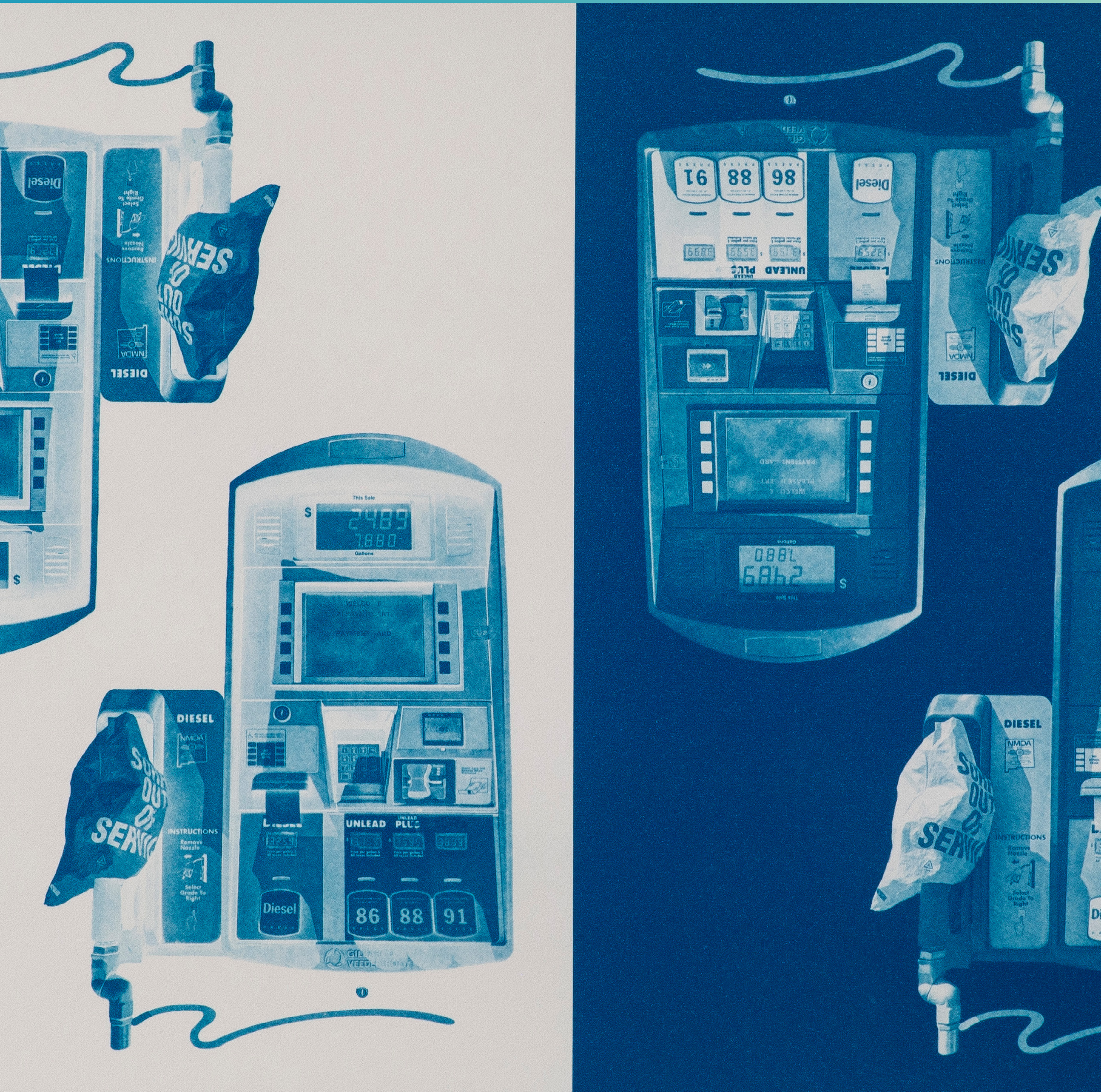
Fifth National Climate Assessment: Chapter 5

# Energy Supply, Delivery, and Demand



# Chapter 5. Energy Supply, Delivery, and Demand

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### Recommended Citation

Zamuda, C.D., D.E. Bilello, J. Carmack, X.J. Davis, R.A. Efroymson, K.M. Goff, T. Hong, A. Karimjee, D.H. Loughlin, S. Upchurch, and N. Voisin, 2023: Ch. 5. Energy supply, delivery, and demand. In: *Fifth National Climate Assessment*. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA. https://doi.org/10.7930/NCA5.2023.CH5

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# Introduction

Reliable and affordable clean energy is important for quality of life, economic competitiveness, and national security. However, much of today's energy infrastructure was designed for the 20th century, making it vulnerable to climate impacts, including more frequent power and fuel interruptions, increased damages to energy infrastructure, increased energy demand and reduced supply, and cascading effects impacting other sectors, including transportation, communication, and health and safety.

Societal changes are altering vulnerabilities of energy systems and communities to climate change. Changing risks result from shifts in the energy generation mix that lower greenhouse gas (GHG) emissions; increased electrification of buildings and transportation; technological innovation creating new demands for energy; greater susceptibility of energy components to domestic and international supply chain disruptions; and an increasingly automated, interconnected system susceptible to physical and cyberattacks.

While atmospheric GHG concentrations continue growing at historically high rates due to factors such as increased global energy use, energy system decarbonization is reducing the rate of GHG emissions.[1] Demand for energy is increasing, outpacing energy efficiency improvements, and electrification is expected to grow.[2,3] Adaptation to environmental change, along with improved resilience of energy production and delivery systems to climate-related events, is underway. Energy system innovations include reductions in technology costs and operational and performance improvements for energy production, delivery, and storage; distributed generation and microgrids; demand-side management; zero-emissions buildings and vehicles; and energy-market design and governance structures.

Evolving policy focuses on a transition to net-zero energy systems and away from fossil fuels. The Bipartisan Infrastructure Law[4] and the Inflation Reduction Act (IRA)[5] are the largest investments in climate and energy in American history (Chs. 25, 32).[6,7,8] These laws prioritize investments for overburdened communities and advance the Justice40 Initiative, which commits to delivering benefits of climate, clean energy, and related federal investments to these communities.[9] State and local actions include building codes, incentives, and bans intended to encourage a shift to clean energy sources.[10,11] Progress is underway, but further actions are needed to increase the pace, scale, and scope of the energy transition to deliver more clean energy and build a more resilient energy future.

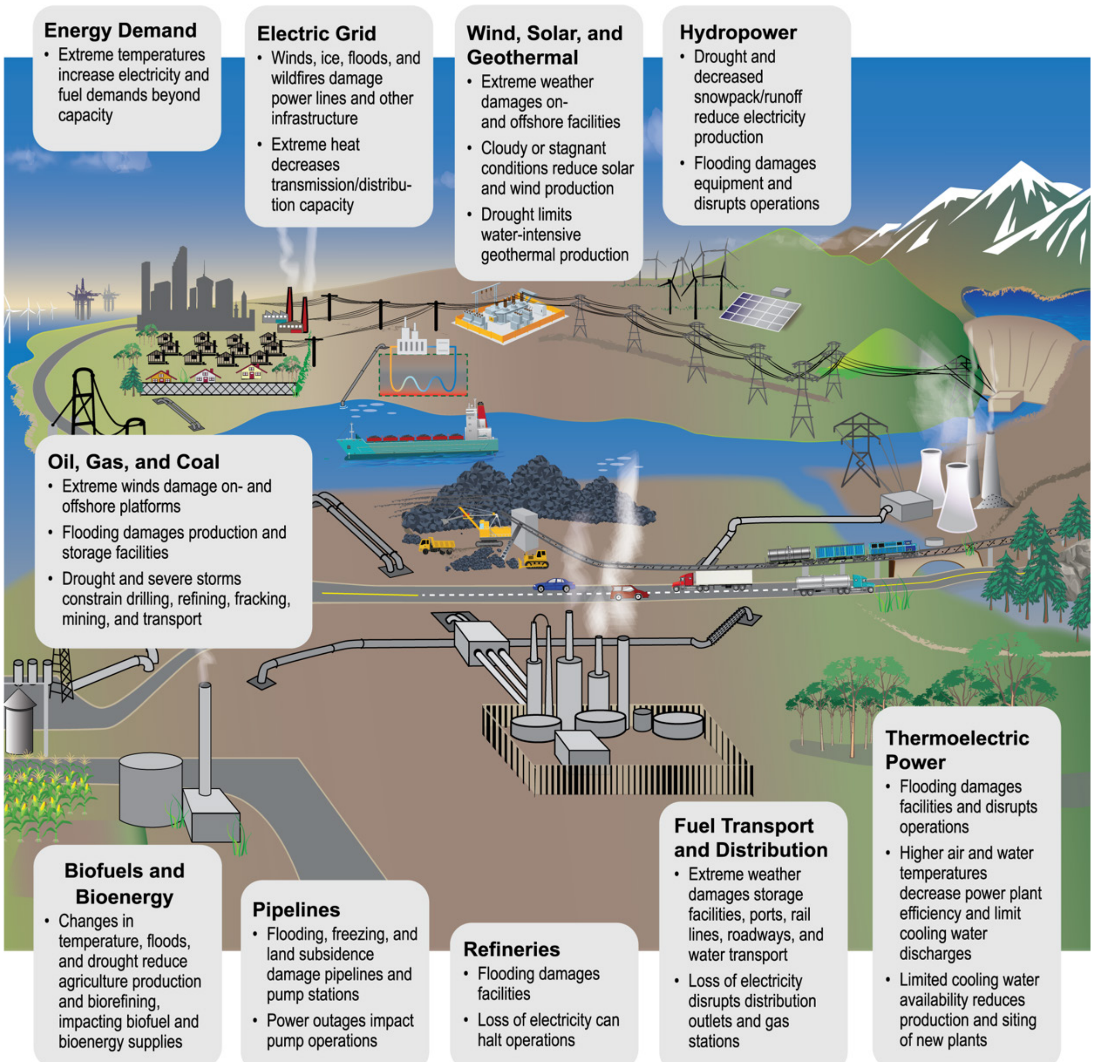
## Key Message 5.1

## Climate Change Threatens Energy Systems

Energy supply and delivery are at risk from climate-driven changes, which are also shifting demand (*virtually certain*, *very high confidence*). Climate change threats, including increases in extreme precipitation, extreme temperatures, sea level rise, and more intense storms, droughts, and wildfires, are damaging infrastructure and operations and affecting human lives and livelihoods (*virtually certain*, *very high confidence*). Impacts will vary over time and location (*virtually certain*, *very high confidence*). Without mitigation and adaptation, projected increases in the frequency, intensity, duration, and variability of extreme events will amplify effects on energy systems (*virtually certain*, *very high confidence*).

Climate change affects all aspects of the energy system—supply, delivery, and demand (Figure 5.1)—through the increased frequency, intensity, and duration of extreme events and through changing climate trends (Ch. 2). Energy production and distribution are vulnerable to flooding, hurricanes, drought, wildfires, and permafrost thaw. Extreme temperatures increase energy demands and stress electricity operations, leading to outages that disrupt societal services. The magnitudes of climate threats vary temporally and spatially (e.g., droughts and wildfires in the Southwest, hurricanes and storm surge on the Gulf and East Coasts).

## Climate Change Impacts on the Energy System




**All aspects of the US energy system are vulnerable to the effects of climate change.**

**Figure 5.1.** Climate change impacts all components of the Nation's energy system—resource extraction and processing, energy transport and storage, electricity generation, and energy end use. Adapted from DOE 2013.[12]

## Energy Supply

### Generation Systems

Sea-level rise, hurricane-force winds, and inland flooding impact coastal energy infrastructure and strategic national assets,[13,14] including the Nation's Strategic Petroleum Reserve.[15] The Gulf of Mexico region accounts for a significant portion of the Nation's crude oil production, petroleum refining, and natural gas processing capacity.[16] Coastal energy supply is especially affected by climate change and can disproportionately impact isolated and overburdened communities.[17,18]

Storm events, extreme temperature, droughts, and wildfires damage inland energy generation systems and impact operations.[19,20] Solar and wind energy generation is affected by heat, smoke, soot, and hail.[21,22,23] Flooding and freezing of extraction, storage, and distribution equipment impact natural gas production and power generation and cause power outages.[24] Extreme heat reduces the capacity and efficiency of natural gas and steam turbines.[25,26] More intense hurricanes have increased disruptions to nuclear power.[27] Drought and extreme weather can limit biofuel feedstock supplies.[28] Renewable energy will be affected by changes in wind and solar resources, although the magnitudes and locations of these effects are uncertain.[29,30,31,32,33,34] Uncertainty regarding climate impacts on wind and solar resources remains, but downscaled climate model data coupled with energy sector models are advancing.

### Electricity Generation and Water Availability

Water is used in electricity generation, including in producing hydropower and hydrogen, cooling thermoelectric generators, maintaining solar photovoltaic (PV) installations,[35] and producing feedstocks for bioenergy. Water-dependent generation is stressed by droughts,[36,37,38] snowpack depletion,[37] increases in stream temperature,[39] reservoir evaporation,[40] dam removal to restore rivers and their societal and ecological roles,[41] increasing demands for other water uses, and pumping limits that increase cost.[42]

Most of the western United States is experiencing a megadrought, disrupting water supply and hydropower generation (Ch. 2).[37,43,44] Increasing energy demand due to higher summer temperatures, coupled with a projected decrease in summer hydropower generation, will magnify the potential for energy shortfalls.[45,46]

Thermoelectric generators provide most of the Nation's electricity and rely on significant volumes of water.[47,48,49] Deployment of some low-carbon technologies, such as carbon capture, utilization, and storage (CCUS), increases this water dependence.[50] New cooling technologies for small modular reactors provide options for addressing water availability constraints.[51] The compounded impacts of decreasing summer river flows, increasing temperatures, and, in many regions, temperature limits on discharge water reduce the efficiency and generation capacity of thermoelectric generators,[52] decreasing reliability during extreme conditions.[39,53,54] Operations relying on reservoir storage for cooling water face increasing vulnerability from storage levels dropping below critical thresholds, particularly in the Southwest.[55]

## Energy Delivery

### Electricity Delivery

Power outages from extreme weather are increasing across the US. The average number of major power outages (exceeding 50,000 customers) increased by roughly 64% during 2011–2021, as compared to 2000–2010, with the most weather-related power outages attributed to extreme cold (22%), tropical cyclones (15%), and severe weather (58%).[56] Annual expenditures on electricity transmission and distribution infrastructure could rise up to 25% by 2090 under a very high scenario (RCP8.5) compared to a scenario without climate change.[57] Additional costs for power interruptions could reach $4.7 to $8.3 billion per year by 2090 (in 2022 dollars).[57]

Extreme heat events are increasing in frequency and duration (KM 2.2).[58,59] High temperatures increase powerline sagging and reduce the efficiency of transmission and distribution, stressing the grid during periods of increased demand.[57,60] Electricity infrastructure, including transformers and transmission lines, deteriorate faster in extreme temperatures, and cables have reduced carrying capacity with rising air temperature.[25,57]

Wildfires and extreme weather events pose challenges to electricity infrastructure.[61,62,63,64] Aboveground powerlines are susceptible to damage from high winds and falling vegetation.[65,66] Powerlines are also susceptible to damage and reduced efficiency from ice[67] and wildfires, including soot.[57,63,68] Flood scours, subsidence, and landslides, which increase with drought and increased groundwater pumping,[69] are damaging buried powerlines and natural gas pipelines. Coastal power substations are at risk from storm surges exacerbated by sea level rise.[70,71]

Examples of extreme-events impacts on electricity delivery include substantial damage to Puerto Rico's transmission and distribution lines after Hurricane Maria;[72] hotter and drier conditions in the Southwest enabling stronger and longer-lasting wildfires,[19] threatening the wildland–urban interface;[20] and risk of wildfires influencing utility-initiated power shutdowns in California during periods of high winds and dry conditions.[20,73,74]

## Oil and Gas Delivery

Climate change and extreme weather disrupt oil and gas supply chains.[75,76,77,78] Hurricanes, flooding, and sea level rise threaten onshore and offshore infrastructure and operations.[79] These threats would become more intense in a warming world (Ch. 2). Disruption of petroleum supplies has broader impacts on transportation, buildings, and industrial products.[80]

In 2020, Hurricane Laura disrupted more Gulf of Mexico crude oil production than any other storm since 2008.[81] Onshore processing facilities and power supplies were damaged, and industry response was limited by lack of resources, personnel, processing facilities, and power. Flooding from Hurricane Harvey in 2017 damaged large pipelines,[82] and excessive precipitation damaged floating-roof storage tanks.[83] Hurricane Ida in 2021 disrupted up to 95% of the Gulf Coast's crude oil and gas production.[84]

Extreme cold events in areas inexperienced with such temperatures are impacting oil and gas equipment and operations.[24] In regions where natural gas is used for heating and power generation, cold events are challenging because of increased demand combined with the risk of infrastructure failure.[85,86]

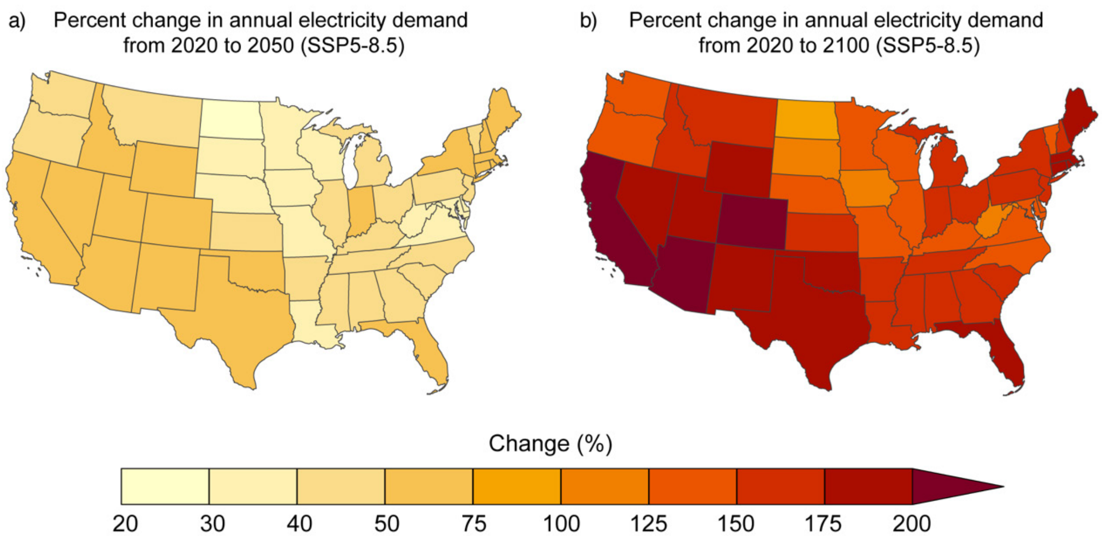
Although climate change often increases risks to energy production and delivery, warming temperatures have mixed effects on oil and gas production in cold regions. Warming benefits offshore production and shipping of petroleum products off the Alaska coast by decreasing sea ice and opening shipping routes. Average annual Arctic sea-ice extent during 2011–2020 reached its lowest level since at least 1850 (Ch. 2).[87] Ice-free summers are projected by 2050.[87,88] Warming temperatures in Alaska endanger inland oil and gas production and delivery as permafrost thawing compromises the structural integrity of wells, pipelines, storage tanks, railroads, and roads, impacting consumers and potentially contributing to methane leakage.[89] Fewer days for road travel on decreasing frozen tundra also has an impact on oil and gas exploration and production.[90,91]

## *Energy Demand*

Energy demand is projected to increase through 2050, driven by warming temperatures, increasing electrification, and economic growth.[3,92] Despite the increase, overall intensity of energy demand (energy consumed per household or per square foot of commercial floorspace) is expected to decrease.[3,92] Energy system modeling projects decreases in overall energy use relative to current levels if net-zero $CO_2$ emissions are achieved (KM 32.2).

Electricity demand is growing in many regions of the US, driven by population and economic growth; increased adoption of electric vehicles, heat pumps, and water heaters; and decarbonization goals, spurring additional electrification of transportation, industry, and buildings.[93] These trends also alter peak demand patterns.[94,95,96] Increased temperatures can further increase overall electricity demand, as illustrated in Figure 5.2.[97,98]

### Projected Changes in Electricity Demand




**Due to climate change, electricity demand is projected to increase over this century.**

**Figure 5.2.** Global change intersectoral modeling forecasts[97] that do not reflect the provisions of the Inflation Reduction Act project a potential increase in annual electricity demand of 25% to 70% from 2020 to 2050 (a) and 96% to over 215% from 2020 to 2100 (b) across much of the country, driven in part by increased ambient temperatures. Alaska, Hawaiʻi and US-Affiliated Pacific Islands, and the US Caribbean are not included due to the lack of high-resolution climate data informing those projections, but similar trends are expected. Increasing electricity demand is expected based on socioeconomic scenarios and adaptation approaches for the grid (KM 23.4). Changes are based on a very high scenario (SSP5-8.5). Figure credit: Pacific Northwest National Laboratory.

### Peak Power Demand

Temperature changes and extreme events alter peak power demands, driving the need for additional investment in energy infrastructure of 3%–22% by 2100.[99] Electricity needs for cooling buildings are projected to increase energy demands through 2050.[100,101,102] By 2050, warming summer temperatures are expected to increase residential electricity demand greatest in the South and Midwest, whereas warmer winter temperatures will reduce residential natural gas demand most in the South.[102,103] By the end of this century, the maximum summer cooling energy demand in the US could increase by 27% under a very high scenario (RCP8.5).[104]

Extreme events are expected to increase residential and commercial cooling demands,[100] placing additional stress on the power grid. Cooling demand in summer accounts for 30%–50% of the total daily electricity usage for the metropolitan areas of Sacramento, Los Angeles, and New York City. For every 1.8°F (1°C) of ambient temperature increase, daily electricity usage increases 6.2% in Sacramento, 4.7% in Los Angeles, and 5.1% in New York City.[105] During the 2021 heatwave in the Pacific Northwest, inland temperatures reached 120°F.[106] In Portland, Oregon, peak electricity demand was one-third higher in 2021 than in either of the prior two years.[107] Heatwaves will increase summer electricity demands if they lead to adoption and use of air-conditioning.[108]

### Oil and Gas Demand

Demand for oil and gas is projected to remain stable in the US through 2050, with technological advances including electrification and electric vehicles reducing potential consumption.[3] However, with high international demand for liquified natural gas, US production may rise, and the US will remain a net exporter of natural gas. Methane emissions associated with increased natural gas production will need to be addressed (Ch. 32).

## Key Message 5.2

## Compounding Factors Affect Energy-System and Community Vulnerabilities

Concurrent changes in technologies, policies, and markets, in addition to their interconnections, can reduce GHG emissions while also increasing vulnerabilities of energy systems and communities to climate change and extreme weather (*very likely*, *very high confidence*). Compound and cascading hazards related to energy systems and additional stressors, such as cyber and physical threats and pandemics, create risks for all but disproportionately affect overburdened communities (*very likely*, *very high confidence*).

### *Decarbonization*

Climate change is driving decarbonization efforts across the Nation, transforming the energy system through increased electrification and applications of wind and solar, hydrogen, bioenergy, modular nuclear, geothermal, hydropower, other long-term storage, and CCUS. Innovative energy market designs are being advanced to accelerate decarbonization. Under decarbonization scenarios that reduce economy-wide carbon emissions by at least 50% by 2030, electricity demand is expected to increase, led by transportation electrification. Demand increases vary across models from 2%–56% higher in 2030, compared to 2019 levels.[109] Projections of growing electricity demand in transportation vary from less than 10% to nearly 100% of sales by 2050,[95,96,110,111] depending on future regulations, incentives, and market acceptance. Additional electrification opportunities exist in buildings, including space and water heating, and in industry, including heat pumps and waste-heat recovery.[112,113] Replacing older air-conditioning equipment with heat pumps can improve energy efficiency for space cooling and heating, and demand-side management can reduce GHG emissions by shifting loads strategically in time.[114]

Clean hydrogen, produced with low-carbon energy, including renewable and nuclear, can help decarbonize transportation and industry (Ch. 32).[115,116,117,118,119] CCUS can reduce the carbon intensity of electricity production and combustion in industry and can be paired with bioenergy to yield additional carbon reductions.[120,121]

Rapid deployment of decarbonization technologies will create additional challenges (KM 32.2).[122,123,124] For example, vehicle electrification requires expansion of electric vehicle and battery manufacturing capacity, development of charging infrastructure, expansion of transmission, adaptation of refining operations to reflect lower demand for gasoline and diesel, and emergence of industries for recycling, repurposing, or disposing of end-of-life batteries (KM 13.4).[125,126] Vulnerabilities to climate change may increase with decarbonization; for example, a greater reliance on electricity and bioenergy could exacerbate the impacts of power outages and droughts.[85,127]

Consumer behaviors and social norms influence the adoption and actual performance of decarbonization technologies, such as home energy management systems and rooftop solar.[128,129,130,131] More efficient technologies can decrease costs to consumers, increasing activities such as driving and space heating.[132]

## *Resource Constraints*

Global disruptions, such as the COVID-19 pandemic,[133,134] cause shortages of materials and available workforce, limiting the transition to energy system decarbonization. Some energy technology supply chains, particularly solar PV and electric vehicle batteries, are more susceptible than others to resource constraints (KM 13.4).[135,136] Island communities are especially vulnerable and slow to recover when supply chains are severed by extreme events (Ch. 23).[137]

Critical materials, such as rare-earth minerals used in batteries and electric motors, are predominantly extracted and produced outside the US (Figure 17.2; Ch. 32). Geopolitical and environmental factors influence how these materials are extracted, used, and recycled (Focus on Risks to Supply Chains).[138] Securing reliable, environmentally sustainable domestic sources of critical minerals is a national priority given the growing demand for low-carbon energy technologies.[139]

Energy system expansion to meet future demands requires suitable land, which may be limited by climate change.[140] As demand for new generation and transmission grows, integrated land-use strategies are emerging to support multiple objectives, including increases in food security, local manufacturing, and energy system resilience, as well as land and water conservation. Examples include combining solar energy with agriculture or mounting solar panels on floating structures.

## *Vulnerable Communities and Equity*

Overburdened communities are disproportionately affected by climate impacts and energy injustice. These populations suffer more from power outages,[141] high energy prices, and health concerns from pollutants and wastes produced by fossil fuel power plants and refineries.[142,143,144,145] After Hurricane Ida (2021), areas with high proportions of Black residents had longer waiting times for power to be restored.[61] Indoor $CO_2$ levels associated with fossil fuel combustion have been linked to reduced human cognition (Ch. 15).[146] Overburdened communities may benefit most from decarbonization and increased energy system resilience.[147,148,149,150,151]

Extreme heat disproportionately impacts overburdened communities,[149,152] especially in urban locations where asphalt is plentiful and trees are rare.[108,153] Lower-income households that do not have or use air-conditioning are at higher health risk, such as witnessed during the unprecedented heatwaves in the Pacific Northwest (Ch. 15).[108,154]

Communities without access to reliable power are more susceptible to hazards from extreme weather events. Following Hurricanes Irma and Maria (2017), rural areas in Puerto Rico and Florida had longer power outages and slower restoration times.[141,155,156] A lack of adequate insulation accentuated effects of the 2021 winter storm in Texas on Black communities of low socioeconomic status.[157] Power outages can increase injuries and deaths from carbon monoxide poisoning through use of gasoline-powered generators, charcoal grills, and kerosene and propane heaters inside homes lacking proper ventilation.[158,159]

Energy burden (energy cost as a percentage of household income) is an indicator of community and household vulnerability.[143,160,161,162] Nationally, rural low-income households experience the highest median energy burden at 9% (with some regions as high as 15%), compared to 3% for rural middle- and high-income households and compared to lower values for metropolitan households.[163]

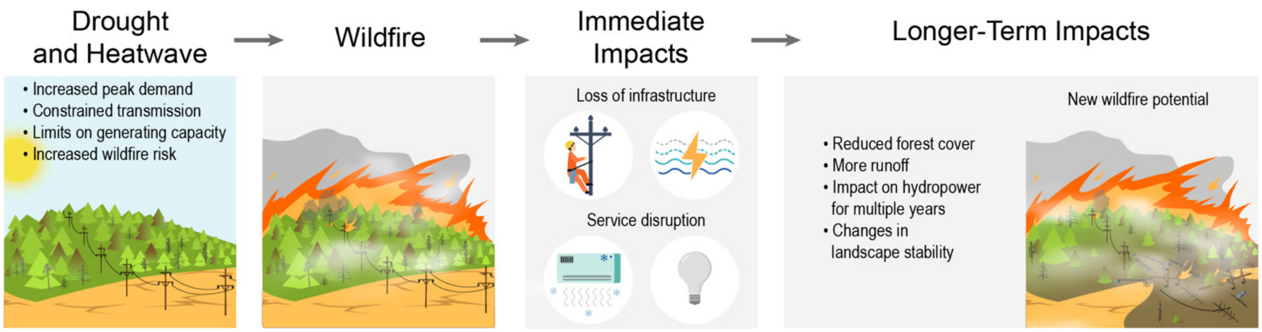
Energy inequities can be associated with lower-carbon energy sources. While the energy transition will create new economic opportunities, communities and individuals relying on employment and tax revenues from coal, oil, or natural gas can become more economically vulnerable. Individuals who held fossil fuel jobs may have difficulty finding a new job because of skills gaps, wage loss, long-distance commutes, or the need to relocate.[164,165] The number of solar and wind energy construction jobs in former coal communities may not be sufficient to replace the supply of former coal jobs.[166] Reuse of existing fossil fuel infrastructure to transition to clean energy sources may allow economically vulnerable communities to transition in place.[167] Employment and wage losses in fossil fuel sectors could be offset by increases in low-carbon resource industries,[168,169,170] although counties in Appalachia, the Gulf Coast region, and the intermountain West are expected to experience the most significant impacts, including to local services, as the tax base diminishes.[105,171,172]

## *Compound and Cascading Hazards*

Climate change poses acute and chronic hazards to the energy system and communities from coinciding or sequential trends and extreme events (Figure 5.3; Ch. 18). Climate projections for 2041–2050 show increased power demand in Texas at the same time power supply may decrease, due in part to potential decreases in renewable resources such as wind, as well as reductions in output power from thermoelectric power plants due to warmer ambient temperatures.[173] Sequential events can compound impacts if recovery has not occurred before the next event or hazard.[174,175] Vulnerable communities near Houston, Texas, were adversely affected by the 2021 winter storm before they had recovered from Hurricane Harvey in 2017.[157] Some areas may be more vulnerable to compound hazards; for example, urbanization exacerbates or combines with flooding to compound effects on coastal infrastructure.[176]

Cyber and physical risks can add to the vulnerability of the power grid to climate change and extreme weather, especially if these events coincide.[177,178] Cyber and physical attacks are sometimes intended to compound damage to the power grid caused by extreme events.[179] Multidirectional flows of data, fuels, and electricity increase vulnerabilities. Furthermore, increased renewable energy penetration and distributed energy systems (technologies that generate electricity at or near point of use) are new variables affecting risk of power outages during extreme events.[177,178] New methods are available to assess power system vulnerability to these stressors and to quantify resilience.[180]

### Consecutive and Cascading Events Involving the Energy System




**Sequential and concurrent climate impacts have near-term and long-term effects on electricity generation and distribution.**

**Figure 5.3.** Drought and heatwaves can reduce electricity generation and delivery through cascading mechanisms. Droughts reduce water availability and electricity generation. Stressed vegetation, including tree mortality following insect outbreaks, fuels wildfires. Concurrently, heatwaves increase electricity demand and reliance on transmission, which can also trigger wildfires. Wildfires damage electricity infrastructure, disrupting power and associated services. Reduced vegetation increases runoff, resulting in floods and landslides and increased risk of wildfires. The cycle of events can accelerate, as new vegetation is more sensitive to droughts and heatwaves. Figure credit: Oak Ridge National Laboratory, National Renewable Energy Laboratory, and Pacific Northwest National Laboratory.

Cascading hazards can cause additional burdens to the energy system. For example, intense rains over areas burned by wildfire are projected to increase in California, intensifying flooding challenges for energy infrastructure.[181] Summer cooling demand resulting from warmer temperatures sometimes coincides with reduced hydropower due to alterations in timing of peak streamflow.[182] Additionally, flooding followed by high temperatures that increase cooling demands can overwhelm the power grid.[183]

During the 2021 winter storm in Texas, extreme low temperatures caused high demand for electricity and fuels, equipment failures in fossil and renewable generation, and supply chain disruptions (Box 26.2).[24,85] Natural gas wells and gathering lines froze, compressor stations experienced power outages, and power plant equipment malfunctioned.[24] Disruptions to power supply and delivery triggered cascading failures in other critical sectors, including municipal water supply and medical services.[24,184] At least 210 deaths resulted from the outages and cold weather.[185]

## Key Message 5.3

## Efforts to Enhance Energy System Resilience Are Underway

Federal, state, local, Tribal, and private-sector investments are being made to increase the resilience of the energy system to climate-related stressors, and opportunities exist to build upon this progress (*very high confidence*). Ongoing investments will need to include improvements in energy-efficient buildings; technology to decarbonize the energy system; advanced automation and communication and artificial intelligence technologies to optimize operations; climate modeling and planning methodologies under uncertainties; and efforts to increase equitable access to clean energy (*very high confidence*). An energy system transition emphasizing decarbonization and electrification would require efforts in new generation, transmission, distribution, and fuel delivery (*very high confidence*).

Activities to increase energy system resilience include upgraded grid design, hardening of energy infrastructure, vegetation management to reduce wildfire[186,187] and trees falling on powerlines,[188] and clean energy microgrids for communities vulnerable to power outages.[189] Battery storage combined with solar PV can improve building resilience during power outages.[190] Strengthening natural gas pipelines, as well as conducting periodic stress evaluation and maintenance, reduces risk from subsidence.[69] Options for oil production include providing heated water systems at drill sites to prevent freezing and upgrading platform rigs to be resilient to hurricanes.[191] Multiple opportunities are available for climate risk management in the electric utility industry,[192,193,194] with some states (e.g., California, Oregon, and New York) requiring electric utilities to conduct climate vulnerability assessments (KMs 21.4, 32.5).

## *Improved Climate Modeling to Inform Planning for Energy System Resilience*

Improved accuracy, detail, and modeling capabilities are allowing high-resolution Earth system models and human–Earth system models to help decision-makers reduce vulnerabilities to climate change and inform energy system plans and operational strategies across spatial scales.[14,45,195,196,197,198] For example, identifying where storm surge may threaten energy infrastructure could lead to fortifying or moving that infrastructure.[199] Projections of the severity and duration of future droughts could guide decisions to reduce water demand for energy supply.[200,201]

Modeling advances are improving understanding of climate impacts and wildfires on transmission lines[165,202] and solar PV,[21] stream temperature for thermoelectric power plants,[52] and water availability for the production of hydropower[45] and hydrogen.[203] Model applications include estimating lost power and restoration costs from hurricane damage.[204] Studies have investigated integration of climate-related impacts into long-term planning to achieve resilience to future extreme events.[39,205,206,207,208]

Efforts are underway to understand the range of climate impacts on interconnected energy systems, including improvements to multisector models,[209,210] observations[48] and analytics,[182,211,212] and development of Earth system models with advanced climate–human feedbacks.[213] Analyses of extreme events such as the 2021 extreme cold event in Texas,[85] the cascading power outages in California in 2020, and Hurricane Maria in Puerto Rico in 2017[214] can be used to plan and design for cross-sector resilience.

## *Addressing Compound Threats*

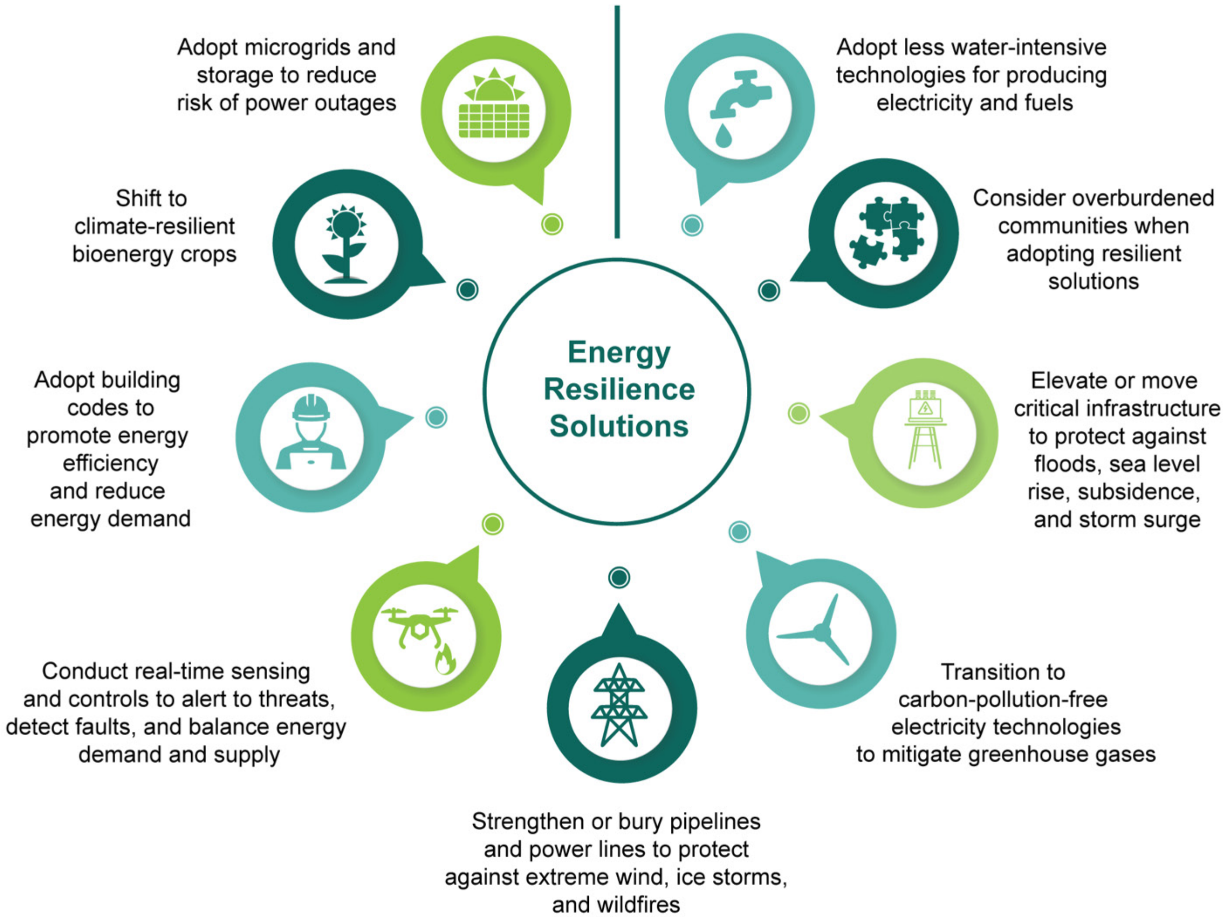
Progress is underway to develop and implement solutions addressing energy system risks from compounding impacts of climate change and threats from pandemics (COVID-19), cyberattacks,[177,215,216] electromagnetic pulse events,[85,174,176,180,217] market shocks,[218] and supply chain disruptions (KM 5.2). Examples include holistic modeling and analyses that reflect the interconnectedness of energy and water systems and the design and operation of energy systems that account for combined effects of climate trends and extreme weather events.[205,219]

## *Hardening Energy Systems to Reduce Vulnerabilities to Climate Change*

Energy system design and operations are being hardened to reduce vulnerabilities to climate change (Figure 5.4). Examples include elevating or moving equipment to avoid floods, strengthening pipelines and powerlines or moving them underground to reduce wind or ice damage and risk from wildfire, and recycling cooling water and deploying dry cooling technologies to reduce power plant susceptibility to drought.[220] Improving building codes can bring changes (e.g., grid-interactive efficient buildings, cool roofs, resilient construction materials) to the built environment (Ch. 12), enabling energy and emissions reductions (Ch. 32) and technologies (e.g., adaptive buildings, PV-ready buildings; Ch. 31) to advance resilience to climate change. Drones and sensors identify wildfire risks in real time, allowing protective actions to be taken.[221]

New tools and models are available for identifying infrastructure vulnerabilities and storm probabilities and for identifying effective hardening approaches,[214,222,223] including accelerated infrastructure investments to improve resilience of coastal systems to storm events.[224]

## Potential Energy System Resilience Solutions




**Many strategies are available to increase energy system resilience to climate change.**

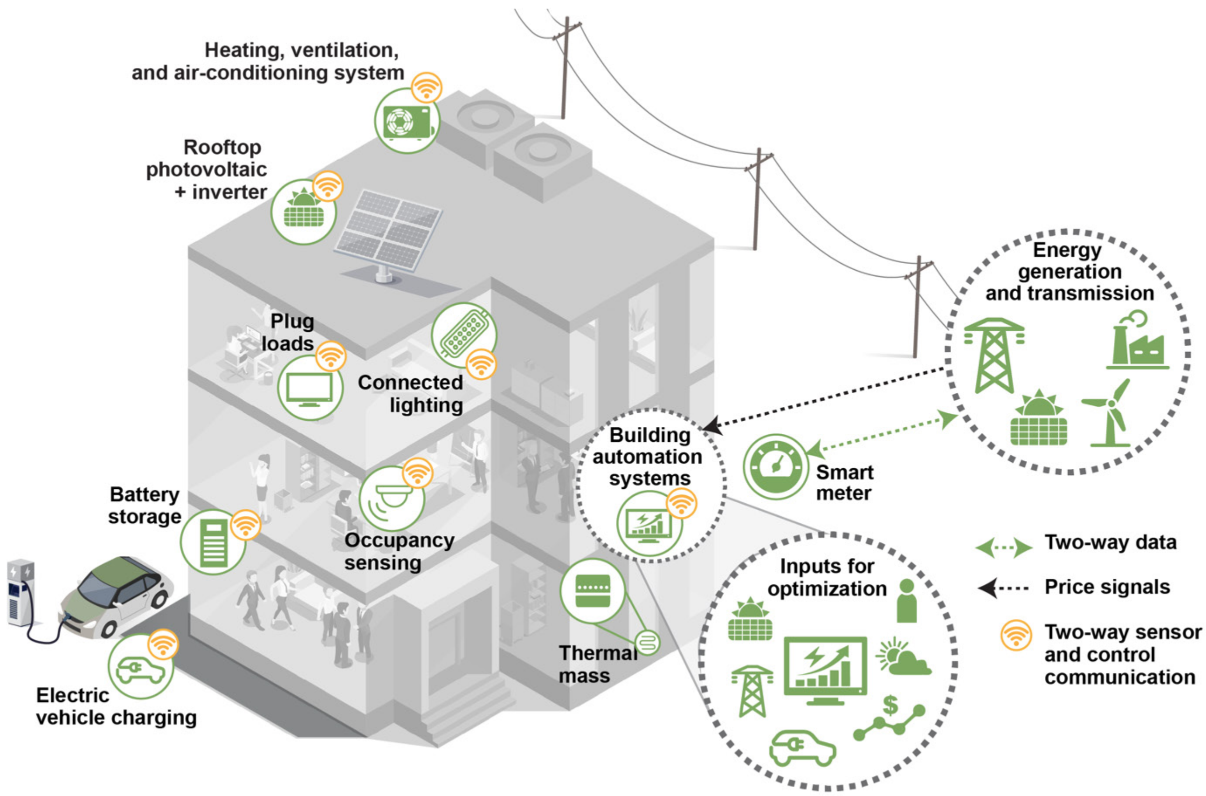
**Figure 5.4.** While climate change results in risks to the energy system, many approaches for enhancing energy system resilience are available. Resilience options include burying powerlines, elevating critical infrastructure, Introducing microgrids and distributed generation, and improved monitoring. Figure credit: EPA, FEMA, and DOE.

## *Automation, Information Technologies, and Grid-Interactive Efficient Buildings*

Advances in sensing, smart metering, and internet-connected appliances have enabled real-time monitoring of energy systems. Machine-learning algorithms are facilitating insights into energy supply, demand, and operations.[225] The electric grid can be more resilient to climate stressors if future renewable energy generation is better forecasted, operational faults are detected and diagnosed, supply and demand are balanced to account for variable generation and vehicle charging, and cyberattacks are detected.[226]

Grid-interactive efficient buildings (Figure 5.5) apply energy efficiency, smart technologies, and flexible load management.[227] Advanced control systems[228,229] predict energy demand in real time and maximize efficiency, minimize cost, and lower carbon emissions of HVAC systems. Application of natural gas demand response to residential heating during extreme cold conditions is projected to reduce demand by up to 29%.[86] By reducing and shifting the timing of electricity consumption, grid-interactive efficient buildings could decrease carbon emissions by 80 million metric tons per year by 2030, or 6% of total power sector carbon emissions.[227]

### Grid-Interactive Efficient Buildings




**A reimagination of building design and operation is being driven by decarbonization goals.**

**Figure 5.5.** Grid-interactive efficient buildings (GEBs) integrate energy efficiency technologies (HVAC, plug loads, lighting), on-site renewable energy (photovoltaics), electric vehicles, and electric storage with smart sensing (HVAC, lighting, and occupancy) and control optimization to enable demand flexibility and provide excess electricity to the power grid through the smart meter when demand exceeds supply or when supply from the grid is constrained. The building automation systems can import the grid electricity pricing and carbon-intensity factor in real time and communicate the potential to reduce demand to the grid through the two-way sensor and communication protocol. Adapted from Nubbe and Yamada 2019,[230] © 2019 Guidehouse Inc.

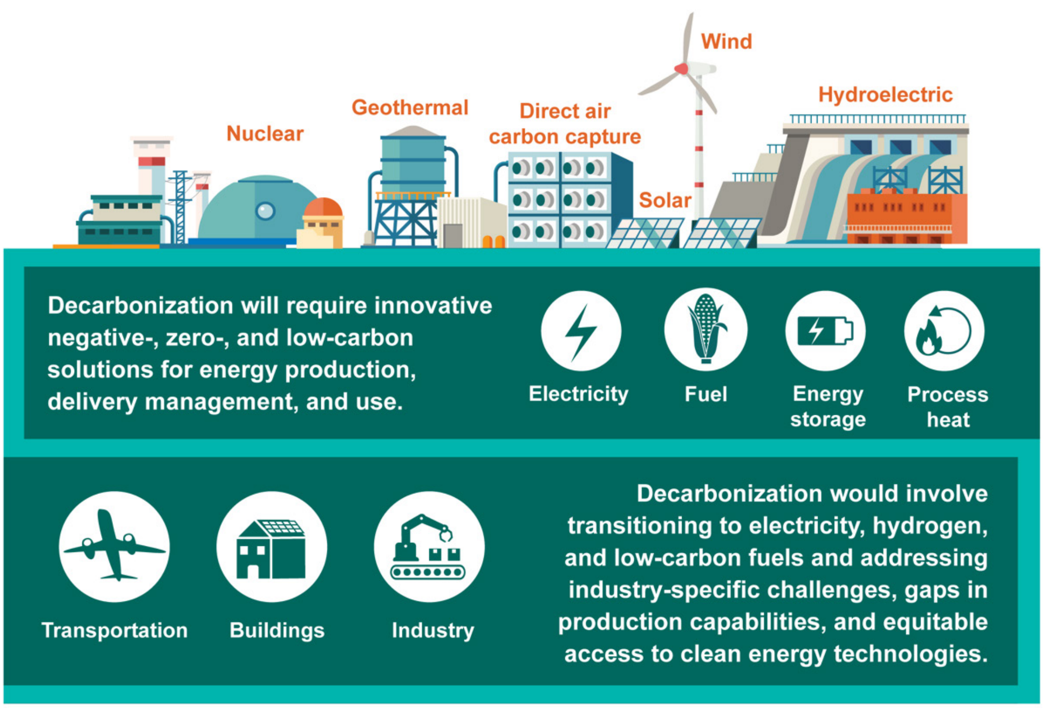
## *Technology Development and Deployment to Decarbonize the Energy System*

A major transition is underway to decarbonize major economic sectors (Figure 5.6),[231,232,233] supported by policies (e.g., mandates to reduce fossil fuel use, tax incentives), falling costs, and technology innovations. Significant advancements in low-carbon energy technologies have been made in the electricity sector.

Growth in electric power demand is projected due to increasing electrification and ongoing economic growth. Declining capital costs and government subsidies, including IRA initiatives, are projected to drive increasing renewable energy generation from solar and wind by about 325% and 138% respectively, by 2050 as compared to 2022.[3] Increased electrification of end-use sectors is projected with the adoption of more heat pumps and electric vehicles, as well as electric arc furnaces in the iron and steel industry.

Some technologies can provide energy benefits to other sectors. For example, nuclear power produces thermal energy that can be used in industrial applications, substituting for fossil fuels. In addition to reducing energy-related emissions, electricity may be more reliable, efficient, and economical compared to other energy sources.[95] High electrification rates could be supported by greater integration of renewables.[93,234]

### Energy System Decarbonization

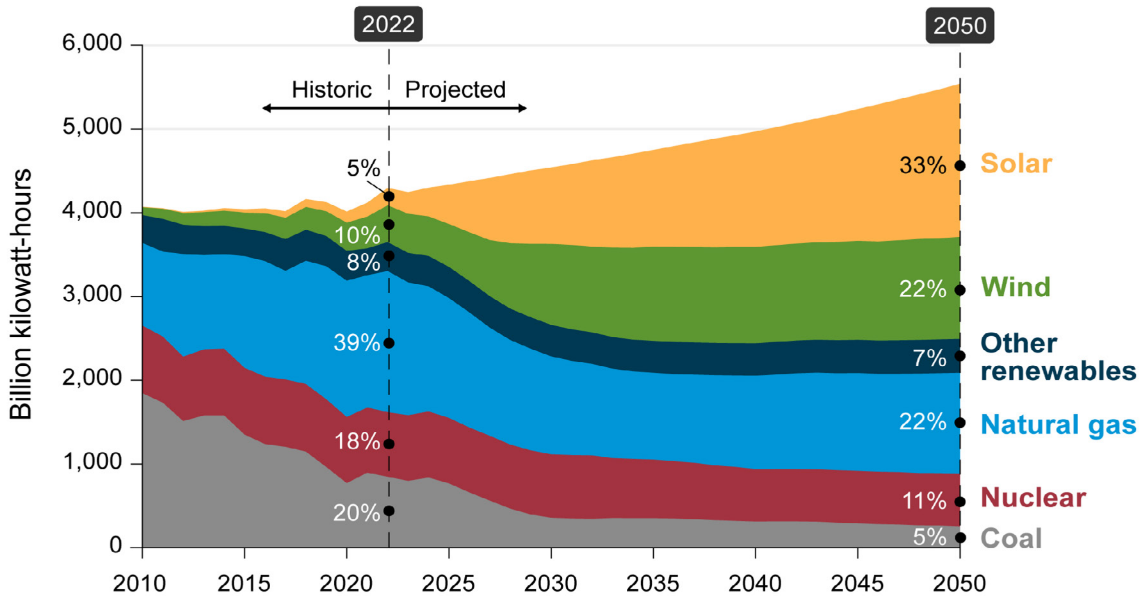



**Decarbonization will require innovative solutions across multiple sectors.**

**Figure 5.6.** Energy system decarbonization will rely on increased innovation, deployment of clean energy technologies including carbon capture, small modular nuclear reactors, hydrogen, and further integration and electrification of residential and commercial buildings, industry, and transportation. Figure credit: DOE, Idaho National Laboratory, NOAA NCEI, and CISESS NC.

With wind and solar costs dropping 70% and 90%, respectively, over the last decade, capacity additions are reaching historic levels[235] and are projected to increase (Figure 5.7).[3,112,236] Advances contributing to cost reduction include technological advances, improved efficiency in energy generation and manufacturing, reduced capital costs, and accumulation of operational experience. However, greater transformation is needed to meet goals of 100% clean electricity in 2035 and net-zero GHG emissions by 2050.[237] Meeting both goals requires electrification of transportation, buildings, and industry and production of low-carbon electricity from renewable, nuclear, and fossil fuel energy with carbon capture.[112,123,238] The rate of decarbonization will be determined, in part, by public acceptance of new energy technologies and infrastructure.[239]

## Historic and Projected US Electricity Generation Sources




**The Nation's electricity grid continues to expand use of clean energy technologies.**

**Figure 5.7.** Most electricity generation projections see significant growth for renewable sources. Recently enacted legislation is anticipated to increase deployment rates for low-carbon technology. Adapted from EIA 2023.[3]

Advances are being made in performance and cost for other energy technologies. Over the last decade, costs of lithium-ion batteries for electric vehicles have dropped 85%,[240] and progress is being made to recycle batteries and develop alternative materials beyond lithium. Efforts to lower production costs for clean hydrogen by 80% to $1 per kilogram could unlock new markets and create jobs in industries such as steel manufacturing, clean ammonia production, energy storage, and heavy-duty trucks.[241]

Demonstrations for advanced small modular nuclear reactors have begun with design approval from the US Nuclear Regulatory Commission,[242] as well as efforts to use existing nuclear power plants and fossil-fueled power plants with carbon capture to generate clean hydrogen and purify water in addition to producing electricity.

## Solutions for Vulnerable Communities and Energy Justice

Policies related to energy system decarbonization can promote energy equity. Procedural justice, which relates to equitable participation in and influence on energy decisions,[243] is key to equitable energy solutions. Opportunities to promote energy equity and reduce energy burdens include collective, inclusive decision-making around utility-initiated power shutdowns; adopting energy storage with decentralized solutions, such as microgrids or off-grid systems;[73] developing community-sharing opportunities for solar energy (including rooftop solar) and energy storage;[144,244] and building emergency cooling or heating shelters to serve overburdened communities.[245] An example of a Tribal community addressing a just transition from fossil fuels to renewable energy is the Blue Lake Rancheria Tribe's large-scale solar and microgrid project.[223,246]

Many decarbonization technologies are expected to decrease environmental impacts such as air pollution (KMs 14.5, 32.4),[247,248,249,250] potentially benefitting overburdened communities that disproportionately experience pollution from roadways, refineries, and power plants.[251,252,253] However, impacts of some decarbonization technologies can shift the magnitude, location, and type of pollution (KM 32.4).[254,255,256,257] Environmental regulations and permitting requirements play an important role in addressing impacts.

Energy burden remains high for overburdened groups. Many policies and programs that promote clean energy or energy efficiency are inaccessible to low-income households.[258] Policies that fix energy prices during extreme events or prioritize energy restoration for overburdened communities can provide more equitable support.[184] Federal assistance programs can help communities overcome climate challenges and enhance resilience (Ch. 31).[259] In addition, federal programs are being established to promote energy equity and serve overburdened communities.[260,261]

# Traceable Accounts

## *Process Description*

The author team was selected to bring diverse experience, expertise, and perspectives to the chapter. Some members have participated in past Assessment processes. The team's diversity appropriately reflects the spectrum of current and projected climate impacts on the Nation's complex energy system, the energy system's roles in national security and economic well-being, and the need for equitable access to reliable and affordable energy and environmental justice. The all-federal composition of the author team was a decision of the National Climate Assessment (NCA) Federal Steering Committee. The author team has demonstrated experience in the following areas:

- characterizing baseline supply and demand for electricity and fuel from diverse sources at multiple scales;
- characterizing effects of climate on the energy sector—as well as opportunities for climate change mitigation and options for increasing resilience to climate-related stressors—at national, regional, state, and local levels;
- developing and implementing energy system models for projecting technology deployment, fuel use, and greenhouse gas (GHG) and air pollutant emissions over wide-ranging scenarios;
- analyzing energy system sensitivities to drivers such as policy, markets, technology, and physical changes;
- developing and implementing climate science models, tools, and information for characterizing energy sector risks;
- supporting local, state, Tribal, federal, and private-sector stakeholders in integrating climate change issues into long-range planning and project implementation;
- assessing the environmental impacts of new and emerging energy technologies; and
- analyzing technological, societal (including justice), economic, and business factors relevant to risk reduction and energy system resilience.

The author team met virtually on a weekly basis to develop the chapter, address issues, and build consensus. In addition, the team met with representative authors from other chapters to identify and address cross-cutting issues. To ensure the chapter is informed by and useful to stakeholders, a public engagement workshop was held to provide participants an opportunity to exchange ideas with the author teams on chapter key topics, share resources, and give feedback on issues of importance to them. Participants in the workshop represented government (federal, state, local, and Tribal), nonprofits, academic institutions, businesses and the private sector, community groups, students, and others.

To develop Key Messages, the team conducted searches of the scientific literature, including peer-reviewed journal articles, government reports, and reports of nongovernmental organizations, as well as incorporating input from the workshop. The team drew on measurements (e.g., data on ongoing effects of past extreme events and government energy data); model outputs (e.g., from climate models, models of energy supply and demand, models of climate effects, and models of resilience of climate change stressors on the energy system); published perspectives of experts, some of which identified sources of uncertainty; and input from the workshop and from peer reviewers of this chapter. The chapter does not reference newspaper articles.

## Key Message 5.1

## Climate Change Threatens Energy Systems

### Description of Evidence Base

The impact of increased concentrations of greenhouse gases (GHGs) on global warming (Ch. 2) and sea level rise (Ch. 3) is well established in the peer-reviewed research and supporting publications, and the impact of climate change on extreme events is growing (Ch. 3). Mechanisms by which climate change impacts energy infrastructure and electricity demand also have a strong research foundation, with extensive documented analyses of climate trends and past extreme events, as well as peer-reviewed research on projected impacts that uses empirical data[262] or downscaled climate projection data[29,263] and detailed models of possible future energy system designs.[264] One new study linked the output of global climate models to a weather forecasting model to project regional energy effects.[32] The importance of extreme events has required new types of empirical models, some of which are integrated with climate models or outputs (e.g., the relationship between smoke and photovoltaic capacity or productivity).[21,22] Historical data on hurricanes are combined with ocean models to better understand variables important to offshore wind energy.[13] New econometric models based on weather variables, consumption data, and population growth estimates are also important components of the evidence base related to electricity demand projections.[103] There is strong agreement in the literature on mechanisms and types of electricity demand impacts,[265] although impacts are expected to differ by location.[103] The magnitudes of projected energy system impacts are dependent on the magnitude of climate change and the increased rate, magnitude, and location of extreme events (KMs 23.4, 27.4). There is a foundation of regional-level studies on how the energy system is being impacted and is projected to be impacted[31,32] and, ultimately, how those impacts may affect energy users locally. Where and when these impacts will occur locally is much harder to model in the context of temperature and precipitation trends and especially in the context of extreme events than at the more regional and continental scales.[8]

### Major Uncertainties and Research Gaps

Much of the key evidence related to extreme events is empirical and opportunistic. Although significant data are available to document the effects of extreme events on energy systems, those data and analyses are typically published two to four years after the event. For example, at the time this report was written, important papers were still being published on infrastructure and energy justice effects of Hurricanes Harvey, Irma, and Maria in 2017.[82,141,155,157] Most analyses of the impacts of Hurricane Ida in 2021 will not be available for several years, although Coleman et al. (2023)[61] is an exception. Opportunities exist for more timely assessments of major impacts of extreme events on energy systems to inform relevant policy discussions, investments, and efforts to increase energy system resilience and human adaptation.

There is more confidence in national projections of climate variables and extreme events than in estimates of local impacts. Therefore, the authors are confident that the frequency and intensity of extreme events will increase nationally (Ch. 2) but not as confident in the locations of specific events that may impact energy supply and demand over the coming decades.[13,266] Similarly, projections of wind power are only as good as the often-coarse spatial and temporal resolution of the climate models used.[31] The authors are confident that the demand for cooling buildings in summer will increase in most regions across the continental United States.[103] In studies where climate projections are downscaled, computational demands and data storage requirements limit the number of projections that can be used and therefore increase uncertainty, as recognized by cited authors.[263] Cost projections for physical damages to infrastructure do not include those from floods, high winds, and ice storms, which are poorly represented at the coarse spatial scale of climate models.[57]

Furthermore, in the studies cited, there is sometimes disagreement among researchers. Whereas emerging research suggests that the frequency of cold-weather events and heavy snowfall may be increasing because of warming Arctic temperature,[267] there is some disagreement in the research community[268,269] regarding this projection and the impact such a change may have on increasing or decreasing future heating demands regionally. Furthermore, there is uncertainty regarding future wind resources and trends.[31,262,270]

Many model inputs are uncertain. For example, potential bioenergy projections are dependent on uncertain $CO_2$ fertilization intensity.[30] Furthermore, projections of electricity and natural gas demand are sensitive to socioeconomic factors, such as the ratio of urban to rural population or changes in energy prices that may reflect the pace of shifts in energy technologies.[103]

### Description of Confidence and Likelihood

Based on historical data, recent trends, modeling projections, and attribution analytics, there is *very high confidence* and it is *virtually certain* that climate change and extreme weather are negatively impacting the Nation's energy system and that, unless action is taken, climate change will continue to affect the energy system, including damaging energy infrastructure and operations. There is *very high confidence* that energy supply and delivery are at high risk from climate-driven changes,[271,272] including shifts in demand,[45,273] damage to infrastructure and operations,[271,274] and resulting effects on human lives and livelihoods. It is *virtually certain*, based on past experience and modeling projections, that climate change trends will continue (Ch. 2), and effects on energy systems will vary over time and location and increase with projected increases in the frequency, intensity, and duration of extreme weather threats, including extreme precipitation, extreme temperatures, sea level rise, and more intense storms, droughts, wildfires, and thawing of permafrost.

## Key Message 5.2

## Compounding Factors Affect Energy-System and Community Vulnerabilities

### Description of Evidence Base

#### Decarbonization

There is growing evidence from peer-reviewed analysis demonstrating both the need for and progress in decarbonization of the energy system through increased electrification and applications of clean energy, including wind and solar; hydrogen, bioenergy; modular nuclear; geothermal; hydropower; other long-term storage; and carbon capture, utilization, and storage (Ch. 32).[95,96,109,110,111,112,113,114,115,117,118,119,121] However, additional studies are needed to better characterize how the rapid deployment of decarbonization technologies will create additional compounding challenges (KM 32.2),[122,123,124] including the need for additional energy infrastructure associated with expansion of electrification demand (including generation, transmission, and distribution), expansion of electric vehicle and battery manufacturing capacity, development of charging infrastructure, adaptation of refining operations to reflect lower demand for gasoline and diesel, and emergence of industries for recycling, repurposing, or disposing of end-of-life batteries (KM 13.4).[125,126] More information is also needed to better characterize consumer behaviors and the cost and performance of decarbonization technologies, which will influence the pace, scale and scope of their adoption by society.[128,129,130,131,132] Opportunities exist for better characterizing the co-benefits of both reducing GHG emissions and increasing climate resilience through decarbonization, including, for example, quantifying the benefits of deployment of distributed clean energy generation with microgrids and storage that reduces emissions and provides backup generation during power outages.

#### Resource Constraints

Whereas there is abundant research and industry knowledge on global supply chain dynamics, commodity markets, and strategic materials, there is less peer-reviewed literature focusing specifically on the current and anticipated future supply chain and resource constraints associated with those parts of the energy system that are gaining, or anticipated to gain, greater market share in the energy economy, including electric vehicles, wind and solar energy, and battery storage. Research is lacking in this area, including on the relationships and sensitivities across parts of the energy sector that may be competing for the same source materials, as well as on the potential for alternative materials or processes that may help address supply chain constraints or risks, particularly where sectors other than energy may be competing for similar feedstocks, materials, or personnel.

### Cyber and Physical Threats to the Power Grid

A growing body of peer-reviewed research related to cyber/physical security argues for the joint consideration of climate change and cyber/physical attacks in grid analyses and resilience responses.[177,178] However, many data-driven analyses of actual system incidents, response measures, and defenses are not publicly available and therefore are not referenced. There is growing research on human and environmental threats to the power system, how they relate to each other, and how multiple objectives like decarbonization of the energy system, system resilience to climate stressors, and cyber defenses can be optimized as the energy generation mix changes and threats evolve across the grid and other energy infrastructure.[177,178]

As with cybersecurity, a significant amount of non-peer-reviewed analysis related to compound and cascading hazards and threats is occurring in the classified domain, particularly in those cases that involve a human threat or cyber incident. Furthermore, anecdotal news reports refer to consecutive extreme events, but insufficient peer-reviewed evidence is available to indicate whether some of these compound threats are increasing, that there is a causal association between them, or that they have a compounded effect on energy systems. In addition, while information is available on characterizing the benefits of a smart grid system that can automatically reroute power to electrical systems that are most needed to minimize impacts of outages, opportunities exist to better characterize the unintended consequences of a smart grid system and its increased susceptibility to extreme weather and cyber threats.

### Vulnerable Communities and Equity

An abundance of peer-reviewed research on environmental justice relates to the placement of fossil fuel power sources and resultant air pollution[145] and health threats in or near overburdened communities. A growing body of evidence shows that overburdened communities are disproportionately affected by the impacts of climate change, including resource-constrained abilities to migrate and low access to high-quality infrastructure such as air-conditioning.[275] Furthermore, inequitable exposure to heat islands in cities is addressed by analysis in the peer-reviewed literature.[149,152] More information is available on inequities in electricity delivery (e.g., energy access, energy burden,[162] and electricity restoration times[61] than on inequities in supply or on differential demand (including cooling-system-use temperatures[154]) in response to climate change and extreme events.

### Compound and Cascading Hazards

There is a growing body of peer-reviewed research focused on understanding climate, ecosystems, and human systems and implications for the energy system. Notably, significant progress has been made over the last decade to better understand the agriculture–energy–water nexus, correlated risks in these three domains, and strategies to address them. Multiple extreme events and other climate-related stressors are affecting the same regions; for example, wildfire may be followed by floods,[181] and multiple hurricanes may affect a single coastal location.[157] Climate projections show that increased demand and decreased supply of electricity will coincide in regions during heatwaves.[173] Recent extreme heat (e.g., Turner et al. 2021[55]), extreme cold (e.g., Busby et al. 2021[24]), and flooding (e.g., Collins et al. 2019[147]) events in Texas, for example, have helped advance a growing body of research to understand the relationships between the electric grid, fuel supply and infrastructure, and market design and pricing, as well as how humans respond to real-time extreme events and how overburdened communities are disproportionately impacted.[157] These are complex, dynamic systems. While emerging multidisciplinary modeling frameworks are improving the understanding of dynamics of multisectoral systems that include energy, many opportunities exist for improving these frameworks, including improving spatial and temporal resolution, sectoral detail, cross-sector interactions, representation of factors impacting energy and environmental justice, and utilization of high-performance computing to address data and computational requirements.[174,176]

## Major Uncertainties and Research Gaps

Increased multidisciplinary and cross-sectoral analysis and research can lead to an improved understanding of the compound and cascading hazards across the energy system. Because cascading threats are correlated, they may be easier to predict than compound threats, which are independent.[176] Data-driven analysis could be undertaken to inform the understanding of complex-system dynamics impacting climate risks and vulnerabilities in the energy sector that involve human behavior, markets, infrastructure, electricity, fuels, and environmental conditions.

Energy justice research results are sensitive to spatial scales of analysis.[239]

The limited sample size of localities, regions, or sectors that have achieved their decarbonization or electrification goals to date limits information that can inform analyses of climate implications for the energy system. The majority of peer-reviewed research does not address past or current efforts but rather is forward-looking, addressing potential implications and opportunities. There is a pressing need for greater insights on the near-term localized impacts of decarbonization efforts on aging distribution networks, particularly where electric vehicle penetration is growing rapidly.

Research gaps include the need to better understand global supply chain implications and relationships across those technologies or materials that will be important for mitigating climate change and increasing resilience of energy systems to climate-related stressors and events. There is also a need to better understand other resource constraints informing rapid scaling of decarbonization strategies, such as land-use optimization and trade-offs, infrastructure constraints, human dimensions of energy transitions including workforce development, and pathways for developing and using alternative feedstocks or materials, particularly those that may mitigate geopolitical or security risk. There is uncertainty regarding how cascading events will change in the future, how human activities will alter the risk of compound events, and how new infrastructure design guidelines might alter risk.[174]

Cross-fertilization of research between utilities and industry, classified domain research, and public peer-reviewed research could help researchers better understand current and future cyberthreats to the energy system, including how and where those threats may exacerbate or exploit climate change–related risks.

## Description of Confidence and Likelihood

Based on a growing body of evidence, including recent trends and peer-reviewed research, there is *very high confidence* that compound and cascading hazards—many of them climate related[175,179,181]—and compounding effects of changes in technologies, policies, and markets will continue to impact the climate change vulnerability of the Nation's energy system. It is *very likely* that energy system decarbonization and increased electrification will create new and growing demands on existing electricity infrastructure and will require significant investment in new generation and delivery.[124] While these changes will reduce dependency on fossil fuel sources, it is *very likely* that, unless addressed, they will result in increased vulnerabilities and supply chain constraints.

## Key Message 5.3

## Efforts to Enhance Energy System Resilience Are Underway

### Description of Evidence Base

Much of the evidence for this key message is qualitative, with citations in the main text. For example, energy resilience options and decarbonization technologies are described in the main text with no additional evidence here.

Evidence that efforts for energy systems are underway include legislation and states' recommendations. Overall, the energy sector is leading the way on decarbonization of the economy, with 22 states, the District of Columbia, and Puerto Rico having enacted legislation to reach 100% clean energy goals.[276] Integrated resources plans (IRPs) are required from electric utilities in 33 states that work with partners on the development of adaptation framework specific to the electric utility sectors.[277] The US Environmental Protection Agency State Energy and Environment Guide to Action[278] provides guiding framework on how to represent climate change to utilities IRPs. Cooke et al. (2021)[279] reviewed best practices in consideration of climate change of IRPs in 40 electric utilities across the US, admitting an increased level of complexity in the process. While IRPs are not legally bounding, some states such as California and New York made legislation of some recommendations. State-scale vulnerability assessments are also leveraged to develop legislation (KMs 21.4, 32.5).

The reduction of uncertainty of future climate projections is essential for future planning, human adaptation, and increasing energy system resilience, and a number of studies have demonstrated progres s.[195,196,201,209,210,280,281,282,283,284,285] Fragility curves of damage to power generating stations (coal, gas, solar, wind) and electrical grid components, as well as replacement and repair costs under hurricane scenarios, have also been developed.[204] Even in contexts where climate projections are uncertain, modeling advancements are helpful for planning; for example, modeling synthetic storms provides extreme wind and wave loads required for planning of offshore wind energy.[14]

Research is ongoing to identify needs for hardening[24] and to reduce the vulnerability of conventional energy system technologies to climate change.[191] For example, a range of studies reflects ongoing efforts by the oil and gas sector to address the challenge of a warming climate in Alaska, including technological improvements implemented in seismic exploration, operation and maintenance practices, and other improvements (e.g., use of thermosiphons, or cooling devices that will chill the ground beneath oil and gas infrastructure to provide protection from the dangers of thawing permafrost).

Significant innovations and deployment of zero-carbon electricity generation technologies are occurring, including in solar photovoltaics and on- and offshore wind. The costs and performance of batteries and long-term storage also are improving as their capacity grows to support the integration of renewables.[190] Advanced nuclear technologies (small modular reactors and microreactors) are now being demonstrated. Studies demonstrate innovative research, development, demonstration, and deployment to address large-scale carbon management. These include applications of CCUS at power plants and industries, as well as an expanding focus on carbon dioxide removal from the atmosphere through direct air capture and bioenergy with carbon capture and storage.[286,287] In addition, advances in low-carbon fuel sources can complement clean electricity, such as hydrogen (i.e., made from natural gas with CCUS or by electrolysis of water using zero-carbon electricity sources) to replace the role currently played by natural gas.

On the demand side, there is evidence of progress in reducing carbon through electrification. This evidence includes increased marketing and sales of electric vehicles and deployment of charging stations.[115,288] In addition, federal policies (e.g., efficiency and emission standards) and incentives (e.g., electric vehicle tax credits) appear to be succeeding in reducing use of fossil fuels. Furthermore, power companies are evaluating how electric vehicles can improve resilience of the electric grid to extreme events by providing backup power during power outages.

Studies demonstrate how new technologies, cost reductions, and a range of enabling state and federal policies are contributing to the transition to a clean energy system (Chs. 25, 32).[4,5,7,8,9,10,11] However, there is inconsistency in the adoption of these policies across the Nation. For example, some states and local communities are adopting building codes, incentives, and bans to shift to clean energy sources,[10,11] while other states are adopting polices that would prohibit actions necessary to reduce GHG emissions, such as prohibiting restrictions on the use of fossil fuels. While progress is underway, actions vary from state to state in establishing an enabling policy framework to increase the pace, scale, and scope of the energy transition to deliver more clean energy and build a more resilient energy future.

## Major Uncertainties and Research Gaps

Research on energy resilience, including current approaches and future methods, has gaps. Much of the resilience and long-term power planning research to date has included case studies developed in silos, and there is a need to further integrate the range of models and associated recommendations on decision-making.[289] For example, effects of increased renewables penetration on electricity system resilience, including planning, response, and restoration, are not well studied.[177] Information is limited on the implications of measures that communities are using to increase resilience to extreme events. During power outages, remote or island communities often turn to backup diesel generation for increased power. However, data on the types of measures employed and costs and benefits associated with these backup options are often lacking in current analyses. Research efforts more specific to power system models include the development of next-generation tools to create multiscale cross-domain dependencies with a strategic computational efficiency for faster adoption, which will enhance the ability to plan for the unpredictable including extreme events and cyberattacks.[289]

Much effort is ongoing in the development of Earth system models that could inform the energy sector, including the regional refined mesh capabilities to enable high-resolution simulations in the region of interest in global settings.[290] In addition, while progress has been made in the energy–environmental–social science modeling, gaps remain in understanding the complex interactions.[210] Potential areas for study and development include the energy–water nexus. Specifically, technology innovation research includes cost-competitive desalination technologies, transforming produced water to a reusable resource, reducing water impacts in the power sector, increasing resource recovery from wastewater, and developing small, modular energy–water systems.[291] Projections of future energy infrastructure under current policies as well as decarbonization pathways now systematically investigate water demands across sectors,[292] as different technologies rely on either water withdrawals or consumptive use with complex interactions and coordination with other water uses. Higher-resolution modeling is needed to address regional institutional priorities and vulnerabilities.[293]

Energy justice is a relatively new research area. Whereas researchers are beginning to record and analyze distributional injustices (e.g., differential times to power restoration for different communities),[141,155,156] the lack of understanding of supply differences and vulnerability differences limits the ability for utilities and governments to study and develop fair policies and responses. Furthermore, data at finer resolution than the census tract scale are often not available; therefore, local distributional injustices are more uncertain than injustices occurring at larger spatial scales.

Considerable research is being conducted using energy system optimization and integrated assessment models to understand the environmental impacts of various climate change mitigation strategies, including on co-emitted pollutants and air quality,[247] as well as on labor and crop impacts.[294] While these studies tend to suggest air quality benefits associated with decarbonization, some suggest that there could be shifts in the location of pollution and potentially the introduction of new sources of air pollution.[257] Opportunities exist to improve our understanding of the air pollutant emissions associated with decarbonization technologies, the degree to which these emissions can be controlled, and the role of permitting and environmental regulations on influencing siting and control decisions. There are also opportunities for more fully understanding how the resulting changes affect vulnerable populations, such as how changes in air-pollutant emissions result in changes in neighborhood-scale impacts.

Life-cycle analysis methods can be used to provide insights into the relative environmental benefits of alternative climate change mitigation technologies and pathways, including the impacts of manufacturing energy technologies and the construction of energy infrastructure.[295] A research gap in more fully understanding environmental impacts of energy transitions could be addressed by linking life-cycle analysis methods with energy system and integrated assessment models.[254,296]

## Description of Confidence and Likelihood

Research by authors in government, academia, and the private sector has produced evidence that allows the authors to conclude with *very high confidence* that enhancements in the resilience of the energy system to climate-related stressors are being made, including improvements in energy-efficient buildings; technology to decarbonize the energy system; advanced automation and communication, artificial intelligence, and machine learning technologies to optimize operations; climate modeling capabilities and planning methodologies; efforts to increase equitable access to clean energy; and federal support to communities for resilience investments. There is *very high confidence* that opportunities exist to build upon these efforts and that increases in the pace, scale, and scope of these efforts would be needed to meet the climate crisis.[87,232,233,236]

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