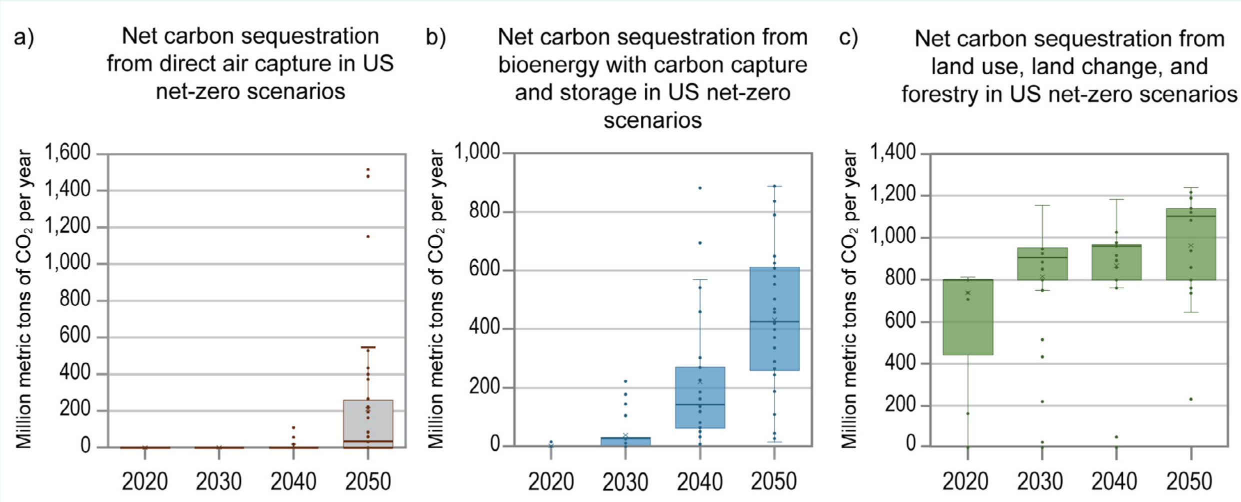
However, a variety of other biological CDR options are being explored and could be cost-effective at carbon prices of \$50–\$100/Mt CO_2: improved management of rangeland and pasture might sequester 0.05–0.74 Mt of CO_2 per acre per year, or a total of 49–490 Mt of CO_2 per year, given the roughly 655 million acres of US grazing land.[121,181,182,183,184] Improved management of cropland soil (e.g., applying biochar, cover crops, or no-till) might sequester 150–250 Mt of CO_2 in the United States each year.[121,185,186,187,188] In forests, extending timber rotations, removing competing vegetation, and selective harvesting could remove 160–315 Mt CO_2 per year.[179,189,190,191,192,193,194,195,196] Finally, rewetting drained US wetlands[197,198] and reconnecting salt marshes to the ocean (which reduces methane emissions)[199] could remove 9 Mt of CO_2 per year.[121] These options are discussed further in other chapters (KMs 6.3, 9.2, 11.1; Boxes 7.2, 30.5; Focus on Blue Carbon).

Although less mature, a growing body of research is also focusing on ocean-based CDR,[200] including ocean fertilization,[201] artificial upwelling and downwelling, seaweed farming,[202] marine restoration, ocean alkalinity enhancement,[203] and electrochemical engineering approaches (see, e.g., KM 10.3).

Additional research could reduce the uncertainty related to these estimates; establish robust monitoring, reporting, and verification protocols; and help to prioritize types and locations for CDR based on co-benefits and trade-offs. A related area of research is the Earth system response to large-scale CDR (i.e., negative emissions); a growing body of literature has shown that emitting GHGs and then removing them from the atmosphere is not the same as not emitting the GHGs at all.[204,205,206]

Reducing sunlight reaching the Earth's surface, or solar radiation modification (SRM), is sometimes discussed alongside CDR because both are intentional interventions in the climate system.[166,207] SRM is not mitigation as defined in this chapter; the effectiveness, costs, environmental trade-offs, and geopolitical implications of SRM are uncertain, and further research on these topics is either underway or may be merited (KM 17.2). Moreover, some scientists and policymakers emphasize that the risks of SRM should be considered in the context of the many risks of continued climate change.[208]

Scale and Type of Carbon Dioxide Removal in US Net-Zero Emissions Scenarios



Net-zero emissions scenarios project substantial carbon dioxide removal by 2050, although the type and quantities used in the scenarios vary considerably.

Figure 32.14. Annual carbon dioxide (CO_2) removals increase between 2020 and 2050 in scenarios that reach net zero by 2050, including nature-based sequestration on land (**c**), bioenergy with carbon capture and storage (**b**), and—after 2040—direct air capture (**a**). Median sequestration (thick horizontal lines) by land use, land-use change, and forestry increases less dramatically in scenarios. Plots show individual scenarios as points, the 25th–75th percentile ranges as rectangles, and the 10th–90th percentile ranges as thin vertical lines. The mean of each set of scenarios is represented by an X. Figure credit: University of California, Irvine.

Changes in Transportation Modes and Behavior

Uncertain changes in mobility and travel behavior could facilitate or hinder mitigation. For example, autonomous vehicles are rapidly evolving but still need to overcome challenges of consistent safety measures, standardization of technology liability, and security and privacy concerns.[209,210] Studies have shown that autonomous vehicles could increase or decrease energy use and GHG emissions depending on the conditions of adoption and use.[211,212,213] New mobility services (e.g., ride-hailing or transit services with a monthly subscription) are becoming widespread and have the potential to transform current patterns of travel behavior, but they still face challenges of cost-competitiveness and consumer acceptance.[214,215,216] And as with automation, these mobility services may reduce emissions under a limited set of conditions (e.g., electrification and shared use cases).[213,217,218,219]

Sector Coupling

The integration of different parts of energy systems, sometimes referred to as sector coupling, involves coordinated planning, operations, and markets for electricity, fuels, and thermal resources to meet end-use service demands. Linking energy industries, processes, and geographies could lower costs, reduce environmental impacts, and increase the reliability of low-carbon energy systems.[75,220,221]

Potential Opportunities to Reduce Land-Related Emissions

Modern Foods

Recent innovations aim to increase food choices with plant-based and cultured meat[222,223,224] and foods synthesized chemically without photosynthetic inputs[225,226] that may be able to displace demand for foods with substantially higher emissions per calorie. However, the potential benefits will depend on the scalability and public demand for such products.

Interventions to Reduce Methane and Nitrous Oxide Emissions

There are a number of options for reducing non-CO_2 GHG emissions from agriculture whose potential remains uncertain. Ruminant feed supplements may suppress methane emissions (although some such supplements have not yet been approved for use in the United States).[227,228] Methane from manure lagoons can be captured and used for bioenergy or reduced through flaring.[229] Seasonally flooded rice paddies can undergo temporary drainage to reduce emissions by about 40%.[230] And crops may be bred to produce root exudates that inhibit nitrification and thereby reduce N_2O emissions from croplands.[231]

Key Message 32.4

Mitigation Can Be Sustainable, Healthy, and Fair

Large reductions in US greenhouse gas emissions could have substantial benefits for human health and well-being (*high confidence*). Mitigation is expected to affect pollution, the use of land and water resources, the labor force, and the affordability, reliability, and security of energy and food (*high confidence*). An equitable and sustainable transition to net-zero-emissions energy and food systems in the United States could help redress legacies of inequity, racism, and injustice while maximizing overall benefits to our economy and environment (*high confidence*).

A number of important dimensions rarely represented in mitigation scenarios may nonetheless determine the pace, feasibility, likelihood, efficacy, and cost-effectiveness of mitigation opportunities.

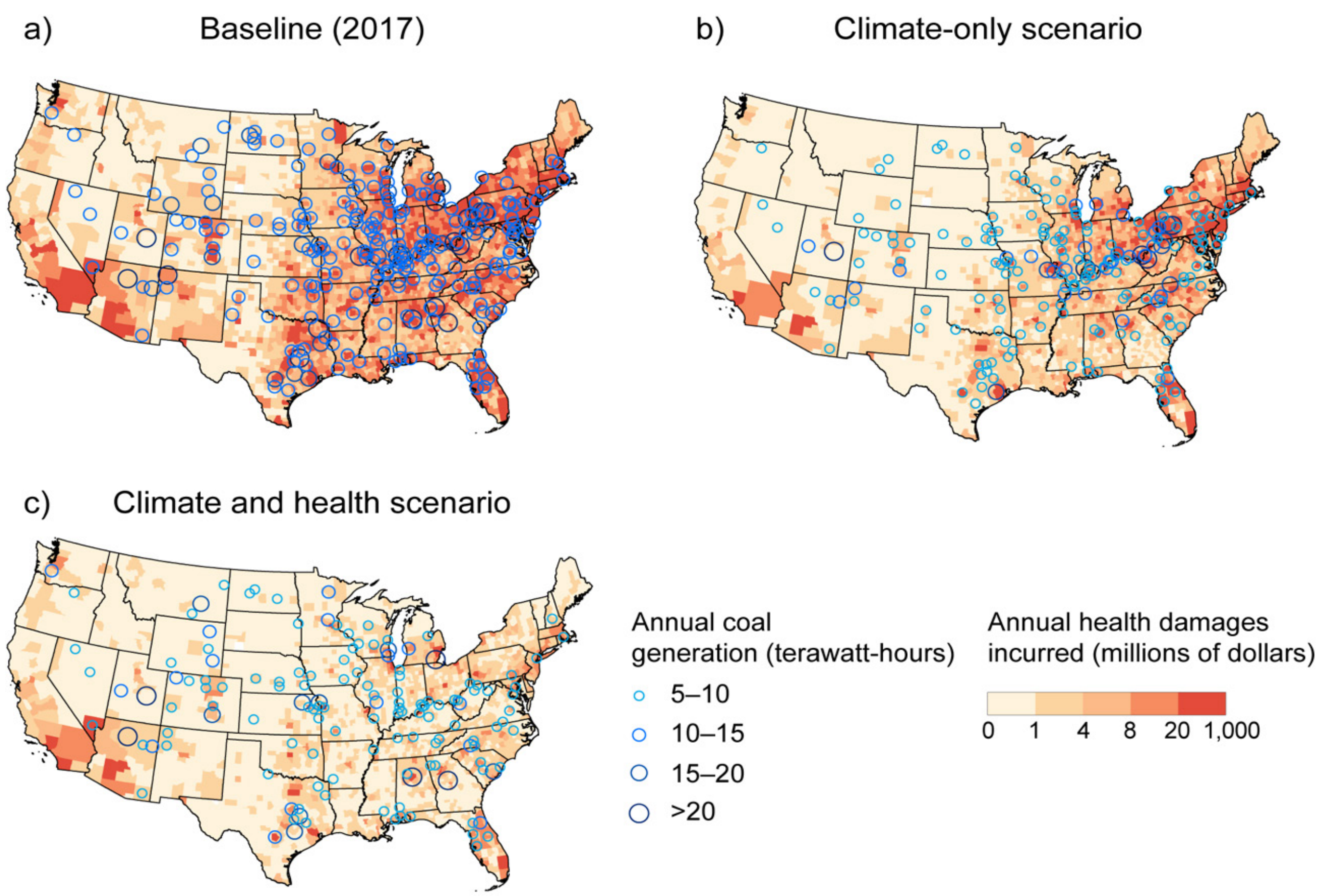
Air Pollution

Air pollutants that impact human health are often co-emitted with greenhouse gases. Exposure to ambient fine particulate matter ($PM_{2.5}$) and ozone, which are among the largest risk factors for disease, causes 60,000–300,000 excess deaths per year in the United States (KM 14.5),[232,233,234,235,236,237,238] with health effects observed at concentrations below the current national standard.[239,240,241] Racial, ethnic, and socioeconomic disparities in air-pollution exposure are well documented[234,242,243,244,245,246,247] and have persisted despite overall decreases in air pollution.[234,240]

Transitioning to a net-zero-emissions energy system has the potential to generate substantial air pollution benefits. Estimates of cumulative net benefits by 2050 range from roughly 200,000 to 2,000,000 avoided deaths,[233,248,249,250] the monetized value (i.e., statistical value) of which could exceed the total expected costs of the transition to net zero.[49,251] However, the distribution and magnitude of air pollution benefits over the transition period depend on the pace of electrification, technology selection, and siting decisions,[49,252,253,254] especially regarding retirement of fossil fuel power plants (Figure 32.15)[254,255,256,257,258,259,260] and vehicle electrification.[261,262] Electrification of heating,[256,263] reduction in fossil fuel production, electrification of the industrial sector, and shifting diets[102] can also all generate meaningful air pollution benefits. Carbon capture and hydrogen technologies may also reduce air pollutant emissions, although it is not yet clear by how much.

It is also possible that mitigation efforts could increase air pollution at local and regional scales, for example, due to increases in bioenergy, residential wood heating, and domestic manufacturing to meet demands for materials and products (e.g., Gallagher and Holloway 2020;[252] Commane and Schiferl 2022[264]).

Health Co-benefits of Strategic Power Plant Retirements



Shutting down coal-fired power plants would produce both health and climate benefits.

Figure 32.15. Blue circles show the location and size of US coal-fired power plants in 2017 (**a**) and in two scenarios: one in which the fewest plants are retired to reduce CO_2 emissions by a fixed amount (**b**) and one in which plants are retired not only to achieve the same CO_2 reduction but also to avoid health damages as much as possible (**c**). Not surprisingly, estimated health damages (red shading) are greatly reduced in the future scenario that prioritizes health. Annual generation from coal power plants (in terawatt-hours) and corresponding annualized health damages (in millions of dollars) from each scenario are both summarized by county. Baseline shows results based on 2017 continuous emissions monitoring systems data, while optimization results shown represent the climate-only and climate-plus-health scenarios. Health damages are shown by the county in which those damages occur; legend breaks are based on quintiles of the data. Although this analysis included only the continental US, its conclusions are consistent with similar analyses in other regions: substantial health benefits would be expected from retiring coal electricity anywhere. Adapted with permission from Sergi et al. 2020.[254]

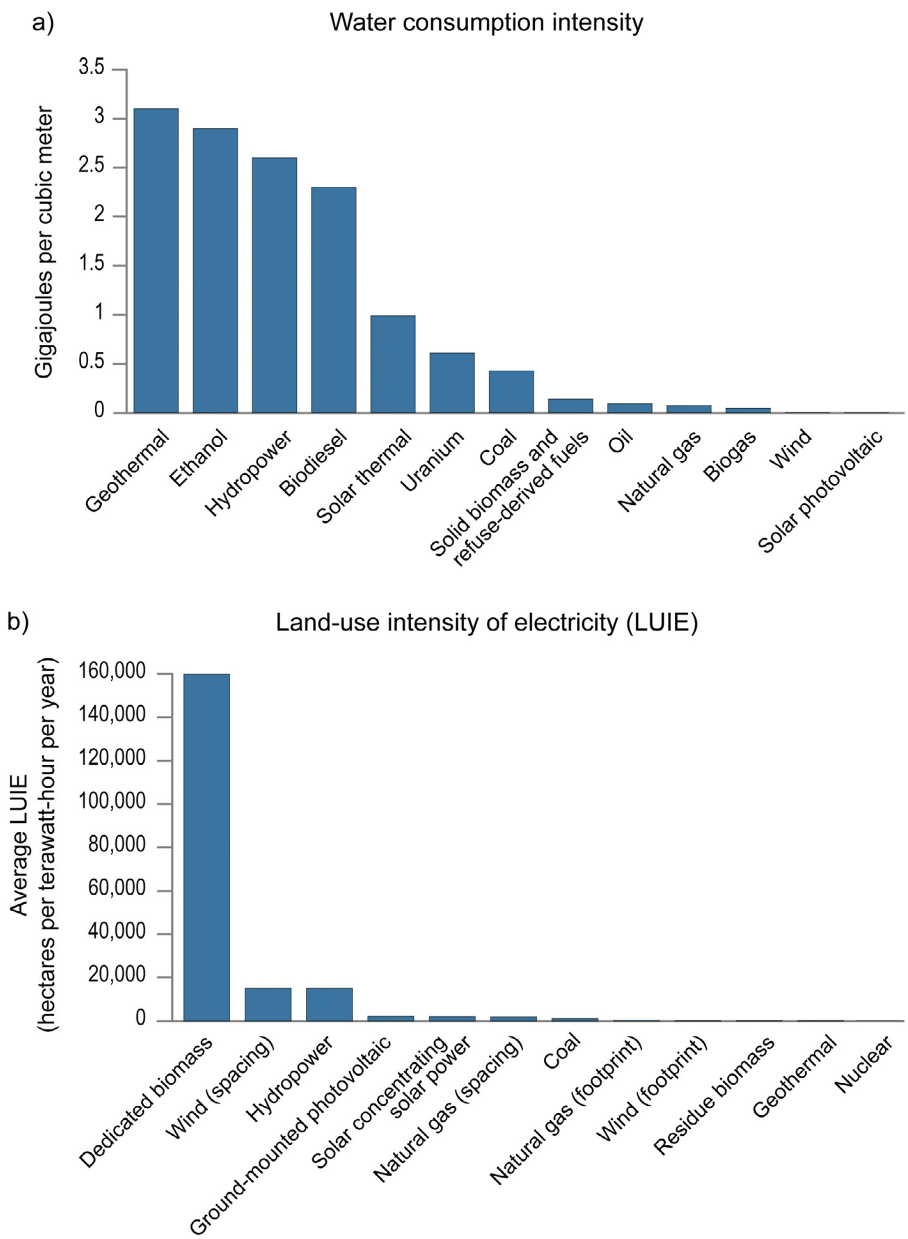
Siting and Land Use

Net-zero-emissions energy systems may require large land areas, with land requirements in rough proportion to the share of wind and solar energy. Cumulative US land use for solar and wind energy in recent net-zero scenarios ranges from about 250,000 to more than 1 million square kilometers (including the entire area of solar and wind farms),[41,42,52] with solar concentrated in the Northeast and Southeast and wind in the Midwest, Great Plains, and Texas (KM 6.3).[49] Even at the low end of this range, the projected scale of land use is massive, and may face public opposition. For example, the visual impact and competition for land of such extensive systems would need to gain and maintain the support of many communities; this recently has been a challenge in the siting of solar and wind projects.[265,266] Similar challenges may apply to siting and demonstration of other infrastructure regardless of its land footprint, such as new electricity transmission,[265] CCS,[267] and CDR.[268] Others express concern over the potential environmental impacts of solar and wind farms, including land-cover change, loss of plant and animal habitats, barriers to migration and collision deaths of birds and bats,[269,270,271] and competition for land between agriculture and renewables.[272] Notably, competition with agriculture has also long been a concern about bioenergy, which may be alleviated if demand for corn ethanol decreases due to electrification of transport.[273,274] Researchers have thus begun developing pathways that take some of these concerns and constraints into account,[49,275] as well as identifying changes in governance and administrative law that may help streamline siting processes;[276] however, siting may prove a key obstacle for renewables-based net-zero-emissions systems.[277] Engagement with community groups and stakeholders early in the planning process has the potential to reduce project delays and cancellations.[278]

Water Use

The water requirements of net-zero-emissions energy systems could be lower than current consumption,[279] largely because wind and solar require little water (Figure 32.16; KM 5.1).[280,281,282,283] However, some processes for energy conversion and carbon management, such as electrolysis for hydrogen production, chemical synthesis of hydrocarbons (e.g., by the Fischer-Tropsch process), and CCS, are water intensive and could offset water savings from fuel switching. Ultimately, water use (and related quality), temporal, and locational needs, depend heavily on the mix of resources and processes used to achieve net-zero emissions.[284,285,286]

Land and Water Requirements of Energy Sources



Different sources of energy entail more or less water and land use.

Figure 32.16. Bars depict water-consumption intensity (**a**) and land-use intensity of electricity (LUIE) for the US in 2014 (**b**) related to different electricity sources. Wind and solar use less water than any of the other energy sources but more land area than nuclear, geothermal, or fossil sources. (a) Adapted with permission from Grubert and Sanders 2018;[280] (b) adapted from Lovering et al. 2022[287] [CC BY 4.0].

Labor

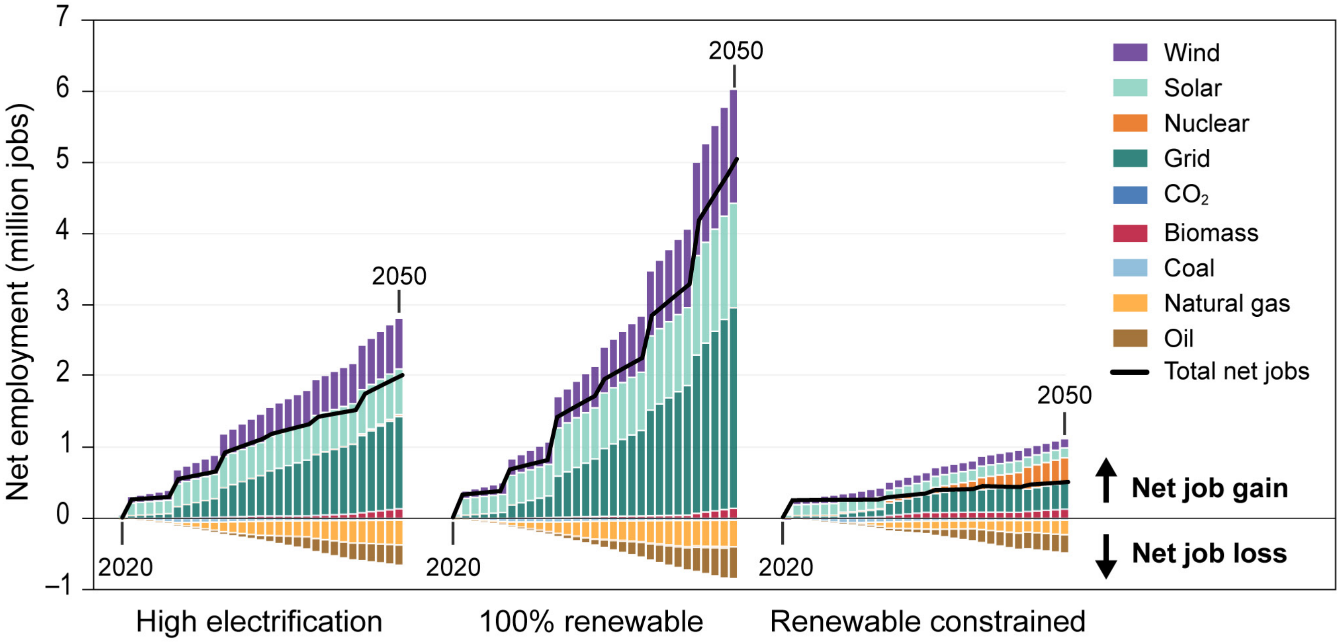
The productivity, supply, and disposition of labor, in addition to national discourse and community-level support and concern regarding labor, has the potential to accelerate or constrain mitigation efforts. Nearly 8 million Americans were directly employed in energy-related jobs in 2021, comprising roughly 5% of the total labor force.[288,289] Of those 8 million energy-related jobs, approximately 41% were in net-zero-emissions-aligned areas in 2022.[290] Energy-related jobs tend to be geographically concentrated in certain states and communities (Figure 32.17). More than 10% of the labor force in 150 counties (of 3,142) is directly employed in energy-related jobs[288,291,292]—often the production of coal, oil, and gas—but employment in mitigation-related activities is growing and is already high in many counties (e.g., energy efficiency in Vermont, wind installations in the Southern Great Plains; KM 26.2).

Reaching net-zero emissions in the United States by 2050 would generate jobs related to manufacturing and deployment of new infrastructure but reduce fossil fuel–related jobs.[293] Many analyses find that employment and wage losses in fossil fuel sectors would be entirely offset (in aggregate) by increases in low-carbon resource industries.[293,294,295,296,297] The number and local distribution of mitigation-related jobs will depend on the ultimate mix of energy sources, siting and investment decisions, labor supply constraints, the extent of domestic manufacturing, and political bargaining; however, decarbonization could lead to long-term expansion in the energy workforce in most states, even when accounting for increased worker productivity (which is often an underlying assumption in technology cost projections). Large-scale and sustained workforce development programs, high-road labor practices and policies, and corresponding federal support could accelerate a transition to net-zero emissions.[293,298]

However, there is already evidence of hiring difficulties in energy labor markets,[291] portending labor supply bottlenecks in the absence of counteracting policies. Although there is public support for employment benefits related to climate mitigation,[294] there is also evidence of mistrust associated with historical energy-related job creation narratives.[299] Moreover, there are existing racial and gender disparities in the energy workforces.[291]

Meanwhile, despite policy and political discourse regarding just transitions for fossil fuel workers,[294,300,301] many fossil fuel–dependent communities have experienced large declines in employment.[26,302,303] Moreover, former fossil fuel workers often relocate because their skills are not always transferable to other local industries, and nearby communities lose tax revenues that support public infrastructure and social services (KM 26.2).[304,305] Going forward, domestic policies that consider when and where workforces in declining energy industries could fill new jobs in emerging energy sectors (e.g., natural gas and carbon capture supply chains; coal mining; and solar manufacturing) have the potential to moderate labor supply bottlenecks, concentrated unemployment, and low-carbon boom-and-bust cycles. Where there is flexibility in siting of infrastructure and allocation of funding, such funds might also be leveraged to build political support and more equitably distribute costs and benefits. For example, provisions in the Inflation Reduction Act of 2022 offer enhanced tax credits to clean energy projects that pay prevailing wages to workers and use registered apprentices,[290] that manufacture and source materials domestically,[306] and/or that are located in "energy communities" defined by thresholds in the share of fossil fuel–related jobs.[307]

Energy Employment from 2020 to 2050 for Alternative Net-Zero Pathways



A shift toward renewables is projected to increase the total number of jobs in the energy sector.

Figure 32.17. Despite decreases in the number of fossil fuel–related jobs, the overall number of energy jobs (specifically those involved in the supply of energy) is generally projected to increase in net-zero-emissions energy scenarios between 2020 and 2050, although by much more in some scenarios than in others. These particular scenarios are from Larson et al. 2021[49] and span a range of energy futures in which nearly all buildings and transport are electrified but there are no constraints (**a**), renewables produce 100% of energy (**b**), or renewables produce much less energy and nuclear and fossil energy with carbon capture and storage are prevalent (**c**). CO_2 = carbon dioxide. Adapted with permission from Jenkins et al. 2021.[308]

Energy Equity and Environmental Justice

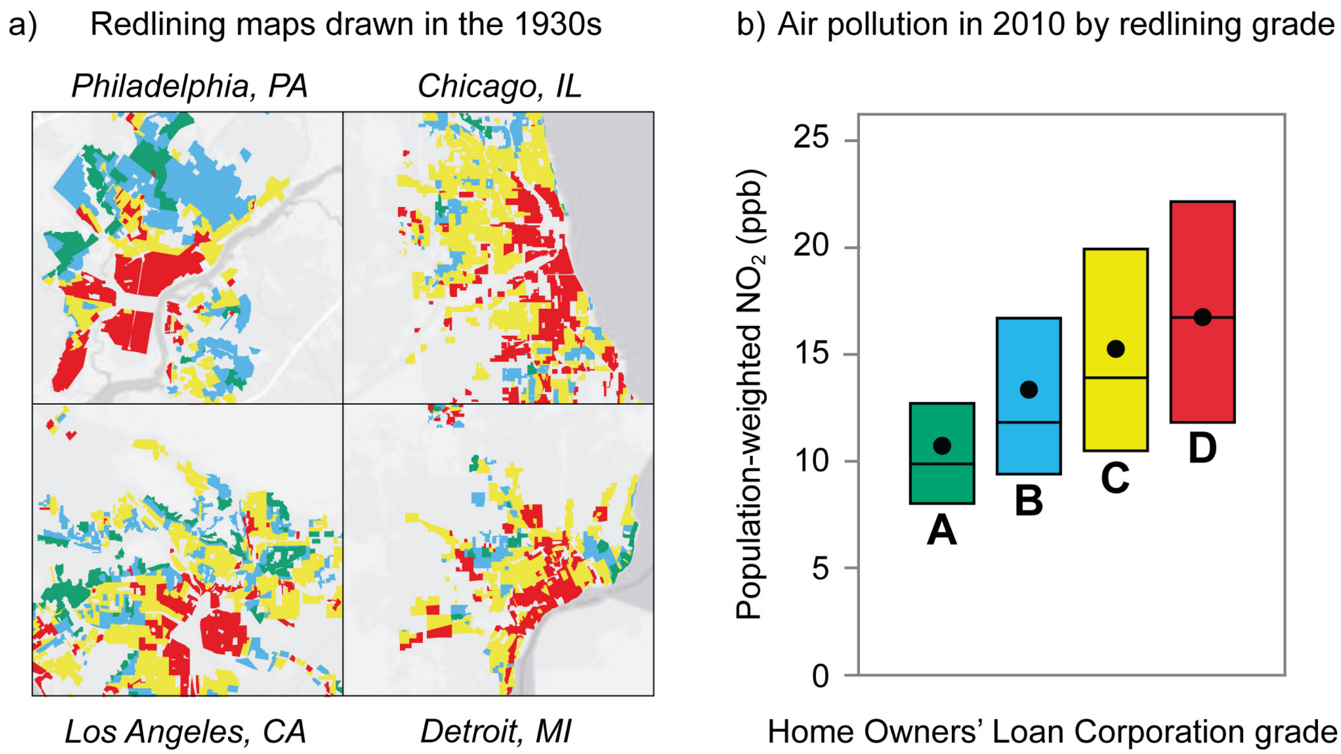
Social inequities in the United States are rooted in systemic discriminatory practices, such as redlining, that marginalize communities based on race or socioeconomics. Social equity involves several energy- and climate-related aspects of recognition, procedural, and distributional justice (KMs 23.4, 27.3).[309,310] In the context of energy and climate decision-making, recognition justice refers to an understanding that certain individuals and groups are presently bearing, and have historically borne, disparate burdens related to our collective energy systems and may therefore require extra resources or mitigation efforts. Procedural justice considers who is involved and has influence in energy and climate decision-making processes, with the goal of ensuring that those who want to be included in decision-making processes—and especially those who will be affected by the outcomes—are meaningfully engaged through fair and inclusive procedures (see, e.g., KM 30.3 regarding mitigation informed by Indigenous Knowledge). Distributional justice refers to the allocation of benefits and burdens based on geography and sociodemographics, with the objective that no single population receives a disproportionate share of energy or climate harms (e.g., energy-related air pollution; KM 14.3) or benefits (e.g., access to low-carbon and efficient energy technologies or clean-tech jobs).

The disproportionate public health burdens of energy systems on communities of color and/or low-income communities, such as from vehicle emissions and power plants, have been extensively documented (Figure 32.18).[311,312,313,314] Energy insecurity (e.g., regularly struggling to pay energy bills) also disproportionately affects low-income households, communities of color, rural and Indigenous communities, families with children, and older adults (Ch. 16).[313,315,316,317,318,319,320] This disproportionate burden of energy insecurity reflects that Black Americans, for example, are more likely to live in older homes that are less energy-efficient.[317,318,321] Moreover, redlined areas often lack trees and green spaces to mitigate the urban heat island effect and thus experience higher summer temperatures than surrounding urban areas,[322,323,324] which in turn increases energy demands and burdens[325] and makes residents more susceptible to the adverse health effects of extreme heat (KM 15.3).[325,326]

Although environmental impacts and energy insecurity are not borne proportionately across social groups, it is possible to pursue mitigation options that also redress current and historical injustices. For example, low-income communities and communities of color could experience disproportionate improvements in air pollution.[251,259] Energy equity considerations also include access to sufficient energy services,[327,328] as well as reductions in energy burden or energy poverty,[321,329,330] and the upfront costs of energy efficiency and low-carbon technologies.[331] Mitigation efforts that increase the availability and affordability of energy services (including safe and comfortable temperatures) could improve energy equity outcomes. For example, improving thermal efficiency of buildings would both reduce energy costs and help to maintain safe indoor thermal temperatures in the absence of functional air-conditioning.[332]

Studies have found that low-carbon and efficient technologies (e.g., electric vehicles, solar panels, battery storage, and LED lightbulbs) tend to be disproportionately owned by—and the financial incentives for such are received by—higher-income, more educated, and White households.[311,312,313,333] Job opportunities in clean energy have also tended to exclude women and people of color.[334] Moreover, insofar as mitigation increases energy costs, more households will experience energy poverty, and energy inequities may get worse.[335,336] In addition, changes in the type, timing, and cost of energy needed to provide safe and comfortable temperatures under climate change and anticipated electrification patterns may exacerbate health risks, financial energy burdens, and other measures of energy equity.[327,335]

Inequitable Air Quality Within Historically Redlined Neighborhoods



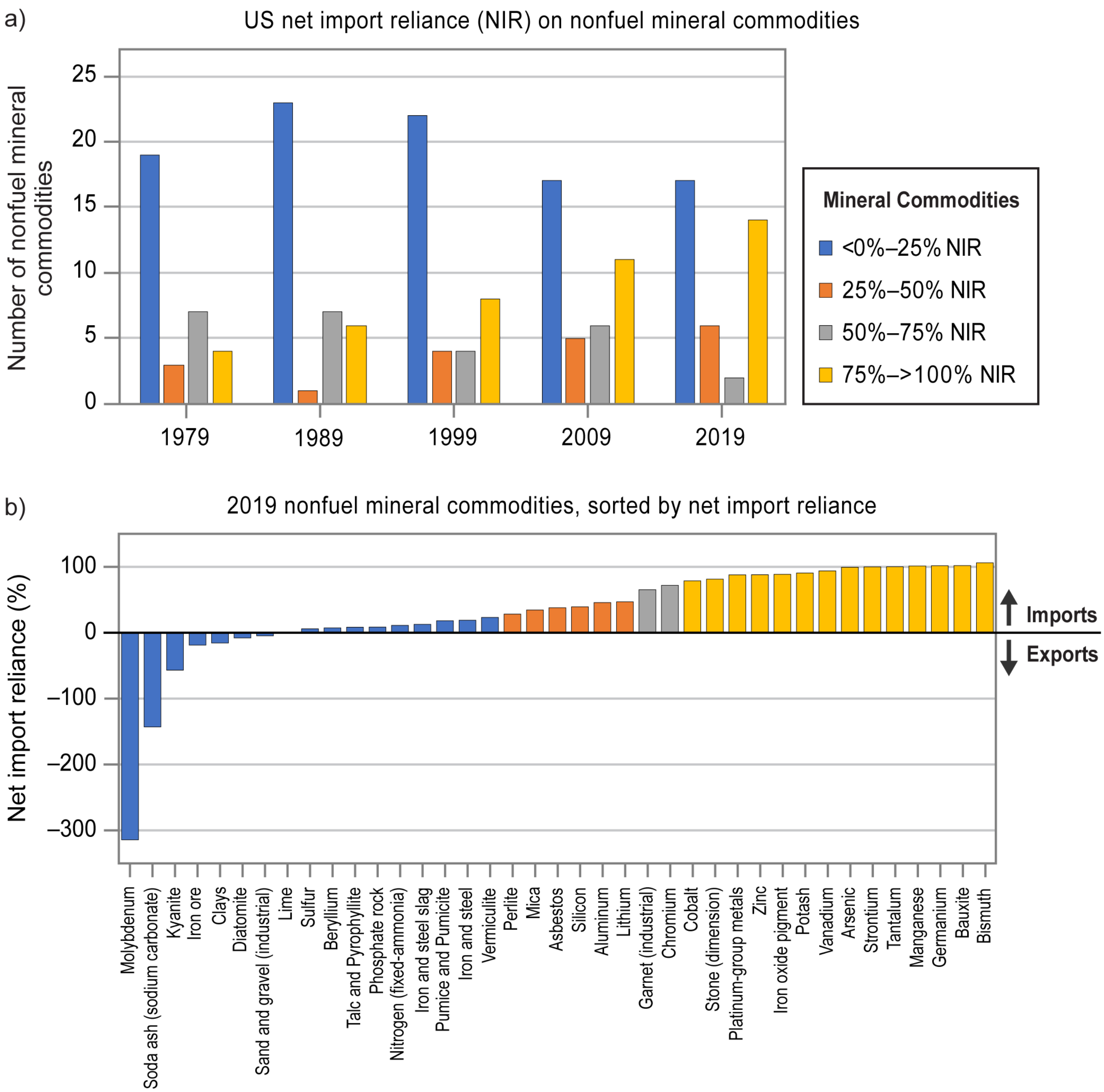
Communities redlined in the 1930s experience more air pollution today.

Figure 32.18. The Home Owners' Loan Corporation (HOLC) grades (A ["best"], B, C, and D ["hazardous," i.e., redlined]) from the 1930s (which effectively denied Black and minority groups access to lending institutions) still corresponded to greater levels of air pollution in 2010. Panel (**a**) shows redlining maps of neighborhoods based on 1930s HOLC grade classifications for four US cities. Panel (**b**) shows the population-weighted distribution of nitrogen dioxide (NO_2) levels (measured as concentration in parts per billion [ppb]) for 2010 across 202 census tracts in the contiguous US. Horizontal lines indicate medians, points indicate averages, and bars indicate 25th to 75th percentiles. Adapted with permission from Lane et al. 2022.[314]

Supply Chains, Energy Security, and Geopolitics

Climate mitigation efforts may drastically increase domestic and global demand for products (e.g., solar photovoltaics, batteries, electric motors, wind turbines) and metal and mineral resources (e.g., lithium, nickel, cobalt, copper), which may have implications for supply security, markets, advanced manufacturing (e.g., robotics and EVs), geopolitics, and mining (Focus on Risks to Supply Chains).[337,338,339,340] Moreover, in the United States there are currently 50 listed critical minerals (up from 35 in 2018),[341,342] defined as those essential to economic or national security and whose supply chains are vulnerable to disruption (Figure 32.19). With increased demand as the system decarbonizes, there could be near-term shortages in several minerals and metals. Note that a series of executive orders anticipates this challenge and calls for monitoring and reduction in US dependence on imported critical materials, for example, by increased recycling (e.g., Executive Order 13817, "A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals,"[343] and Executive Order 13953, "Addressing the Threat to the Domestic Supply Chain from Reliance on Critical Minerals from Foreign Adversaries and Supporting the Domestic Mining and Processing Industries"[344]) and more resilient supply chains generally (Executive Order 14017, "America's Supply Chains";[345] see also Focus on Risks to Supply Chains; KMs 17.2, 18.1).

Increasing Reliance on Imported Nonfuel Minerals



The US has grown increasingly dependent on imported minerals.

Figure 32.19. Panel (**a**) shows that the US has become increasingly dependent on imports of 39 nonfuel mineral commodities since 1979; commodities of which 75%–100% is imported (yellow bars) are increasing in number, and commodities of which less than 25% is imported (blue bars) are decreasing in number. Panel (**b**) shows the specific commodities and the degree of import reliance for each in 2019. Figure credits: (a) adapted from Fortier et al. 2015;[346] (b) University of California, Irvine.

Key Message 32.5

Governments, Organizations, and Individuals Can Act to Reduce Emissions

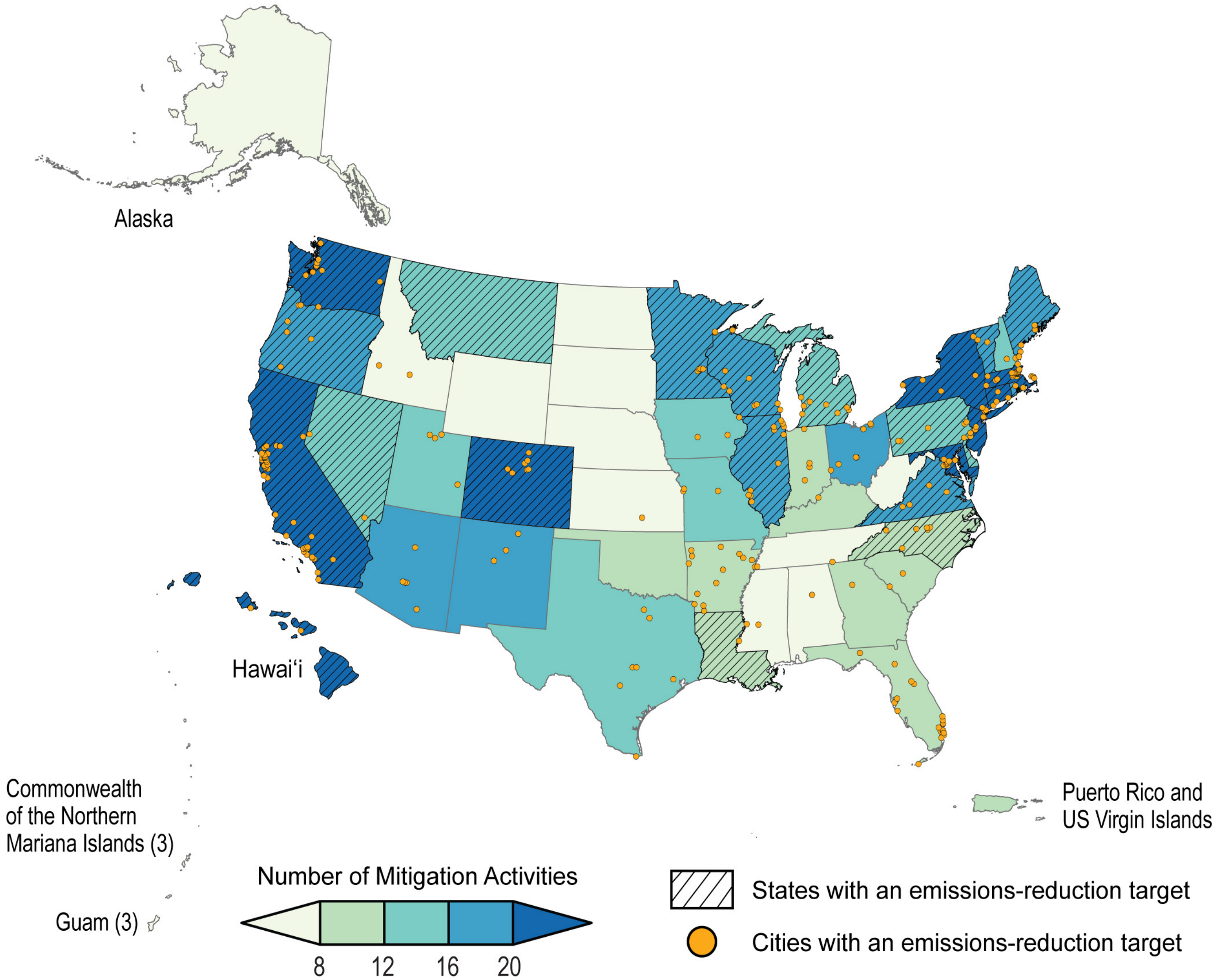
Mitigation efforts can be supported by a range of actors and actions, from choices made by individuals to decisions made by businesses and local, Tribal, state, and national governments (*high confidence*). Actions with significant near-term potential include sector-based policies accelerating deployment of low-carbon technologies, city-level efforts to promote public transportation and improve building efficiency, and individual behavioral changes to reduce energy demand and meat consumption (*high confidence*).

A wide range of actors across the US have been involved in efforts to accelerate clean energy transition and mitigate GHG emissions, including new legislation; rules, regulations, and executive orders; and voluntary actions. For example,

- the US has committed under the Paris Agreement to reduce GHG emissions by 50%–52% in 2030 relative to 2005;
- through the Bipartisan Infrastructure Law and the Inflation Reduction Act and relevant programs, there are federal subsidies to clean energy businesses and for household purchases of EVs and heat pumps;[347]
- 25 states,[348] 675 cities, 300 universities, and hundreds of companies have announced net-zero-emissions targets; and
- bottom-up coalitions such as the America Is All In initiative have support from subnational leaders who represent a constituency of more than half the US population (see, e.g., KMs 21.4, 30.3).

Since 2018, the total number of state-level mitigation activities has increased by 83%, and 169 more cities have introduced emissions reduction targets since then (Figure 32.20; see also Ch. 12).[349]

Mitigation-Related Activities at the State and City Levels

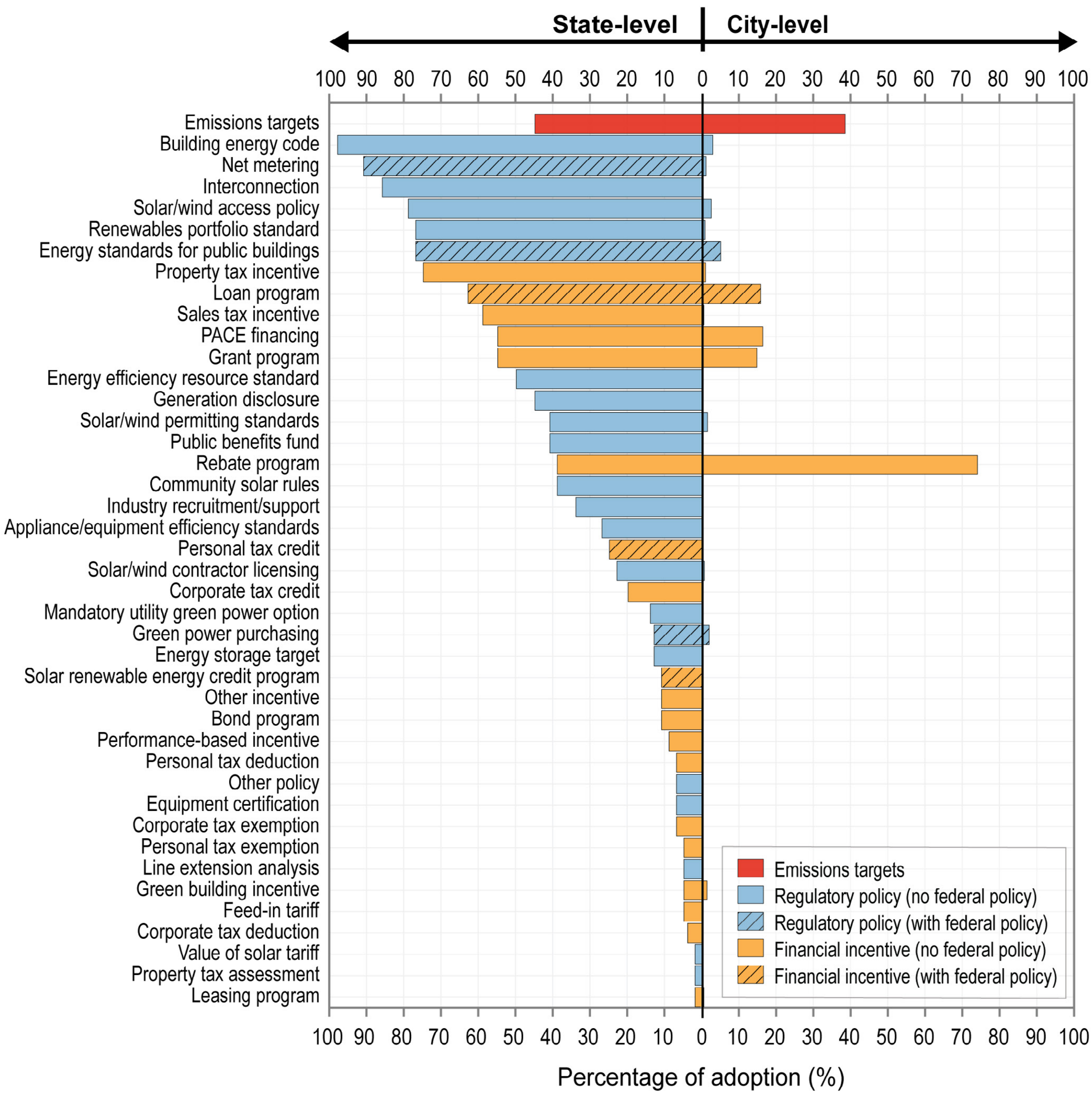


Many states and cities have taken action to reduce greenhouse gas emissions.

Figure 32.20. Shading indicates the number of mitigation activities taken by each state, and orange circles indicate cities with emissions-reduction targets (as of April 2023). Almost every region has taken some action, with hotspots of activity in the Northeast, Southwest, Colorado, Hawai'i, and along the West Coast. See Figure 32.21 for examples of the types of actions taken. Figure credit: The Pennsylvania State University, NOAA NCEI, and CISESS NC.

The pathways toward achieving these goals often include a broad collection of measures and policies, including investments in infrastructure and clean technologies that will require substantial capital, financial backing, and resource allocation. The feasibility and impact of these measures are dependent on local and regional factors, which are often reflected in more granular sector- or economy-specific mitigation targets and actions (see Figure 32.21).[350]

Adoption Rate of Various Forms of Policy Instruments and Climate Action



States and cities have adopted a range of climate actions and policies.

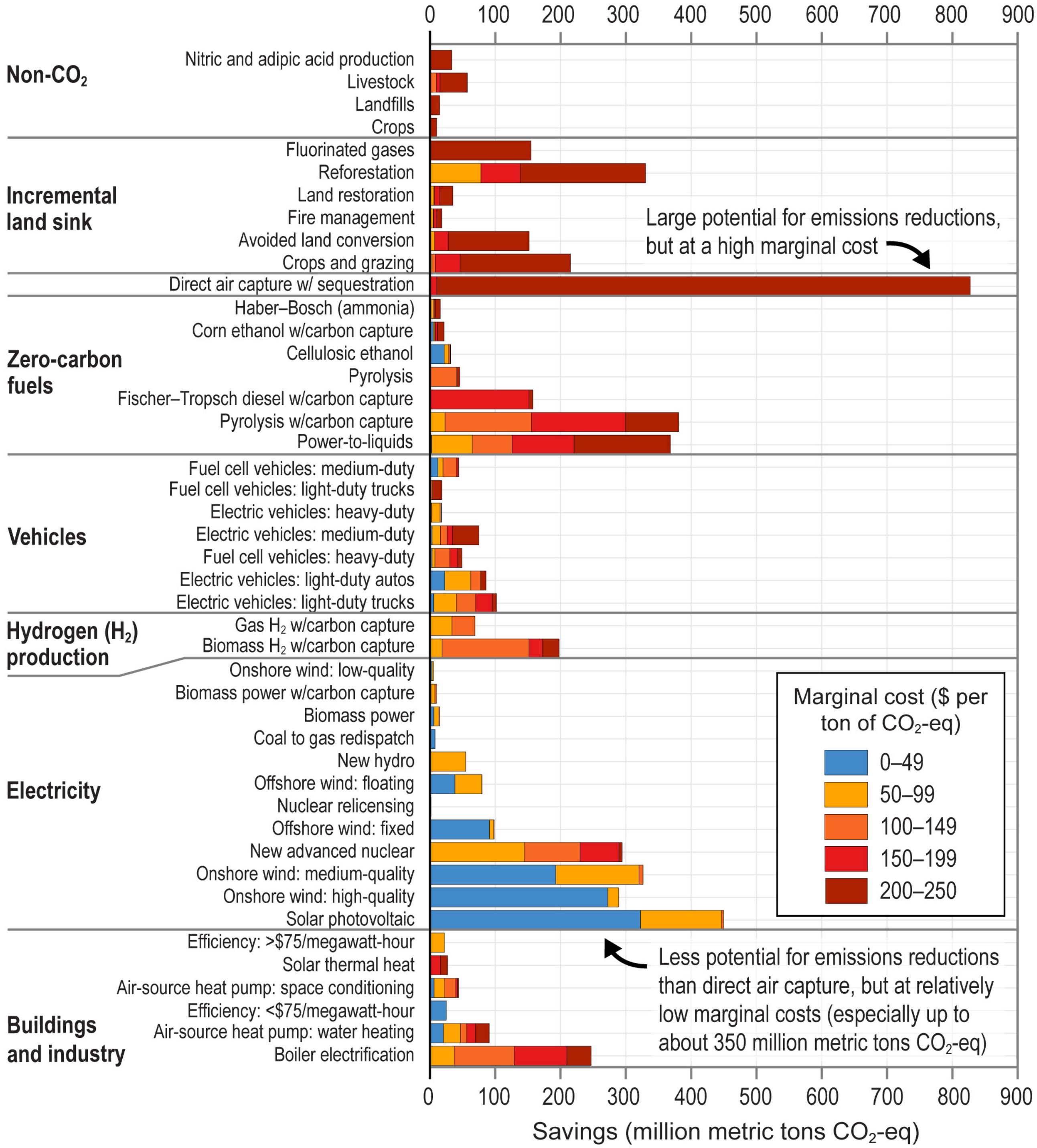
Figure 32.21. Bars show the percentages of states (**left**) and cities (**right**) that have announced emissions targets (tracked by the United Nations Framework Convention on Climate Change Non-state Actor Zone for Climate Action dataset) or adopted the selected clean energy policies (tracked in North Carolina State University's Database of State Incentives for Renewables & Efficiency dataset) as of April 2023. The color of the bars indicates the type of policy, and hashing denotes that the policy action is also being adopted or announced by the Federal Government. PACE stands for property assessed clean energy. Figure credit: The Pennsylvania State University, NOAA NCEI, and CISESS NC.

To this end, nearly 40 states have introduced renewable portfolio standards or voluntary renewable energy goals, which further guide and codify decarbonization efforts within the energy sector and induce incremental shifts toward increased penetration of renewable electricity (KM 32.1). Similarly, more than 30 local governments have enacted requirements for energy efficiency, ranging from building codes and benchmarking ordinances to establishing performance standards (see, e.g., KM 12.3). With federal corporate average fuel economy (CAFE) standards in place for vehicles, local transportation-sector efforts are often focused on behavioral mode-shift goals, such as promoting clean and public transport options and reducing vehicle-miles traveled. The proposed federal Agriculture Resilience Act is designed to address the adaptive needs of US farmers and consumers as a result of a changing climate, as well as to reduce the emissions associated with agricultural production.[351] In addition, the Securities and Exchange Commission is in the process of finalizing new rules that would require public companies to disclose greenhouse gas emissions related to their operations and supply chains, as well as climate risks to their business.[352] Such rules would build on the voluntary reporting and reduction efforts of corporations under the Carbon Disclosure Project; Science Based Targets initiative; and Environmental, Social, and Corporate Governance frameworks and will need to be supported by improved accounting protocols and focused scientific research.[174,353,354,355,356]

Beyond goal-setting and implementing regulatory measures, the enabling of financial mechanisms is often a core element of mitigation strategy. Regional cap-and-trade programs utilize a system of accountability and performance to incentivize emissions reductions at the electricity-generation level. Meanwhile, federal subsidies, such as those provided to clean energy businesses and tax credits for electric vehicle purchases, can bolster behavior change.[54] By enabling access to financial capital—whether within the government, commercial, or residential sectors—investments in infrastructure and the built environment, as well as research and development, may further drive these advances.

Available mitigation strategies vary in terms of emissions-reduction potential and costs (Figure 32.22), as well as in environmental, technical, and social implications (Figure 32.23). However, with the advancement of measurement technologies and insights gained from the deployment of various actions taken in vastly different environments, there is now more empirical evidence to inform strategy design for a given community (see regional chapters for examples of state, city, community, and Tribal mitigation actions; e.g., Box 21.1; KM 30.3). Additionally, more jurisdictions are adopting community-driven and holistic approaches to climate action planning, incorporating practices that address equitable access to information (including considerations for languages used and internet access) and events (including transportation vouchers, food and childcare provisions, and payment for subject-matter expertise to community members with lived experience), with a goal of improving and increasing capacity and ability to influence decision-making and, ultimately, assisting elected leaders in making the best-informed and most-impactful decisions for their unique communities.[357,358,359]

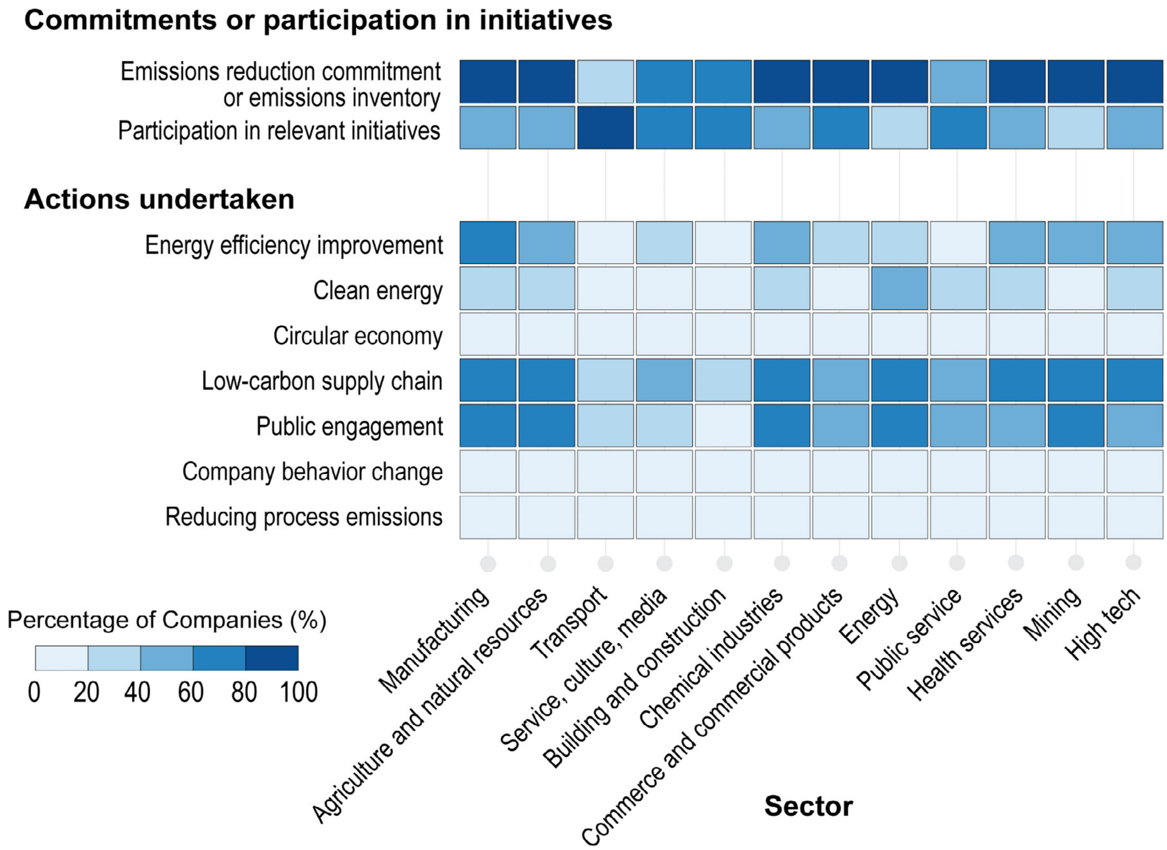
Potential Emissions Reductions by Action, for the Year 2050



The size and cost of emissions reductions depend on available technologies and the source of related emissions.

Figure 32.22. Energy system, land-sector, and non-CO_2 (carbon dioxide) mitigation options for the year 2050 are shown along with estimated marginal costs, excluding the impact of policy incentives. The sum of the mitigation options shown results in net-negative CO_2-eq (carbon dioxide equivalent) emissions in the United States, not only demonstrating the possibility of reaching net-zero emissions using a combination of these actions but also highlighting a large range of costs for such actions (costs as of 2021). Mitigation options from conservation and lifestyle change are not assessed due to the difficulty in assessing costs for these measures. H_2 = hydrogen. Adapted with permission from Farbes et al. 2021[360] and Figure SPM.7 in IPCC 2022.[361]

US Company-Level Mitigation Actions



A majority of US companies have made mitigation commitments, inventoried emissions, or participated in initiatives, but fewer are taking action.

Figure 32.23. As of April 2023, a majority of US companies across many sectors have committed to reducing emissions or conducted emissions inventories, and many have participated in mitigation initiatives (**top**). Percentages are smaller in terms of actions taken (**bottom**). For example, many companies are involved in energy efficiency improvements, efforts to reduce supply chain emissions, and public engagement efforts. But 20% or fewer across all sectors are reported as reducing process emissions or effecting company behavior changes. Figure credit: The Pennsylvania State University, NOAA NCEI, and CISESS NC.

Box 32.3. Orlando Case Study: Mitigation in the Country's Most Visited City

In the five decades since the opening of Walt Disney World, Orlando has become the most highly visited city in the United States. As a result, this community faces the unique challenge of managing the costs, demands, and emissions of more than 75 million annual visitors, or nearly 300 visitors for each individual resident.[362,363] To address these impacts, local governments have adopted an ambitious, socially inclusive, and innovative climate strategy.

The prevalence of resort and multifamily developments, for example, has led to the adoption of energy efficiency requirements for commercial buildings and a community-wide commitment to 100% renewable energy to drive the decarbonization of the local building stock. Meanwhile, to address the needs of local residents, many of whom work in lower-wage jobs associated with the tourism industry, an energy-burden analysis was conducted to identify the neighborhoods most in need of assistance.

As the largest rental car market in the world, the region has served as a proving ground for enhanced electric and autonomous vehicle piloting,[364,365] as well as the adoption of an electric vehicle readiness policy.[366] Research efforts have focused on public safety when various modes of transportation, such as single-passenger vehicles (more likely to be utilized by visitors and more affluent residents), are active in the same vicinity as buses, cyclists, and pedestrians.

Enhanced waste-reduction efforts previously included an anaerobic digestion facility that utilizes the gray water and food scraps from the Disney parks and resorts to generate biogas, a renewable energy source that is used to power these same facilities. In tandem with this localized solution, waste avoidance and gleaning programs (e.g., improved collection of excess produce and perishables from farms, retailers, and restaurants)[367] provide options for those who are food insecure.

Together, these mitigation strategies serve to protect the local environment, enhance the quality of life for local residents, and showcase a variety of solutions to the nearly 76 million guests who visit the region each year.

Traceable Accounts

Process Description

Based on their own experience, nominations, and relevant recent literature, the chapter lead author and federal coordinating lead author discussed and selected a set of experts to invite as authors, seeking diverse representation of topical expertise, disciplinary perspectives, career stages, professional backgrounds, geographies, and demographics. Of 25 invitations, 16 were accepted, forming an author team with the requisite expertise to cover the chapter topics and provide a good balance of other characteristics. The author team began meeting regularly as a group and then divided into smaller working groups focused on different key topic areas, which also met regularly (all meetings were virtual, except for the in-person All-Author Meeting held in Washington, DC, in April 2023). During these meetings, the team worked together to develop key topic areas for the chapter, identify key literature and sources, and plan syntheses and figures for the chapter. The team also planned the public engagement workshop for the chapter and afterward discussed inputs and feedbacks from that workshop.

Key Message 32.1

Successful Mitigation Means Reaching Net-Zero Emissions

Description of Evidence Base

The assessment and summary of the sources and trends of US greenhouse gas emissions relies primarily on inventories and estimates from the EPA,[7,8] supplemented by socioeconomic, energy activity, and agricultural production data from official sources such as the US Energy Information Administration (EIA)[18,368,369,370,371] and the World Bank.[372,373] EPA estimates of energy-related emissions are primarily based on tracked masses and volumes of combusted fuels (and in some case continuous emissions monitoring at point sources) publicly reported to the EIA, EPA, or Bureau of Transportation Statistics. EPA estimates of land sector (i.e., land use, land-use change, and agricultural) emissions are primarily based on activity data (e.g., area of land converted, number and kinds of livestock, mass of fertilizer applied) and associated emissions factors that have been developed based on numerous case studies.[11,374] Federal- and state-level greenhouse gases (GHG) targets were compiled from publicly available sources and are not uncertain.

Major Uncertainties and Research Gaps

Although there is no uncertainty as to the current emissions targets and it is well-established that global warming will be proportional to cumulative carbon dioxide (CO_2) emissions (e.g., Matthews et al. 2009[375]), there is relatively little scientific literature and relatively few national and international goals that address long-term management of the climate after net-zero emissions have been achieved and into the 22nd century.[376]

Estimates of agricultural and fugitive non-CO_2 GHG emissions have greater uncertainty because they are spatially heterogenous “area” sources that are more challenging to measure directly,[97,377] as evidenced by discrepancies between “top-down” estimates of global methane emissions based on measurements of the atmosphere and “bottom-up” estimates based on activity data such as number and kinds of livestock and extent of rice cultivation.[378,379] For this reason, these are active areas of research, and analysts are bringing to bear a variety of different and innovative tools and methods to reduce the uncertainty and prioritize mitigation efforts (e.g., Liu et al. 2022;[380] Norooz Oliaee et al. 2022;[381] Conrad et al. 2023[382]).

Description of Confidence and Likelihood

Based on the multiple sources of high-quality energy system data, the authors have *very high confidence* in both the overall magnitude of energy-related US GHG emissions from each major source and their relative changes over time. There is also broad agreement among dynamic vegetation models, bookkeeping models of land-use change, and atmospheric observations as to the magnitude of the US land sink in recent years,[51] but the sink has been decreasing[22] and future uptake by US forests will depend on management and climate change impacts, both of which are uncertain.[21,180,383,384] Given current emissions levels and stated goals, however, the required rate of decrease is not in question. For these reasons, we have *very high confidence* in the statements made in the Key Message.

Key Message 32.2

We Know How to Drastically Reduce Emissions

Description of Evidence Base

The assessment of established options for reducing energy-related GHG emissions reflects a large body of literature and recent energy-system modeling,[60,385] including a database of 40 US net-zero emissions scenarios.[41,42] Although there are substantial differences in the cost-effective energy systems modeled in these scenarios depending on model design and key assumptions, the Key Message and text emphasize characteristics that are robust across most, if not all, of the scenarios.[47,50,130,386,387,388]

Major Uncertainties and Research Gaps

The assessment of established options for reducing land-related GHG emissions reflects a substantial literature, but there are few quantitative scenarios to support potential reductions.[96,98,121,177,185,191,389,390,391] Instead, potential reductions are often extrapolated from the localized studies that are available. Further research is warranted to test key sensitivities in energy model scenarios and to quantitatively assess factors beyond cost, such as social and political acceptance of (or opposition to) changes in use of land and water resources and adoption of energy technologies, and the associated distribution of benefits and impacts (as well as other non-cost factors discussed in KM 32.4).

Description of Confidence and Likelihood

Across 40 of the most recent and detailed energy system scenarios of net-zero US emissions, produced by 14 independent models and assuming a wide range of costs and constraints, the share of final energy met by electricity increases from about 20% today to 43%–57% by 2050 (the 25th–75th percentile range; Figure 32.11), and solar and wind are consistently major sources of energy, typically ranging from 57%–80% of primary energy by 2050 (the 25th–75th percentile range; Figure 32.10). Yet fuels continue to be used across those scenarios for some transportation and industry applications. The robustness of these numbers despite many methodological differences gives us *high confidence* in the energy-related statements in the Key Message.

A large literature also supports the opportunities for large reductions in land-related emissions, giving us *high confidence* in the land-related statement in the Key Message.[96,98,121,177,185,191,389,390,391]

Current costs of technologies such as solar, wind, and electric vehicles and the projected large-scale deployment of these technologies in cost-optimized energy system models,[41,42,45,66,392] as well as many studies demonstrating the potential cost savings of energy efficiency improvements,[393,394] optimization of agricultural inputs,[395] shifts in diet,[96,98,396] and repair of leaky infrastructure, all give the authors similarly *high confidence* that many mitigation options are now cost-effective.

Key Message 32.3

To Reach Net-Zero Emissions, Additional Mitigation Options Need to Be Explored

Description of Evidence Base

The assessment of potential options for reducing energy-related GHG emissions reflects a large body of literature and recent energy system modeling, including a database of 40 US net-zero emissions scenarios,[41,42] but this Key Message highlights that the scale and mix of energy technologies and mitigation options remain sensitive to assumed—and yet uncertain—costs and constraints. Similarly, the potential options for reducing land-related GHG emissions presented in this Key Message are not as well studied, and there is open debate about the efficacy and/or cost-effectiveness of, for example, different energy storage technologies,[397,398] advanced nuclear technology,[399,400] and carbon management options,[52,168,401,402] as well as future agricultural productivity.[403,404]

Major Uncertainties and Research Gaps

We assign *medium confidence* to the list of attractive targets for further research, development, and demonstration because existing literature either disagrees as to the potential of these technologies or only a few studies have made the case that they have great potential. Where analyses disagree, it may be because their findings depend on assumptions regarding deeply uncertain aspects of economic development, human behavior, or technological innovation. In general, additional research is needed to quantitatively assess a greater number of emerging energy technologies and land management options, and especially work that incorporates the various non-cost factors discussed in Key Message 32.4.

Description of Confidence and Likelihood

We have *high confidence* that we do not yet know which net-zero-emissions energy system will be cost-optimal (or socially and politically acceptable) and that we do not know the ideal types or scales of carbon management to support net-zero emissions and sustainability more broadly.[405,406] This is because there is substantial variation in the type and scale of energy and carbon management technologies deployed in model scenarios, long-term projections of technology costs span large ranges, and the social and political support for different mitigation efforts is unclear. Although the effectiveness and scalability of some of the approaches to reduce land-related non-CO_2 emissions remain uncertain (e.g., soil amendments, livestock feed supplements), other options are becoming clear, such as managing manure, cover cropping, and decreasing nitrogen fertilizer applications. Thus, we have *medium confidence* as to the options for reducing these land-related non-CO_2 emissions.

Key Message 32.4

Mitigation Can Be Sustainable, Healthy, and Fair

Description of Evidence Base

The assessment of historical and future impacts of energy systems on, for example, water,[279,280,283,284] air pollution,[102,234,245,246,253,254] energy security,[31,339] labor,[233,247,293,298,305] and energy equity and environmental justice[217,251,259,300,309,329] is based on a diverse and rapidly growing academic literature as cited in the chapter.

Major Uncertainties and Research Gaps

As mentioned in regard to other Key Messages, there is a lack of specific qualitative and quantitative analyses and decision-making tools regarding how mitigation may affect and be affected by energy equity, environmental justice, land use, labor, water, air pollution, and energy security in different places, times, and social, demographic, and political contexts (Carley, Evans et al. 2018). There is also a lack of analyses and tools to reflect interacting technological, social, political, and environmental uncertainties and choices to inform multistakeholder decision-making.[407]

Description of Confidence and Likelihood

An extensive literature demonstrates the potential health benefits of climate mitigation, especially in regard to related decreases in air pollution. Fewer but still numerous studies have shown that the cost and resource savings or net social benefits of many mitigation options can accrue to specific populations. We therefore have *high confidence* in the potential benefits to human health and well-being, including specific environmental and socioeconomic effects. However, the available research also gives us *high confidence* that the benefits of mitigation may be distributed unevenly in the absence of proactive efforts to ensure fairness.

Key Message 32.5

Governments, Organizations, and Individuals Can Act to Reduce Emissions

Description of Evidence Base

Our assessment of possible actors and mitigation actions is drawn from both the actions represented in models and studies by researchers,[408,409,410,411,412] as well as reports and databases that have compiled lists of past actions taken (e.g., the Center for Climate and Energy Solutions State Climate Policy Maps,[348] North Carolina State University Database of State Incentives for Renewables & Efficiency,[413] CDP States and Regions Climate Tracker,[414] and United Nations Framework Convention on Climate Change Non-state Actor Zone for Climate Action dataset[415]).

Major Uncertainties and Research Gaps

No jurisdiction has yet transitioned from a fossil-based economy to a deeply decarbonized or net-zero-emissions one. Moreover, actions to start down that road may be different from those that reach the end of it.[416,417] Future research may productively explore the limits of actions by certain groups or jurisdictions, and seek to assess where collaborations are necessary and most valuable to support mitigation.[417,418]

Description of Confidence and Likelihood

Public commitments made and actions already taken (as tracked by the sources cited in the evidence base above) give us *high confidence* that mitigation can be supported by a wide range of actors in a wide variety of ways. Historical progress in reducing emissions (e.g., US electricity emissions since 2007) and forward-looking modeling analyses give us similarly *high confidence* that substantial near-term potential in the US lies in actions to boost low-carbon technologies,[50,255,387,419,420,421] moderate use of internal combustion vehicles,[65,66,68] improved building efficiency,[32,33] and diet shifts.[96,98,396]

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