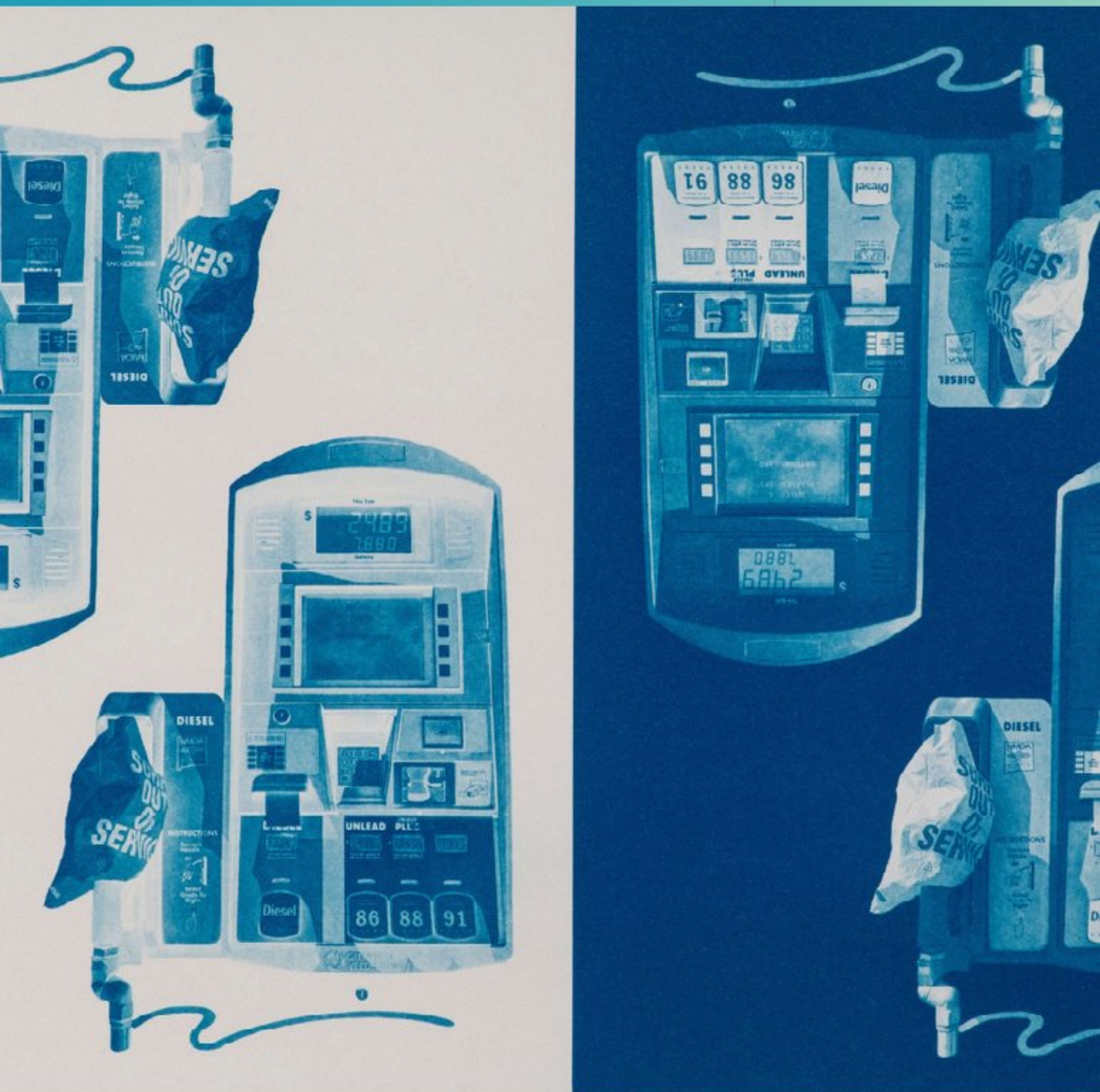


Energy Supply, Delivery, and Demand



Chapter 5. Energy Supply, Delivery, and Demand

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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 Law⁴ 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.

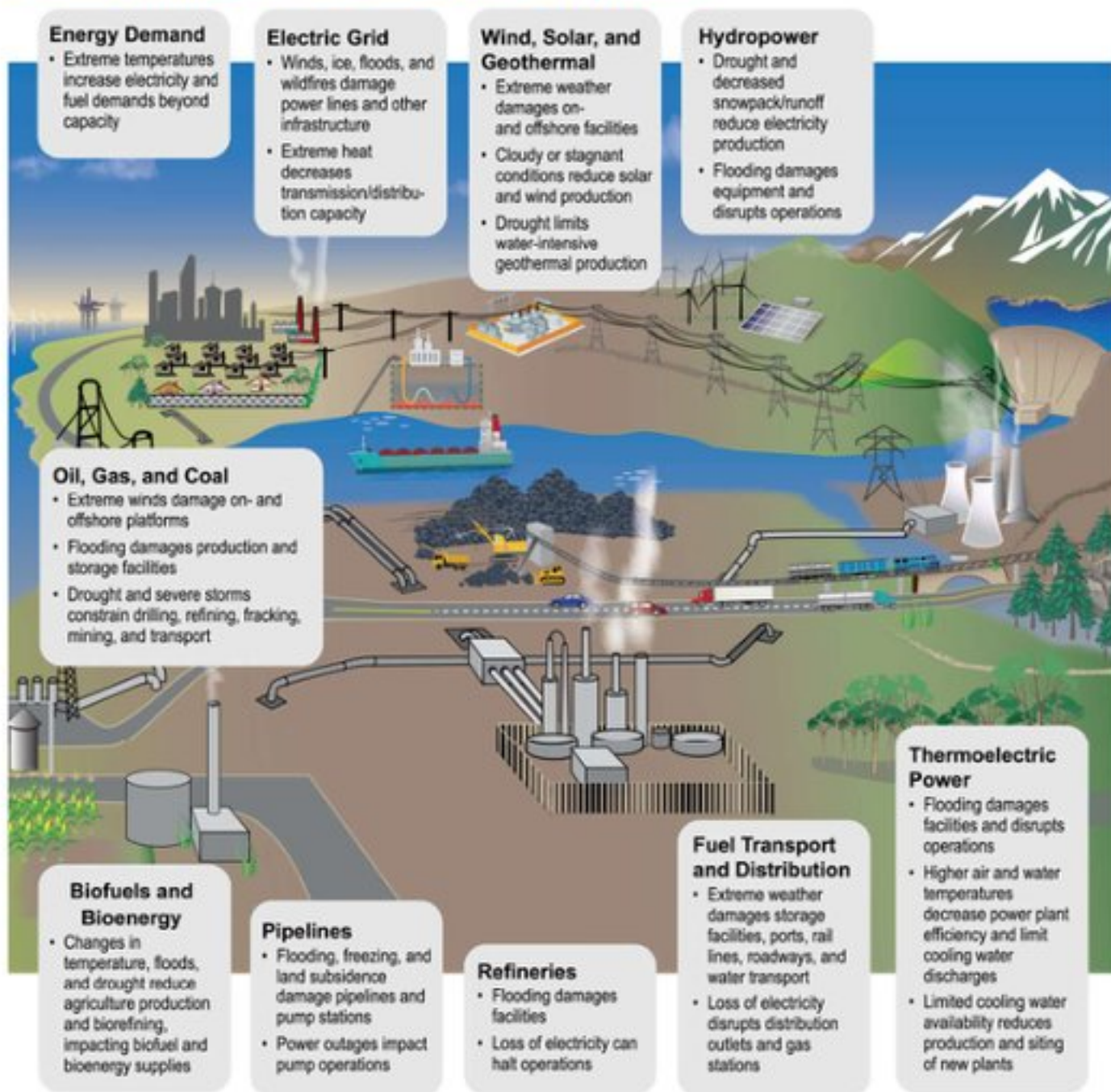
Key Message 5.1

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 ice⁶⁷ 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}

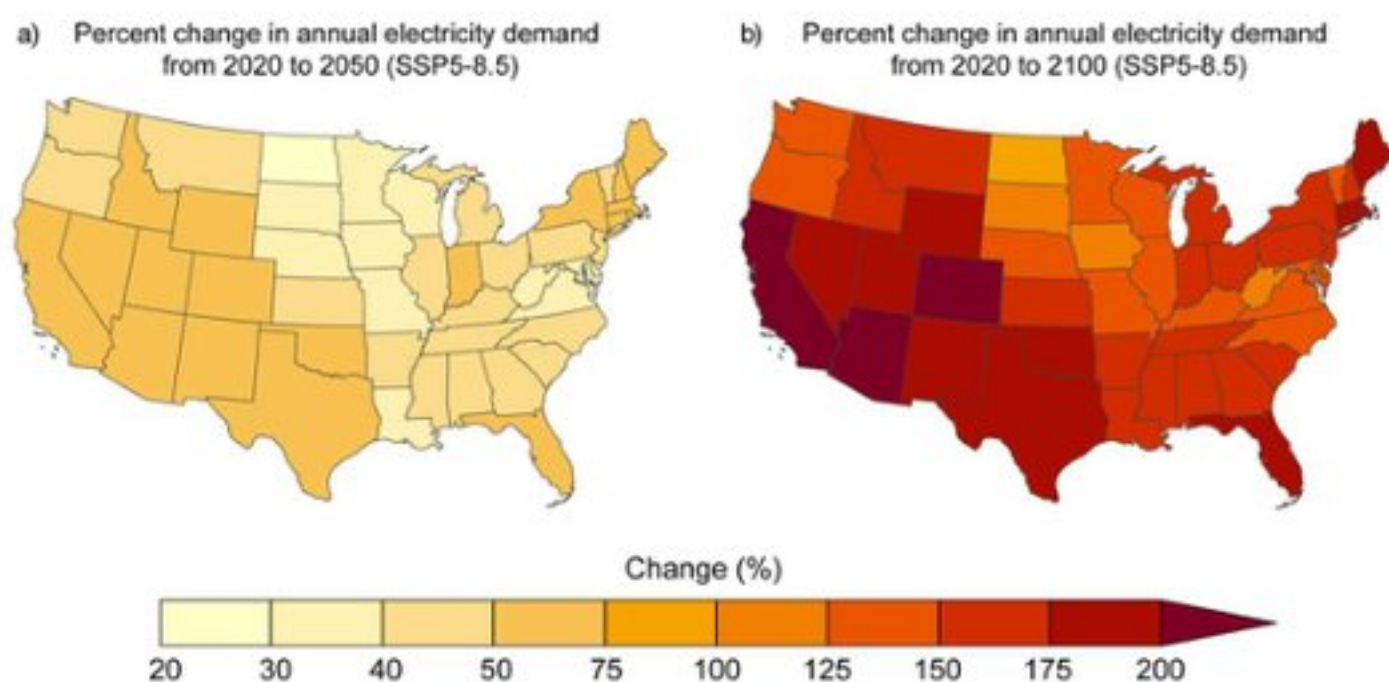
Although climate change often increases risks to energy production and delivery, warming temperatures have mixed effects on oil and gas production in cold regions. Warming benefits offshore production and shipping of petroleum products off the Alaska coast by decreasing sea ice and opening shipping routes. 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 CO₂ 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 forecasts⁹⁷ 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, Hawaii 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 CO₂ 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 hydropower⁴⁵ 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} observations⁴⁸ 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 2017²¹⁴ can be used to plan and design for cross-sector resilience.

Addressing Compound Threats

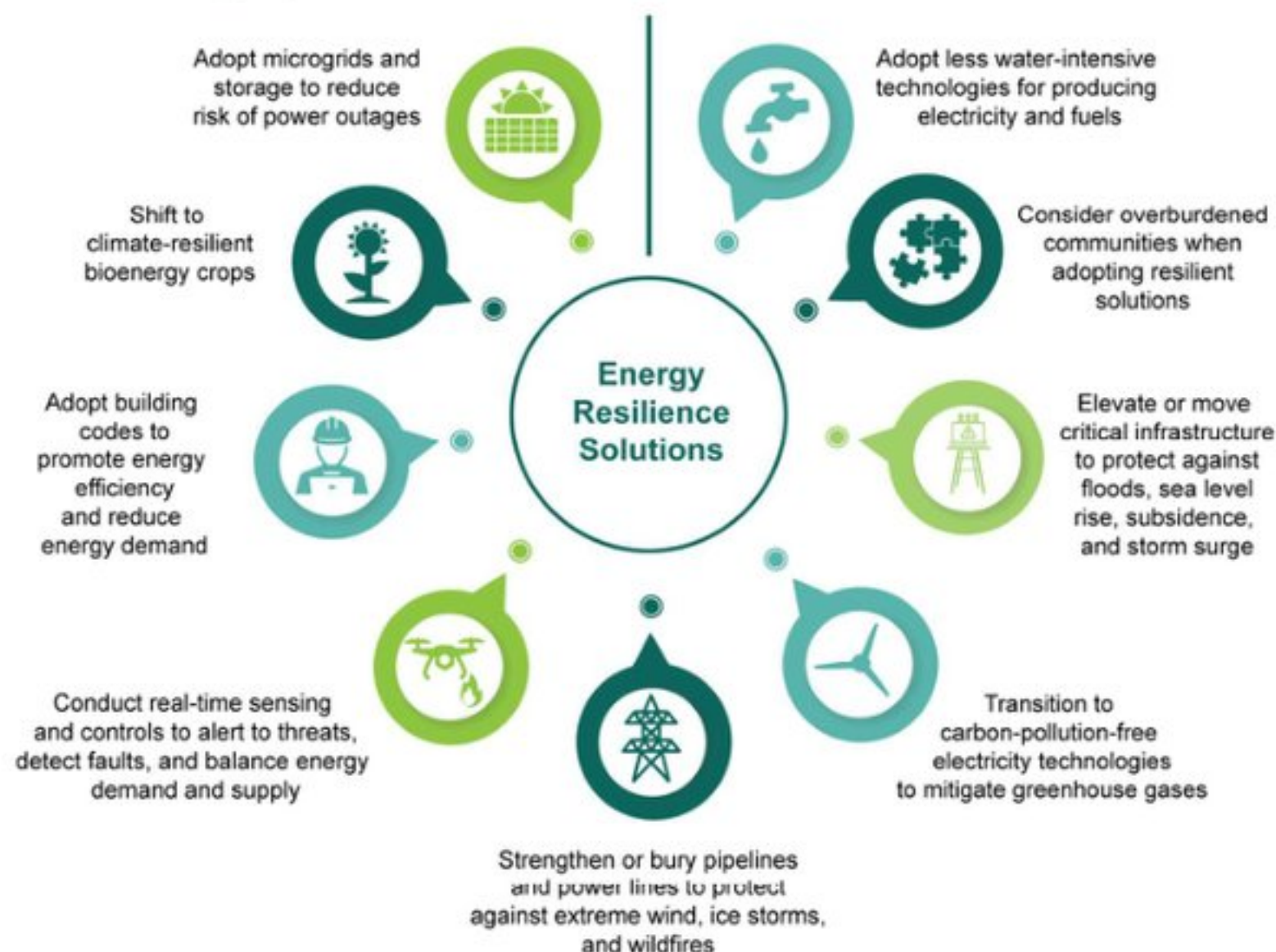
Progress is underway to develop and implement solutions addressing energy system risks from compounding impacts of climate change and threats from pandemics (COVID-19), cyberattacks,^{177,215,216} electromagnetic pulse events,^{85,174,176,180,217} market shocks,²¹⁸ and supply chain disruptions (KM 5.2). 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.

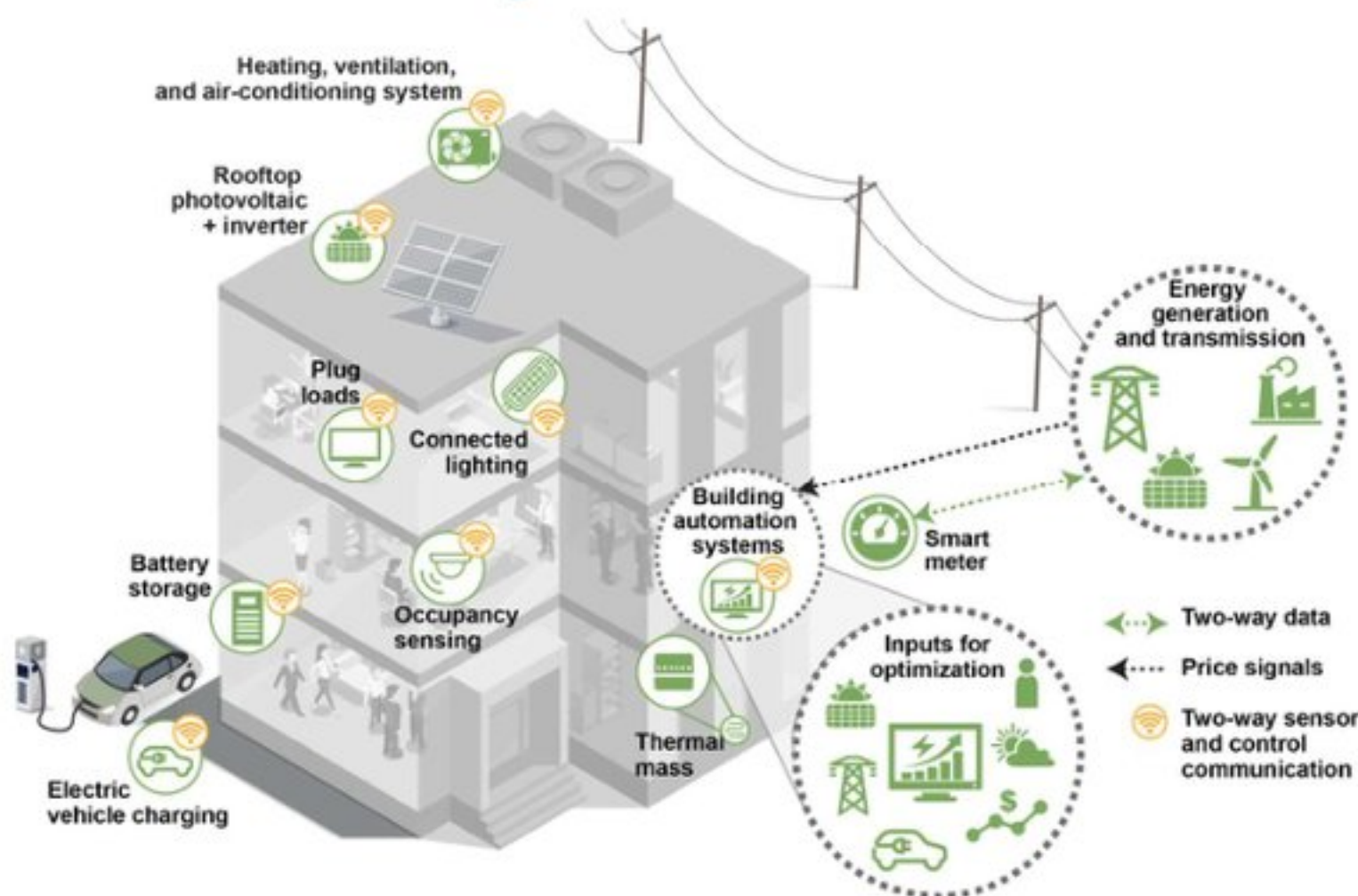
Figure 5.4. While climate change results in risks to the energy system, many approaches for enhancing energy system resilience are available. Resilience options include burying powerlines, elevating critical infrastructure, introducing microgrids and distributed generation, and improved monitoring. Figure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

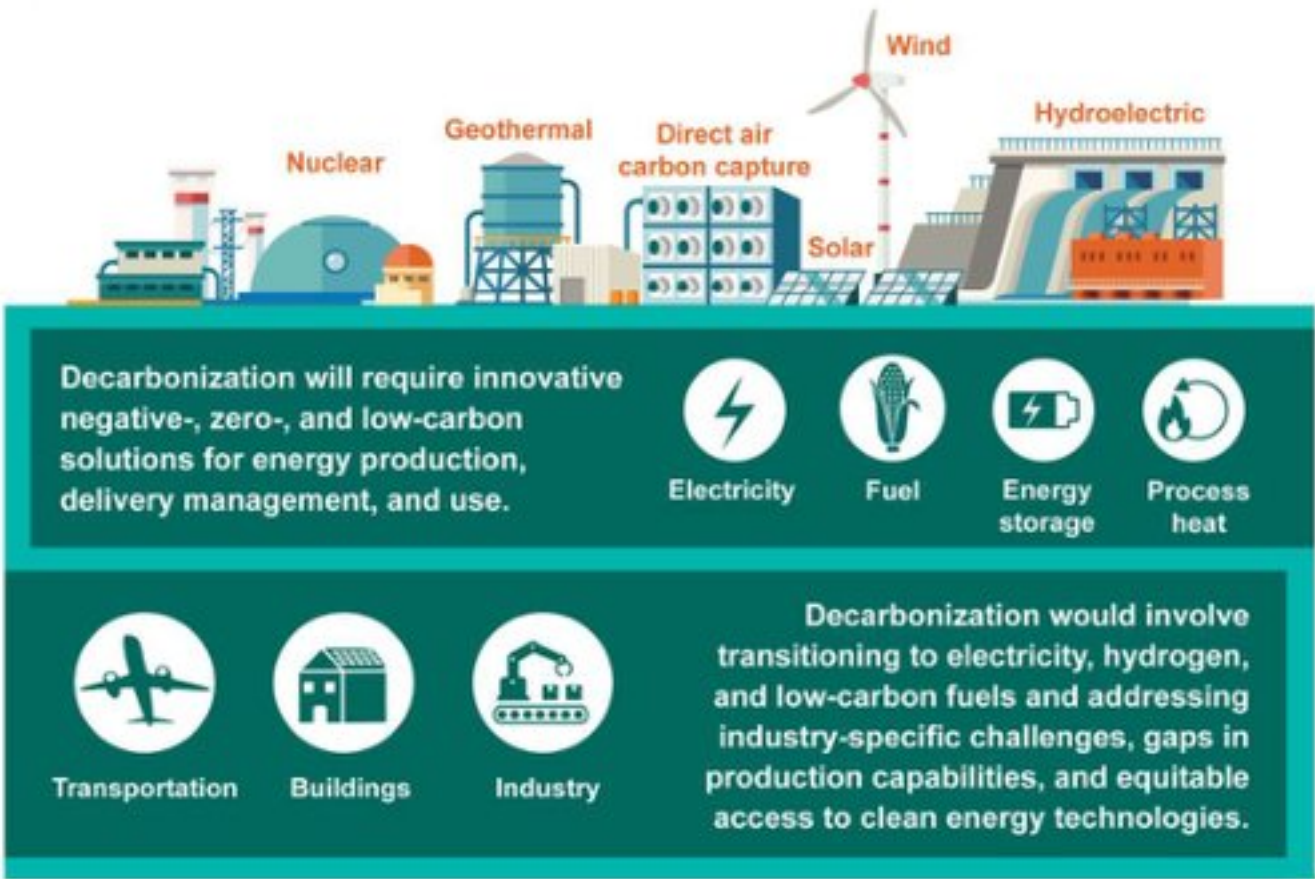
Technology Development and Deployment to Decarbonize the Energy System

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

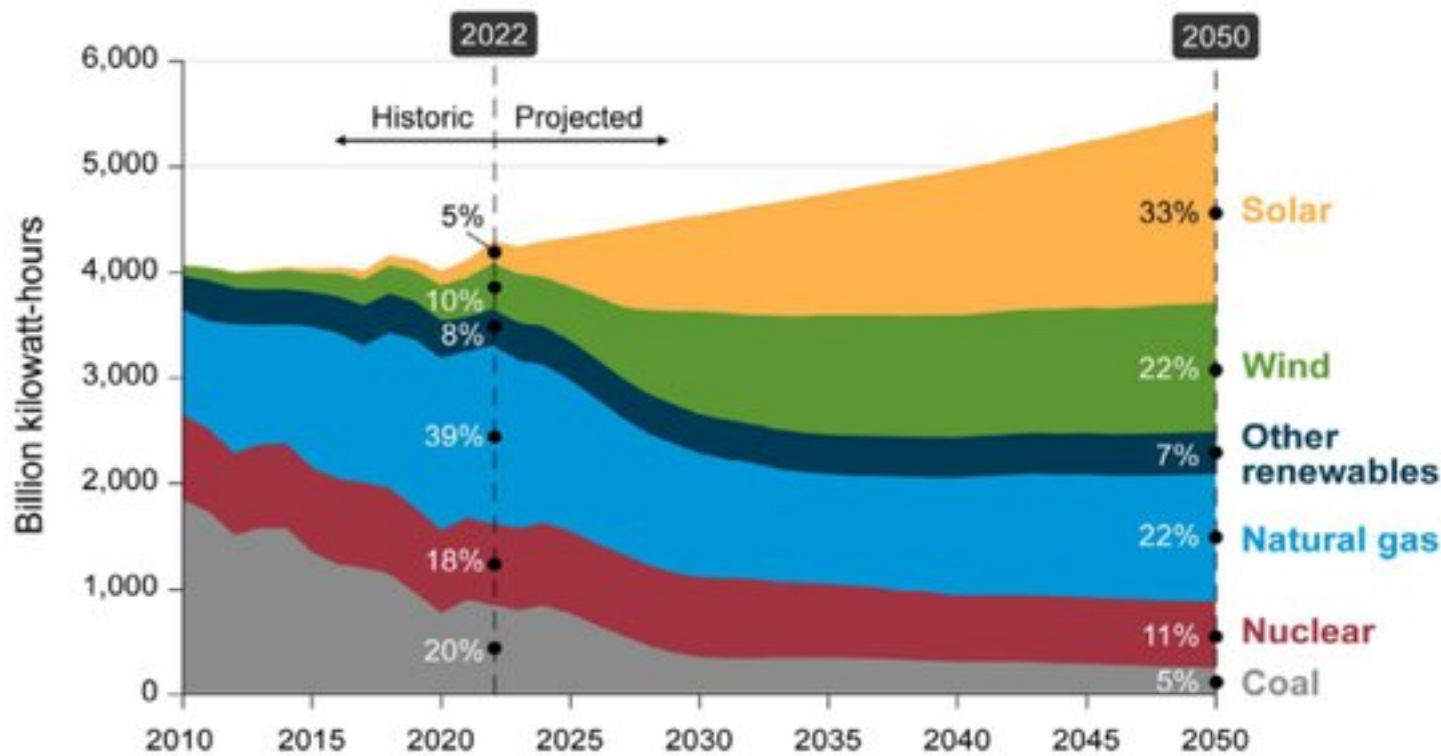


Decarbonization will require innovative solutions across multiple sectors.

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 levels²³⁵ 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 data²⁶² 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 CO₂ 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).^{95,96,109,130,111,112,113,114,115,117,118,119,121} 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 pollution¹⁴⁵ 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 times⁶¹) than on inequities in supply or on differential demand (including cooling-system-use temperatures¹⁵⁴) 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. 2021⁵⁵), extreme cold (e.g., Busby et al. 2021²⁴), and flooding (e.g., Collins et al. 2019¹⁴⁷) 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 Action²⁷⁸ 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 progress.^{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 hardening²⁴ 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 policies 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}

References

1. NOAA, 2023: Greenhouse gases continued to increase rapidly in 2022. National Oceanic and Atmospheric Administration, April 5, 2023. <https://www.noaa.gov/news-release/greenhouse-gases-continued-to-increase-rapidly-in-2022>
2. EIA, 2021: U.S. Energy-Related Carbon Dioxide, 2021. U.S. Energy Information Administration, Washington, DC. https://www.eia.gov/environment/emissions/carbon/pdf/2021_co2analysis.pdf
3. EIA, 2023: Annual Energy Outlook 2023. AEO2023 Narrative. U.S. Energy Information Administration. https://www.eia.gov/outlooks/aeo/pdf/aeo2023_narrative.pdf
4. Infrastructure Investment and Jobs Act. 117th Congress, Pub. L. No. 117-58, 135 Stat. 429, November 15, 2021. <https://www.congress.gov/117/plaws/publ58/PLAW-117publ58.pdf>
5. Inflation Reduction Act of 2022. 117th Congress, Pub. L. No. 117-169, 136 Stat. 1818, August 16, 2022. <https://www.congress.gov/bill/117th-congress/house-bill/5376/text>
6. DOE, 2022: The Inflation Reduction Act Drives Significant Emissions Reductions and Positions America to Reach our Climate Goals. DOE/OP-0018. U.S. Department of Energy, Office of Policy, 6 pp. https://www.energy.gov/sites/default/files/2022-08/8.18%20InflationReductionAct_Factsheet_Final.pdf
7. IEA, 2023: World Energy Investment 2023. International Energy Agency, Paris, France. <https://www.iea.org/reports/world-energy-investment-2023>
8. Steinberg, D.C., M. Brown, R. Wiser, P. Donohoo-Vallett, P. Gagnon, A. Hamilton, M. Mowers, C. Murphy, and A. Prasana, 2023: Evaluating Impacts of the Inflation Reduction Act and Bipartisan Infrastructure Law on the U.S. Power System. NREL/TP-6A20-85242. U.S. Department of Energy, National Renewable Energy Laboratory, Golden, CO. <https://www.nrel.gov/docs/fy23osti/85242.pdf>
9. CRS, 2022: Inflation Reduction Act of 2022 (IRA): Provisions Related to Climate Change. CRS Report R47262. Congressional Research Service. <https://crsreports.congress.gov/product/pdf/r/r47262>
10. To Amend the Administrative Code of the City of New York, in Relation to the Use of Substances with Certain Emissions Profiles. Local Law No. 154 of 2021, Council Int. No. 2317-A of 2021, City of New York, December 22, 2021. http://www.nyc.gov/assets/buildings/local_laws/ll154of2021.pdf
11. CEC, 2022: 2022 Building Energy Efficiency Standards. California Energy Commission. <https://www.energy.ca.gov/programs-and-topics/programs/building-energy-efficiency-standards/2022-building-energy-efficiency>
12. DOE, 2013: U.S. Energy Sector Vulnerabilities to Climate Change and Extreme Weather. U.S. Department of Energy. <https://www.energy.gov/articles/us-energy-sector-vulnerabilities-climate-change-and-extreme-weather>
13. Hashemi, M.R., B. Kresning, J. Hashemi, and I. Ginis, 2021: Assessment of hurricane generated loads on onshore wind farms: A closer look at most extreme historical hurricanes in New England. *Renewable Energy*, **175**, 593–609. <https://doi.org/10.1016/j.renene.2021.05.042>
14. Kresning, B., M. Reza Hashemi, and C. Gallucci, 2020: Simulation of hurricane loading for proposed offshore windfarms off the US Northeast coast. *Journal of Physics: Conference Series*, **1452** (1), 012026. <https://doi.org/10.1088/1742-6596/1452/1/012026>
15. Davlasheridze, M., Q. Fan, W. Highfield, and J. Liang, 2021: Economic impacts of storm surge events: Examining state and national ripple effects. *Climatic Change*, **166** (1), 11. <https://doi.org/10.1007/s10584-021-03106-z>
16. EIA, 2022: Gulf of Mexico Fact Sheet. U.S. Energy Information Administration, Washington, DC. http://www.eia.gov/special/gulf_of_mexico/
17. Cinner, J.E., W.N. Adger, E.H. Allison, M.L. Barnes, K. Brown, P.J. Cohen, S. Gelcich, C.C. Hicks, T.P. Hughes, J. Lau, N.A. Marshall, and T.H. Morrison, 2018: Building adaptive capacity to climate change in tropical coastal communities. *Nature Climate Change*, **8** (2), 117–123. <https://doi.org/10.1038/s41558-017-0065-x>
18. Hinkel, J., J.C.J.H. Aerts, S. Brown, J.A. Jiménez, D. Lincke, R.J. Nicholls, P. Scussolini, A. Sanchez-Arcilla, A. Vafeidis, and K.A. Addo, 2018: The ability of societies to adapt to twenty-first-century sea-level rise. *Nature Climate Change*, **8** (7), 570–578. <https://doi.org/10.1038/s41558-018-0176-z>

19. Balch, J.K., J.T. Abatzoglou, M.B. Joseph, M.J. Koontz, A.L. Mahood, J. McGlinchy, M.E. Cattau, and A.P. Williams, 2022: Warming weakens the night-time barrier to global fire. *Nature*, **602** (7897), 442–448. <https://doi.org/10.1038/s41586-021-04325-1>
20. Muhs, J.W., M. Parvania, and M. Shahidehpour, 2020: Wildfire risk mitigation: A paradigm shift in power systems planning and operation. *Journal of Power and Energy*, **7**, 366–375. <https://doi.org/10.1109/oajpe.2020.3030023>
21. Donaldson, D.L., D.M. Piper, and D. Jayaweera, 2021: Temporal solar photovoltaic generation capacity reduction from wildfire smoke. *IEEE Access*, **9**, 79841–79852. <https://doi.org/10.1109/access.2021.3084528>
22. Gilletly, S.D., N.D. Jackson, and A. Staid, 2021: Quantifying wildfire-induced impacts to photovoltaic energy production in the western United States. In: 2021 IEEE 48th Photovoltaic Specialists Conference (PVSC). Fort Lauderdale, FL, 20–25 June 2021. IEEE, 1619–1625. <https://doi.org/10.1109/pvsc43889.2021.9518514>
23. Muehleisen, W., G.C. Eder, Y. Voronko, M. Spielberger, H. Sonnleitner, K. Knoeb, R. Ebner, G. Ujvari, and C. Hirschl, 2018: Outdoor detection and visualization of hailstorm damages of photovoltaic plants. *Renewable Energy*, **118**, 138–145. <https://doi.org/10.1016/j.renene.2017.11.010>
24. Busby, J.W., K. Baker, M.D. Bazilian, A.Q. Gilbert, E. Grubert, V. Rai, J.D. Rhods, S. Shidore, C.A. Smith, and M.E. Webber, 2021: Cascading risks: Understanding the 2021 winter blackout in Texas. *Energy Research & Social Science*, **77**, 102106. <https://doi.org/10.1016/j.erss.2021.102106>
25. Allen-Dumas, M., B. Kc, and C.I. Cunliff, 2019: Extreme Weather and Climate Vulnerabilities of the Electric Grid: A Summary of Environmental Sensitivity Quantification Methods. ORNL/TM-2019/1252. U.S. Department of Energy, Oak Ridge National Laboratory, Oak Ridge, TN. <https://doi.org/10.2172/1558514>
26. Murphy, S., L. Lavin, and J. Apt, 2020: Resource adequacy implications of temperature-dependent electric generator availability. *Applied Energy*, **262**, 114424. <https://doi.org/10.1016/j.apenergy.2019.114424>
27. Ahmad, A., 2021: Increase in frequency of nuclear power outages due to changing climate. *Nature Energy*, **6** (7), 755–762. <https://doi.org/10.1038/s41560-021-00849-y>
28. Morrow, W.R., A. Gopal, G. Fitts, S. Lewis, L. Dale, and E. Masanet, 2014: Feedstock loss from drought is a major economic risk for biofuel producers. *Biomass and Bioenergy*, **69**, 135–143. <https://doi.org/10.1016/j.biombioe.2014.05.006>
29. Coburn, J. and S.C. Pryor, 2023: Projecting future energy production from operating wind farms in North America. Part II: Statistical downscaling. *Journal of Applied Meteorology and Climatology*, **62** (1), 81–101. <https://doi.org/10.1175/jamc-d-22-0047.1>
30. Gernaat, D.E.H.J., H.S. de Boer, V. Daioglou, S.G. Yalew, C. Müller, and D.P. van Vuuren, 2021: Climate change impacts on renewable energy supply. *Nature Climate Change*, **11** (2), 119–125. <https://doi.org/10.1038/s41558-020-00949-9>
31. Karauskas, K.B., J.K. Lundquist, and L. Zhang, 2018: Southward shift of the global wind energy resource under high carbon dioxide emissions. *Nature Geoscience*, **11** (1), 38–43. <https://doi.org/10.1038/s41561-017-0029-9>
32. Losada Carreño, I., M.T. Craig, M. Rossol, M. Ashfaq, F. Batibeniz, S.E. Haupt, C. Draxl, B.-M. Hodge, and C. Brancucci, 2020: Potential impacts of climate change on wind and solar electricity generation in Texas. *Climatic Change*, **163** (2), 745–766. <https://doi.org/10.1007/s10584-020-02891-3>
33. Solaun, K. and E. Cerdá, 2019: Climate change impacts on renewable energy generation. A review of quantitative projections. *Renewable and Sustainable Energy Reviews*, **116**, 109415. <https://doi.org/10.1016/j.rser.2019.109415>
34. Yin, J., A. Molini, and A. Porporato, 2020: Impacts of solar intermittency on future photovoltaic reliability. *Nature Communications*, **11** (1), 4781. <https://doi.org/10.1038/s41467-020-18602-6>
35. Bukhary, S., S. Ahmad, and J. Batista, 2018: Analyzing land and water requirements for solar deployment in the Southwestern United States. *Renewable and Sustainable Energy Reviews*, **82**, 3288–3305. <https://doi.org/10.1016/j.rser.2017.10.016>
36. EIA, 2021: Electricity Data Browser: Net Generation, Conventional Hydroelectric, All Sectors, Annual. U.S. Energy Information Administration, Washington, DC. <https://www.eia.gov/electricity/data/browser/>

37. EIA, 2022: Today in Energy: California Drought Could Reduce Hydroelectric Generation to Half of Normal Levels. U.S. Energy Information Administration, Washington, DC. <https://www.eia.gov/todayinenergy/detail.php?id=52578>
38. Voisin, N., A. Dyreson, T. Fu, M. O'Connell, S.W.D. Turner, T. Zhou, and J. Macknick, 2020: Impact of climate change on water availability and its propagation through the western U.S. power grid. *Applied Energy*, **276**, 115467. <https://doi.org/10.1016/j.apenergy.2020.115467>
39. Webster, M., K. Fisher-Vanden, V. Kumar, R.B. Lammers, and J. Perla, 2022: Integrated hydrological, power system and economic modelling of climate impacts on electricity demand and cost. *Nature Energy*, **7** (2), 163–169. <https://doi.org/10.1038/s41560-021-00958-8>
40. Zhao, G., H. Gao, and S.-C. Kao, 2021: The implications of future climate change on the blue water footprint of hydropower in the contiguous US. *Environmental Research Letters*, **16** (3), 034003. <https://doi.org/10.1088/1748-9326/abd78d>
41. Sharma, S., J. Waldman, S. Afshari, and B. Fekete, 2019: Status, trends and significance of American hydropower in the changing energy landscape. *Renewable and Sustainable Energy Reviews*, **101**, 112–122. <https://doi.org/10.1016/j.rser.2018.10.028>
42. Brown, T.C., V. Mahat, and J.A. Ramirez, 2019: Adaptation to future water shortages in the United States caused by population growth and climate change. *Earth's Future*, **7** (3), 219–234. <https://doi.org/10.1029/2018ef001091>
43. Williams, A.P., B.I. Cook, and J.E. Smerdon, 2022: Rapid intensification of the emerging southwestern North American megadrought in 2020–2021. *Nature Climate Change*, **12** (3), 232–234. <https://doi.org/10.1038/s41558-022-01290-z>
44. Williams, A.P., E.R. Cook, J.E. Smerdon, B.I. Cook, J.T. Abatzoglou, K. Bolles, S.H. Baek, A.M. Badger, and B. Livneh, 2020: Large contribution from anthropogenic warming to an emerging North American megadrought. *Science*, **368** (6488), 314–318. <https://doi.org/10.1126/science.aaz9600>
45. Kao, S.C., M. Ashfaq, D. Rastogi, S. Gangrade, R.U. Martinez, A. Fernandez, G. Konapala, N. Voisin, T. Zhou, W. Xu, H. Gao, B. Zhao, and C. Zhao, 2022: The Third Assessment of the Effects of Climate Change on Federal Hydropower. ORNL/TM-2021/2278. U.S. Department of Energy, Oak Ridge National Laboratory, Oak Ridge, TN. <https://doi.org/10.2172/1887712>
46. Turner, S.W.D., N. Voisin, J. Fazio, D. Hua, and M. Jourabchi, 2019: Compound climate events transform electrical power shortfall risk in the Pacific Northwest. *Nature Communications*, **10** (1), 8. <https://doi.org/10.1038/s41467-018-07894-4>
47. EIA, 2021: Electricity Explained: How Electricity is Generated. U.S. Energy Information Administration, Washington, DC. <https://www.eia.gov/energyexplained/electricity/how-electricity-is-generated.php>
48. Grubert, E. and K.T. Sanders, 2018: Water use in the United States energy system: A national assessment and unit process inventory of water consumption and withdrawals. *Environmental Science & Technology*, **52** (11), 6695–6703. <https://doi.org/10.1021/acs.est.8b00139>
49. Sanders, K.T., 2015: Critical review: Uncharted waters? The future of the electricity-water nexus. *Environmental Science & Technology*, **49** (1), 51–66. <https://doi.org/10.1021/es504293b>
50. Rosa, L., D.L. Sanchez, G. Realmonte, D. Baldocchi, and P. D'Odorico, 2021: The water footprint of carbon capture and storage technologies. *Renewable and Sustainable Energy Reviews*, **138**, 110511. <https://doi.org/10.1016/j.rser.2020.110511>
51. Mays, G., 2021: Ch. 21. Small modular reactors (SMRs): The case of the United States of America. In: *Handbook of Small Modular Nuclear Reactors*, 2nd ed. Ingersoll, D.T. and M.D. Carelli, Eds. Woodhead Publishing, 521–553. <https://doi.org/10.1016/b978-0-12-823916-2.00021-7>
52. Cheng, Y., N. Voisin, J.R. Yearsley, and B. Nijssen, 2020: Thermal extremes in regulated river systems under climate change: An application to the southeastern U.S. rivers. *Environmental Research Letters*, **15** (9), 094012. <https://doi.org/10.1088/1748-9326/ab8f5f>
53. Liu, L., M. Hejazi, H. Li, B. Forman, and X. Zhang, 2017: Vulnerability of US thermoelectric power generation to climate change when incorporating state-level environmental regulations. *Nature Energy*, **2** (8), 17109. <https://doi.org/10.1038/nenergy.2017.109>

54. Miara, A., J.E. Macknick, C.J. Vörösmarty, V.C. Tidwell, R. Newmark, and B. Fekete, 2017: Climate and water resource change impacts and adaptation potential for US power supply. *Nature Climate Change*, **7** (11), 793–798. <https://doi.org/10.1038/nclimate3417>
55. Turner, S.W.D., K. Nelson, N. Voisin, V. Tidwell, A. Miara, A. Dyreson, S. Cohen, D. Mantena, J. Jin, P. Warnken, and S.-C. Kao, 2021: A multi-reservoir model for projecting drought impacts on thermoelectric disruption risk across the Texas power grid. *Energy*, **231**, 120892. <https://doi.org/10.1016/j.energy.2021.120892>
56. Climate Central, 2022: Climate Matters: Surging Weather-related Power Outages [Webpage]. <https://www.climatecentral.org/climate-matters/surging-weather-related-power-outages>
57. Fant, C., B. Boehlert, K. Strzepek, P. Larsen, A. White, S. Gulati, Y. Li, and J. Martinich, 2020: Climate change impacts and costs to U.S. electricity transmission and distribution infrastructure. *Energy*, **195**, 116899. <https://doi.org/10.1016/j.energy.2020.116899>
58. Emerton, R., C. Brimicombe, L. Magnusson, C. Roberts, C. Di Napoli, H.L. Cloke, and F. Pappenberger, 2022: Predicting the unprecedented: Forecasting the June 2021 Pacific Northwest heatwave. *Weather*, **77** (8), 272–279. <https://doi.org/10.1002/wea.4257>
59. Song, F., G.J. Zhang, V. Ramanathan, and L.R. Leung, 2022: Trends in surface equivalent potential temperature: A more comprehensive metric for global warming and weather extremes. *Proceedings of the National Academy of Sciences of the United States of America*, **119** (6), e2117832119. <https://doi.org/10.1073/pnas.2117832119>
60. Bartos, M., M. Chester, N. Johnson, B. Gorman, D. Eisenberg, I. Linkov, and M. Bates, 2016: Impacts of rising air temperatures on electric transmission ampacity and peak electricity load in the United States. *Environmental Research Letters*, **11** (11), 114008. <https://doi.org/10.1088/1748-9326/11/11/114008>
61. Coleman, N., A. Esmalian, C.-C. Lee, E. Gonzales, P. Koirala, and A. Mostafavi, 2023: Energy inequality in climate hazards: Empirical evidence of social and spatial disparities in managed and hazard-induced power outages. *Sustainable Cities and Society*, **92**, 104491. <https://doi.org/10.1016/j.scs.2023.104491>
62. EIA, 2021: Today in Energy: U.S. Electricity Customers Experienced Eight Hours of Power Interruptions in 2020. U.S. Energy Information Administration, Washington, DC. <https://www.eia.gov/todayinenergy/detail.php?id=50316>
63. Nazaripouya, H., 2020: Power grid resilience under wildfire: A review on challenges and solutions. In: 2020 IEEE Power & Energy Society General Meeting (PESGM). Montreal, QC, Canada, 2–6 August 2020. IEEE. <https://doi.org/10.1109/pesgm41954.2020.9281708>
64. Panteli, M. and P. Mancarella, 2015: Influence of extreme weather and climate change on the resilience of power systems: Impacts and possible mitigation strategies. *Electric Power Systems Research*, **127**, 259–270. <https://doi.org/10.1016/j.epsr.2015.06.012>
65. Cerrai, D., D.W. Wanik, M.A.E. Bhuiyan, X. Zhang, J. Yang, M.E.B. Frediani, and E.N. Anagnostou, 2019: Predicting storm outages through new representations of weather and vegetation. *IEEE Access*, **7**, 29639–29654. <https://doi.org/10.1109/access.2019.2902558>
66. D'Amico, D.F., S.M. Quiring, C.M. Maderia, and D.B. McRoberts, 2019: Improving the Hurricane Outage Prediction Model by including tree species. *Climate Risk Management*, **25**, 100193. <https://doi.org/10.1016/j.crm.2019.100193>
67. Brettschneider, S. and I. Fofana, 2021: Evolution of countermeasures against atmospheric icing of power lines over the past four decades and their applications into field operations. *Energies*, **14** (19), 6291. <https://doi.org/10.3390/en14196291>
68. Arab, A., A. Khodaei, R. Eskandarpour, M.P. Thompson, and Y. Wei, 2021: Three lines of defense for wildfire risk management in electric power grids: A review. *IEEE Access*, **9**, 61577–61593. <https://doi.org/10.1109/access.2021.3074477>
69. Oruji, S., M. Ketabdar, D. Moon, V. Tsao, and M. Ketabdar, 2022: Evaluation of land subsidence hazard on steel natural gas pipelines in California. *Upstream Oil and Gas Technology*, **8**, 100062. <https://doi.org/10.1016/j.upstre.2021.100062>
70. de Bruijn, K.M., C. Maran, M. Zygnerski, J. Jurado, A. Burzel, C. Jeuken, and J. Obeysekera, 2019: Flood resilience of critical infrastructure: Approach and method applied to Fort Lauderdale, Florida. *Water*, **11** (3), 517. <https://doi.org/10.3390/w11030517>

71. Khanam, M., G. Sofia, M. Koukoulou, R. Lazin, E.I. Nikolopoulos, X. Shen, and E.N. Anagnostou, 2021: Impact of compound flood event on coastal critical infrastructures considering current and future climate. *Natural Hazards and Earth System Sciences*, **21** (2), 587–605. <https://doi.org/10.5194/nhess-21-587-2021>
72. Kwasinski, A., F. Andrade, M.J. Castro-Sitiriche, and E. O'Neill-Carrillo, 2019: Hurricane Maria effects on Puerto Rico electric power infrastructure. *IEEE Power and Energy Technology Systems Journal*, **6** (1), 85–94. <https://doi.org/10.1109/jpets.2019.2900293>
73. Abatzoglou, J.T., C.M. Smith, D.L. Swain, T. Ptak, and C.A. Kolden, 2020: Population exposure to pre-emptive de-energization aimed at averting wildfires in Northern California. *Environmental Research Letters*, **15**, 094046. <https://doi.org/10.1088/1748-9326/aba135>
74. Rhodes, N., L. Ntamo, and L. Roald, 2021: Balancing wildfire risk and power outages through optimized power shut-offs. *IEEE Transactions on Power Systems*, **36** (4), 3118–3128. <https://doi.org/10.1109/tpwrs.2020.3046796>
75. Antoniou, A., A. Dimou, E. Zacharis, F. Konstantopoulou, and P. Karvelis, 2020: Adapting oil & gas infrastructures to climate change. *Pipeline Technology Journal*. <https://www.pipeline-journal.net/articles/adapting-oil-gas-infrastructures-climate-change>
76. National Academies of Sciences, Engineering, and Medicine, 2020: *Strengthening Post-Hurricane Supply Chain Resilience: Observations from Hurricanes Harvey, Irma, and Maria*. The National Academies Press, Washington, DC, 136 pp. <https://doi.org/10.17226/25490>
77. Ni, W., Y. Liang, Z. Li, Q. Liao, S. Cai, B. Wang, H. Zhang, and Y. Wang, 2022: Resilience assessment of the downstream oil supply chain considering the inventory strategy in extreme weather events. *Computers & Chemical Engineering*, **163**, 107831. <https://doi.org/10.1016/j.compchemeng.2022.107831>
78. Sichani, M.E. and J.E. Padgett, 2021: Performance assessment of oil supply chain infrastructure subjected to hurricanes. *Journal of Infrastructure Systems*, **27** (4), 04021033. [https://doi.org/10.1061/\(asce\)is.1943-555x.0000637](https://doi.org/10.1061/(asce)is.1943-555x.0000637)
79. Dong, J., Z. Asif, Y. Shi, Y. Zhu, and Z. Chen, 2022: Climate change impacts on coastal and offshore petroleum infrastructure and the associated oil spill risk: A review. *Journal of Marine Science and Engineering*, **10** (7), 849. <https://doi.org/10.3390/jmse10070849>
80. EIA, 2022: *Oil and Petroleum Products Explained: Use of Oil*. U.S. Energy Information Administration. <https://www.eia.gov/energyexplained/oil-and-petroleum-products/use-of-oil.php>
81. EIA, 2020: *Today in Energy: Hurricane Laura Shut in More Gulf of Mexico Crude Oil Production Than Any Storm Since 2008*. U.S. Energy Information Administration, Washington, DC, accessed October 2, 2020. <https://www.eia.gov/todayinenergy/detail.php?id=45376>
82. Davis, A., D. Thrift-Viveros, and C.M.S. Baker, 2021: NOAA scientific support for a natural gas pipeline release during Hurricane Harvey flooding in the Neches River Beaumont, Texas. *International Oil Spill Conference Proceedings*, **2021** (1), 687018. <https://doi.org/10.7901/2169-3358-2021.1.687018>
83. Qin, R., N. Khakzad, and J. Zhu, 2020: An overview of the impact of Hurricane Harvey on chemical and process facilities in Texas. *International Journal of Disaster Risk Reduction*, **45**, 101453. <https://doi.org/10.1016/j.ijdrr.2019.101453>
84. GAO, 2021: *Offshore Oil and Gas: Updated Regulations Needed to Improve Pipeline Oversight and Decommissioning*. GAO-21-293. U.S. Government Accountability Office. <https://www.gao.gov/products/gao-21-293>
85. Doss-Gollin, J., D.J. Farnham, U. Lall, and V. Modi, 2021: How unprecedented was the February 2021 Texas cold snap? *Environmental Research Letters*, **16** (6), 064056. <https://doi.org/10.1088/1748-9326/ac0278>
86. Speake, A., P. Donohoo-Vallett, E. Wilson, E. Chen, and C. Christensen, 2020: Residential natural gas demand response potential during extreme cold events in electricity-gas coupled energy systems. *Energies*, **13** (19), 5192. <https://doi.org/10.3390/en13195192>
87. IPCC, 2021: Summary for policymakers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3–32. <https://doi.org/10.1017/9781009157896.001>

88. Ileri, E.C., H. Her, A. Mazounie, and L. Pinson, 2021: DRILL, BABY, DRILL: How Banks, Investors and Insurers Are Driving Oil and Gas Expansion in the Arctic. Reclaim Finance. https://reclaimfinance.org/site/wp-content/uploads/2021/09/Drill_Baby_Drill_RF_Arctic_Report_23_09_2021.pdf
89. Zamuda, C., D.E. Bilello, G. Conzelmann, E. Mecray, A. Satsangi, V. Tidwell, and B.J. Walker, 2018: Ch. 4. Energy supply, delivery, and demand. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D. Easterling, K. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 174–201. <https://doi.org/10.7930/nca4.2018.ch4>
90. Gädeke, A., M. Langer, J. Boike, E.J. Burke, J. Chang, M. Head, C.P.O. Reyer, S. Schaphoff, W. Thiery, and K. Thonicke, 2021: Climate change reduces winter overland travel across the Pan-Arctic even under low-end global warming scenarios. *Environmental Research Letters*, **16** (2), 024049. <https://doi.org/10.1088/1748-9326/abdcf2>
91. Hori, Y., V.Y.S. Cheng, W.A. Gough, J.Y. Jien, and L.J.S. Tsui, 2018: Implications of projected climate change on winter road systems in Ontario's Far North, Canada. *Climatic Change*, **148** (1), 109–122. <https://doi.org/10.1007/s10584-018-2178-2>
92. EIA, 2023: AEO2023 Issues in Focus: Inflation Reduction Act Cases in the AEO2023. U.S. Department of Energy, U.S. Energy Information Administration, Washington, DC. https://www.eia.gov/outlooks/aeo/iif_ira/pdf/ira_iif.pdf
93. Zhou, E. and T. Mai, 2021: Electrification Futures Study: Operational Analysis of U.S. Power Systems with Increased Electrification and Demand-Side Flexibility. NREL/TP-6A20-79094. U.S. Department of Energy, National Renewable Energy Laboratory, Golden, CO. <https://www.nrel.gov/docs/fy21osti/79094.pdf>
94. Bistline, J.E.T., C.W. Roney, D.L. McCollum, and G.J. Blanford, 2021: Deep decarbonization impacts on electric load shapes and peak demand. *Environmental Research Letters*, **16** (9), 094054. <https://doi.org/10.1088/1748-9326/ac2197>
95. EPRI, 2018: U.S. National Electrification Assessment. Electric Power Research Institute. <https://www.epri.com/research/products/000000003002013582>
96. EPRI, 2021: Strategies and Actions for Achieving a 50% Reduction in U.S. Greenhouse Gas Emissions by 2030. Electric Power Research Institute, Palo Alto, CA. <https://www.epri.com/research/products/000000003002023165>
97. Khan, Z., M. Zhao, H. Ahsan, P. Wolfram, A. Snyder, P. Kyle, J. Rice, C. Vernon, Y. Ou, M. Binsted, and G. Iyer. 2023: Version of GCAM-USA used for National Climate Assessment 5, Chapter 5: GCAM-USA-v5.3-IM3-NCA5. MSD-LIVE Data Repository. <https://doi.org/10.57931/1963007>
98. Murphy, C., T. Mai, E. Zhou, M. Muratori, and P. Jadun, 2022: Electrification futures study. In: *Electrify the Big Sky Conference*. Missoula, MT. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, National Renewable Energy Laboratory. <https://www.osti.gov/biblio/1888234>
99. Khan, Z., G. Iyer, P. Patel, S. Kim, M. Hejazi, C. Burleyson, and M. Wise, 2021: Impacts of long-term temperature change and variability on electricity investments. *Nature Communications*, **12** (1), 1643. <https://doi.org/10.1038/s41467-021-21785-1>
100. Obringer, R., R. Nateghi, D. Maia-Silva, S. Mukherjee, V. Cr, D.B. McRoberts, and R. Kumar, 2022: Implications of increasing household air conditioning use across the United States under a warming climate. *Earth's Future*, **10** (1), e2021EF002434. <https://doi.org/10.1029/2021ef002434>
101. Ralston Fonseca, F., P. Jaramillo, M. Bergés, and E. Severnini, 2019: Seasonal effects of climate change on intra-day electricity demand patterns. *Climatic Change*, **154** (3), 435–451. <https://doi.org/10.1007/s10584-019-02413-w>
102. van Ruijven, B.J., E. De Cian, and I. Sue Wing, 2019: Amplification of future energy demand growth due to climate change. *Nature Communications*, **10** (1), 2762. <https://doi.org/10.1038/s41467-019-10399-3>
103. Rastogi, D., J.S. Holladay, K.J. Evans, B.L. Preston, and M. Ashfaq, 2019: Shift in seasonal climate patterns likely to impact residential energy consumption in the United States. *Environmental Research Letters*, **14** (7), 074006. <https://doi.org/10.1088/1748-9326/ab22d2>
104. Ortiz, L., J.E. González, and W. Lin, 2018: Climate change impacts on peak building cooling energy demand in a coastal megacity. *Environmental Research Letters*, **13** (9), 094008. <https://doi.org/10.1088/1748-9326/aad8d0>
105. Wang, Z., T. Hong, H. Li, and M. Ann Piette, 2021: Predicting city-scale daily electricity consumption using data-driven models. *Advances in Applied Energy*, **2**, 100025. <https://doi.org/10.1016/j.adapen.2021.100025>

106. Overland, J.E., 2021: Causes of the record-breaking Pacific Northwest heatwave, late June 2021. *Atmosphere*, **12** (11), 1434. <https://doi.org/10.3390/atmos12111434>
107. EIA, 2021: Today in Energy: June Heat Wave in the Northwest United States Resulted in More Demand for Electricity. U.S. Energy Information Administration, Washington, DC. <https://www.eia.gov/todayinenergy/detail.php?id=48796>
108. Rempel, A.R., J. Danis, A.W. Rempel, M. Fowler, and S. Mishra, 2022: Improving the passive survivability of residential buildings during extreme heat events in the Pacific Northwest. *Applied Energy*, **321**, 119323. <https://doi.org/10.1016/j.apenergy.2022.119323>
109. Bistline, J., N. Abhyankar, G. Blanford, L. Clarke, R. Fakhry, H. McJeon, J. Reilly, C. Roney, T. Wilson, M. Yuan, and A. Zhao, 2022: Actions for reducing US emissions at least 50% by 2030. *Science*, **376** (6596), 922–924. <https://doi.org/10.1126/science.abn0661>
110. Mai, T.T., P. Jadun, J.S. Logan, C.A. McMillan, M. Muratori, D.C. Steinberg, L.J. Vimmerstedt, B. Haley, R. Jones, and B. Nelson, 2018: Electrification Futures Study: Scenarios of Electric Technology Adoption and Power Consumption for the United States. NREL/TP-6A20-71500. U.S. Department of Energy, National Renewable Energy Laboratory, Golden, CO. <https://doi.org/10.2172/1459351>
111. Muratori, M., M. Alexander, D. Arent, M. Bazilian, P. Cazzola, E.M. Dede, J. Farrell, C. Gearhart, D. Greene, A. Jenn, M. Keyser, T. Lipman, S. Narumanchi, A. Pesaran, R. Sioshansi, E. Suomalainen, G. Tal, K. Walkowicz, and J. Ward, 2021: The rise of electric vehicles—2020 status and future expectations. *Progress in Energy*, **3** (2), 022002. <https://doi.org/10.1088/2516-1083/abe0ad>
112. National Academies of Sciences, Engineering, and Medicine, 2021: *Accelerating Decarbonization of the U.S. Energy System*. The National Academies Press, Washington, DC, 268 pp. <https://doi.org/10.17226/25932>
113. Rightor, E., A. Whitlock, and N. Elliot, 2020: Beneficial Electrification in Industry. American Council for an Energy-Efficient Economy. <https://www.aceee.org/research-report/ie2002>
114. Langevin, J., C.B. Harris, A. Satre-Meloy, H. Chandra-Putra, A. Speake, E. Present, R. Adhikari, E.J.H. Wilson, and A.J. Satchwell, 2021: US building energy efficiency and flexibility as an electric grid resource. *Joule*, **5** (8), 2102–2128. <https://doi.org/10.1016/j.joule.2021.06.002>
115. Cheng, A.J., B. Tarroja, B. Shaffer, and S. Samuelsen, 2018: Comparing the emissions benefits of centralized vs. decentralized electric vehicle smart charging approaches: A case study of the year 2030 California electric grid. *Journal of Power Sources*, **401**, 175–185. <https://doi.org/10.1016/j.jpowsour.2018.08.092>
116. DOE, 2022: Clean Hydrogen Production Standard (CHPS) Draft Guidance. U.S. Department of Energy. <https://www.energy.gov/eere/fuelcells/articles/clean-hydrogen-production-standard>
117. Oliveira, A.M., R.R. Beswick, and Y. Yan, 2021: A green hydrogen economy for a renewable energy society. *Current Opinion in Chemical Engineering*, **33**, 100701. <https://doi.org/10.1016/j.coche.2021.100701>
118. Rose, S.K., N. Bauer, A. Popp, J. Weyant, S. Fujimori, P. Havlik, M. Wise, and D.P. van Vuuren, 2020: An overview of the Energy Modeling Forum 33rd study: Assessing large-scale global bioenergy deployment for managing climate change. *Climatic Change*, **163** (3), 1539–1551. <https://doi.org/10.1007/s10584-020-02945-6>
119. Thombs, R.P., 2019: When democracy meets energy transitions: A typology of social power and energy system scale. *Energy Research & Social Science*, **52**, 159–168. <https://doi.org/10.1016/j.erss.2019.02.020>
120. Fajardy, M. and N. Mac Dowell, 2017: Can BECCS deliver sustainable and resource efficient negative emissions? *Energy and Environmental Science*, **10** (6), 1389–1426. <https://doi.org/10.1039/c7ee00465f>
121. Greig, C. and S. Uden, 2021: The value of CCUS in transitions to net-zero emissions. *The Electricity Journal*, **34** (7), 107004. <https://doi.org/10.1016/j.tej.2021.107004>
122. Arent, D.J., P. Green, Z. Abdullah, T. Barnes, S. Bauer, A. Bernstein, D. Berry, J. Berry, T. Burrell, B. Carpenter, J. Cochran, R. Cortright, M. Curry-Nkansah, P. Denholm, V. Gevorian, M. Himmel, B. Livingood, M. Keyser, J. King, B. Kroposki, T. Mai, M. Mehos, M. Muratori, S. Narumanchi, B. Pivovar, P. Romero-Lankao, M. Ruth, G. Stark, and C. Turchi, 2022: Challenges and opportunities in decarbonizing the U.S. energy system. *Renewable and Sustainable Energy Reviews*, **169**, 112939. <https://doi.org/10.1016/j.rser.2022.112939>

123. IPCC, 2022: Summary for policymakers. In: *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Shukla, P.R., J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, and J. Malley, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA. <https://doi.org/10.1017/9781009157926.001>
124. NREL, 2021: Electrification Futures Study. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, National Renewable Energy Laboratory. <https://www.nrel.gov/analysis/electrification-futures.html>
125. Gaines, L., K. Richa, and J. Spangenberg, 2018: Key issues for Li-ion battery recycling. *MRS Energy & Sustainability*, **5** (1), 12. <https://doi.org/10.1557/mre.2018.13>
126. Pereirinha, P.G., M. González, I. Carrilero, D. Anseán, J. Alonso, and J.C. Viera, 2018: Main trends and challenges in road transportation electrification. *Transportation Research Procedia*, **33**, 235–242. <https://doi.org/10.1016/j.trpro.2018.10.096>
127. Freitas, E.N., J.C. Salgado, R.C. Alnoch, A.G. Contato, E. Habermann, M. Michelin, C.A. Martínez, M. de Polizeli, and T.M. Lourdes, 2021: Challenges of biomass utilization for bioenergy in a climate change scenario. *Biology*, **10** (12). <https://doi.org/10.3390/biology10121277>
128. Chen, C.-f., X. Xu, J. Adams, J. Brannon, F. Li, and A. Walzem, 2020: When East meets West: Understanding residents' home energy management system adoption intention and willingness to pay in Japan and the United States. *Energy Research & Social Science*, **69**, 101616. <https://doi.org/10.1016/j.erss.2020.101616>
129. Goodarzi, S., A. Masini, S. Aflaki, and B. Fahimnia, 2021: Right information at the right time: Reevaluating the attitude–behavior gap in environmental technology adoption. *International Journal of Production Economics*, **242**, 108278. <https://doi.org/10.1016/j.ijpe.2021.108278>
130. Sharma, N., 2021: Public perceptions towards adoption of residential solar water heaters in USA: A case study of Phoenixians in Arizona. *Journal of Cleaner Production*, **320**, 128891. <https://doi.org/10.1016/j.jclepro.2021.128891>
131. Wolske, K.S., K.T. Gillingham, and P.W. Schultz, 2020: Peer influence on household energy behaviours. *Nature Energy*, **5** (3), 202–212. <https://doi.org/10.1038/s41560-019-0541-9>
132. Gillingham, K., D. Rapson, and G. Wagner, 2016: The rebound effect and energy efficiency policy. *Review of Environmental Economics and Policy*, **10** (1), 68–88. <https://doi.org/10.1093/reep/rev017>
133. Hald, K.S. and P. Coslugeanu, 2022: The preliminary supply chain lessons of the COVID-19 disruption—What is the role of digital technologies? *Operations Management Research*, **15** (1), 282–297. <https://doi.org/10.1007/s12063-021-00207-x>
134. Olabi, V., T. Wilberforce, K. Elsaid, E.T. Sayed, and M.A. Abdelkareem, 2022: Impact of COVID-19 on the renewable energy sector and mitigation strategies. *Chemical Engineering & Technology*, **45** (4), 558–571. <https://doi.org/10.1002/ceat.202100504>
135. Ballinger, B., M. Stringer, D.R. Schmeda-Lopez, B. Kefford, B. Parkinson, C. Greig, and S. Smart, 2019: The vulnerability of electric vehicle deployment to critical mineral supply. *Applied Energy*, **255**, 113844. <https://doi.org/10.1016/j.apenergy.2019.113844>
136. IEA, 2021: World Energy Outlook 2021. International Energy Agency, Paris, France. <https://www.iea.org/reports/world-energy-outlook-2021>
137. Kim, K. and L. Bui, 2019: Learning from Hurricane Maria: Island ports and supply chain resilience. *International Journal of Disaster Risk Reduction*, **39**, 101244. <https://doi.org/10.1016/j.ijdrr.2019.101244>
138. IEA, 2021: The Role of Critical Minerals in Clean Energy Transitions. International Energy Agency. <https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions>
139. The White House, 2021: Building Resilient Supply Chains, Revitalizing American Manufacturing, and Fostering Broad-Based Growth. The White House, Washington, DC, 250 pp. <https://www.whitehouse.gov/wp-content/uploads/2021/06/100-day-supply-chain-review-report.pdf>
140. UNECE, 2021: Life Cycle Assessment of Electricity Generation Options. United Nations Economic Commission for Europe, Geneva, Switzerland. https://unece.org/sites/default/files/2021-11/LCA_final.pdf

141. Mitsova, D., A.-M. Esnard, A. Sapat, and B.S. Lai, 2018: Socioeconomic vulnerability and electric power restoration timelines in Florida: The case of Hurricane Irma. *Natural Hazards*, **94** (2), 689–709. <https://doi.org/10.1007/s11069-018-3413-x>
142. Hendricks, M.D. and S. Van Zandt, 2021: Unequal protection revisited: Planning for environmental justice, hazard vulnerability, and critical infrastructure in communities of color. *Environmental Justice*, **14** (2), 87–97. <https://doi.org/10.1089/env.2020.0054>
143. Howard, L., 2021: LIHEAP American Rescue Plan Funding: Racial and Economic Justice Is Also Equity in Energy. U.S. Department of Health and Human Services, Administration for Children and Families, Washington, DC. <https://acfmdev.acf.hhs.gov/blog/2021/05/liheap-american-rescue-plan-funding-racial-economic-justice-also-equity-energy>
144. PNNL, 2021: Energy Storage for Social Equity: Capturing Benefits from Power Plant Decommissioning. PNNL-31451. U.S. Department of Energy, Pacific Northwest National Laboratory. <https://www.pnnl.gov/sites/default/files/media/file/Energy%20Storage%20for%20Social%20Equity%20Case%20Study.pdf>
145. Thind, M.P.S., C.W. Tessum, I.L. Azevedo, and J.D. Marshall, 2019: Fine particulate air pollution from electricity generation in the US: Health impacts by race, income, and geography. *Environmental Science & Technology*, **53** (23), 14010–14019. <https://doi.org/10.1021/acs.est.9b02527>
146. Karnauskas, K.B., S.L. Miller, and A.C. Schapiro, 2020: Fossil fuel combustion is driving indoor CO₂ toward levels harmful to human cognition. *GeoHealth*, **4** (5), e2019GH000237. <https://doi.org/10.1029/2019gh000237>
147. Collins, T.W., S.E. Grineski, J. Chakraborty, and A.B. Flores, 2019: Environmental injustice and Hurricane Harvey: A household-level study of socially disparate flood exposures in Greater Houston, Texas, USA. *Environmental Research*, **179**, 108772. <https://doi.org/10.1016/j.envres.2019.108772>
148. EPA, 2021: Climate Change and Social Vulnerability in the United States: A Focus on Six Impacts. EPA 430-R-21-003. U.S. Environmental Protection Agency. <https://www.epa.gov/cira/social-vulnerability-report>
149. Voelkel, J., D. Hellman, R. Sakuma, and V. Shandas, 2018: Assessing vulnerability to urban heat: A study of disproportionate heat exposure and access to refuge by socio-demographic status in Portland, Oregon. *International Journal of Environmental Research and Public Health*, **15** (4), 640. <https://doi.org/10.3390/ijerph15040640>
150. Wilhelmi, O.V., P.D. Howe, M.H. Hayden, and C.R. O'Lenick, 2021: Compounding hazards and intersecting vulnerabilities: Experiences and responses to extreme heat during COVID-19. *Environmental Research Letters*, **16** (8), 084060. <https://doi.org/10.1088/1748-9326/ac1760>
151. Wing, O.E.J., W. Lehman, P.D. Bates, C.C. Sampson, N. Quinn, A.M. Smith, J.C. Neal, J.R. Porter, and C. Kousky, 2022: Inequitable patterns of US flood risk in the Anthropocene. *Nature Climate Change*, **12** (2), 156–162. <https://doi.org/10.1038/s41558-021-01265-6>
152. Hsu, A., G. Sheriff, T. Chakraborty, and D. Manya, 2021: Disproportionate exposure to urban heat island intensity across major US cities. *Nature Communications*, **12** (1), 2721. <https://doi.org/10.1038/s41467-021-22799-5>
153. Hoffman, J.S., V. Shandas, and N. Pendleton, 2020: The effects of historical housing policies on resident exposure to intra-urban heat: A study of 108 US urban areas. *Climate*, **8** (1), 12. <https://doi.org/10.3390/cli8010012>
154. Cong, S., D. Nock, Y.L. Qiu, and B. Xing, 2022: Unveiling hidden energy poverty using the energy equity gap. *Nature Communications*, **13** (1), 2456. <https://doi.org/10.1038/s41467-022-30146-5>
155. Román, M.O., E.C. Stokes, R. Shrestha, Z. Wang, L. Schultz, E.A.S. Carlo, Q. Sun, J. Bell, A. Molthan, V. Kalb, C. Ji, K.C. Seto, S.N. McClain, and M. Enenkel, 2019: Satellite-based assessment of electricity restoration efforts in Puerto Rico after Hurricane Maria. *PLoS ONE*, **14** (6), e0218883. <https://doi.org/10.1371/journal.pone.0218883>
156. Sotolongo, M., L. Kuhl, and S.H. Baker, 2021: Using environmental justice to inform disaster recovery: Vulnerability and electricity restoration in Puerto Rico. *Environmental Science & Policy*, **122**, 59–71. <https://doi.org/10.1016/j.envsci.2021.04.004>
157. Adepoju, O.E., D. Han, M. Chae, K.L. Smith, L. Gilbert, S. Choudhury, and L. Woodard, 2021: Health disparities and climate change: The intersection of three disaster events on vulnerable communities in Houston, Texas. *International Journal of Environmental Research and Public Health*, **19** (1), 35. <https://doi.org/10.3390/ijerph19010035>

158. Falise, A.M., I. Griffin, D. Fernandez, X. Rodriguez, E. Moore, A. Barrera, J. Suarez, L. Cutie, and G. Zhang, 2019: Carbon monoxide poisoning in Miami-Dade County following Hurricane Irma in 2017. *Disaster Medicine and Public Health Preparedness*, **13** (1), 94–96. <https://doi.org/10.1017/dmp.2018.67>
159. Waddell, S.L., D.T. Jayaweera, M. Mirsaedi, J.C. Beier, and N. Kumar, 2021: Perspectives on the health effects of hurricanes: A review and challenges. *International Journal of Environmental Research and Public Health*, **18** (5), 2756. <https://doi.org/10.3390/ijerph18052756>
160. DOE. 2020: Low-Income Energy Affordability Data - LEAD Tool - 2018 Update. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. <https://doi.org/10.25984/1784729>
161. Dreihobl, A., L. Ross, and R. Ayala, 2020: How High Are Household Energy Burdens? An Assessment of National and Metropolitan Energy Burden across the United States. American Council for an Energy-Efficient Economy, Washington, DC. <https://www.aceee.org/sites/default/files/pdfs/u2006.pdf>
162. Kontokosta, C.E., V.J. Reina, and B. Bonczak, 2020: Energy cost burdens for low-income and minority households. *Journal of the American Planning Association*, **86** (1), 89–105. <https://doi.org/10.1080/01944363.2019.1647446>
163. Ross, L., A. Dreihobl, and B. Stickles, 2018: The High Cost of Energy in Rural America: Household Energy Burdens and Opportunities for Energy Efficiency. American Council for an Energy-Efficient Economy, Washington DC. <https://www.aceee.org/sites/default/files/publications/researchreports/u1806.pdf>
164. Jolley, G.J., C. Khalaf, G. Michaud, and A.M. Sandler, 2019: The economic, fiscal, and workforce impacts of coal-fired power plant closures in Appalachian Ohio. *Regional Science Policy & Practice*, **11** (2), 403–422. <https://doi.org/10.1111/rsp3.12191>
165. Wang, S.S.-C., Y. Qian, L.R. Leung, and Y. Zhang, 2021: Identifying key drivers of wildfires in the contiguous US using machine learning and game theory interpretation. *Earth's Future*, **9** (6), e2020EF001910. <https://doi.org/10.1029/2020ef001910>
166. Pai, S., H. Zerriffi, J. Jewell, and J. Pathak, 2020: Solar has greater techno-economic resource suitability than wind for replacing coal mining jobs. *Environmental Research Letters*, **15** (3), 034065. <https://doi.org/10.1088/1748-9326/ab6c6d>
167. Hansen, J.K., W.D. Jenson, A.M. Wrobel, N. Stauff, K. Biegel, T.K. Kim, R. Belles, and F. Omitaomu, 2022: Investigating Benefits and Challenges of Converting Retiring Coal Plants into Nuclear Plants. INL/RPT-22-67964-Rev000. U.S. Department of Energy, Idaho National Laboratory, Idaho Falls, ID. <https://doi.org/10.2172/1886660>
168. Mayfield, E., J. Jenkins, E. Larson, and C. Greig, 2023: Labor pathways to achieve net-zero emissions in the United States by mid-century. *Energy Policy*, **177**, 113516. <https://doi.org/10.1016/j.enpol.2023.113516>
169. Pollin, R., J. Wicks-Lim, and S. Chakraborty, 2020: Ch. 3. Industrial policy employment, and just transition. In: *America's Zero Carbon Action Plan*. Sustainable Development Solutions Network, 50–104. <https://irp-cdn.multiscreensite.com/6f2c9f57/files/uploaded/zero-carbon-action-plan-ch-03.pdf>
170. Wei, M., S. Patadia, and D.M. Kammen, 2010: Putting renewables and energy efficiency to work: How many jobs can the clean energy industry generate in the US? *Energy Policy*, **38** (2), 919–931. <https://doi.org/10.1016/j.enpol.2009.10.044>
171. Raimi, D., S. Carley, and D. Konisky, 2022: Mapping county-level vulnerability to the energy transition in US fossil fuel communities. *Scientific Reports*, **12** (1), 15748. <https://doi.org/10.1038/s41598-022-19927-6>
172. Righetti, T.K., T. Stoellinger, and R. Godby, 2021: Adapting to coal plant closures: A framework to understand state energy transition resistance. *Environmental Law*, **51** (4), 957–990. <https://doi.org/10.13140/rg.2.2.32801.74083>
173. Craig, M.T., P. Jaramillo, B.-M. Hodge, B. Nijssen, and C. Brancucci, 2020: Compounding climate change impacts during high stress periods for a high wind and solar power system in Texas. *Environmental Research Letters*, **15** (2), 024002. <https://doi.org/10.1088/1748-9326/ab6615>
174. AghaKouchak, A., F. Chiang, L.S. Huning, C.A. Love, I. Mallakpour, O. Mazdiyasni, H. Moftakhari, S.M. Papalexioiu, E. Ragno, and M. Sadegh, 2020: Climate extremes and compound hazards in a warming world. *Annual Review of Earth and Planetary Sciences*, **48** (1), 519–548. <https://doi.org/10.1146/annurev-earth-071719-055228>
175. Zscheischler, J., S. Westra, B.J.J.M. van den Hurk, S.I. Seneviratne, P.J. Ward, A. Pitman, A. AghaKouchak, D.N. Bresch, M. Leonard, T. Wahl, and X. Zhang, 2018: Future climate risk from compound events. *Nature Climate Change*, **8** (6), 469–477. <https://doi.org/10.1038/s41558-018-0156-3>

176. Wells, E.M., M. Boden, I. Tseytlin, and I. Linkov, 2022: Modeling critical infrastructure resilience under compounding threats: A systematic literature review. *Progress in Disaster Science*, **15**, 100244. <https://doi.org/10.1016/j.pdisas.2022.100244>
177. Mahzarnia, M., M.P. Moghaddam, P.T. Baboli, and P. Siano, 2020: A review of the measures to enhance power systems resilience. *IEEE Systems Journal*, **14** (3), 4059–4070. <https://doi.org/10.1109/jsyst.2020.2965993>
178. Ratnam, E.L., K.G.H. Baldwin, P. Mancarella, M. Howden, and L. Seebeck, 2020: Electricity system resilience in a world of increased climate change and cybersecurity risk. *The Electricity Journal*, **33** (9), 106833. <https://doi.org/10.1016/j.tej.2020.106833>
179. Bommareddy, S., B. Gilby, M. Khan, I. Chiu, M. Panteli, J.W. van de Lindt, L. Wells, Y. Amir, and A. Babay, 2022: Data-centric analysis of compound threats to critical infrastructure control systems. In: *52nd Annual IEEE/IFIP International Conference on Dependable Systems and Networks Workshops (DSN-W)*. IEEE, 72–79. <https://doi.org/10.1109/DSN-W54100.2022.00022>
180. Paul, S., F. Ding, K. Utkarsh, W. Liu, M.J. O'Malley, and J. Barnett, 2022: On vulnerability and resilience of cyber-physical power systems: A review. *IEEE Systems Journal*, **16** (2), 2367–2378. <https://doi.org/10.1109/jsyst.2021.3123904>
181. Moftakhari, H. and A. AghaKouchak, 2019: Increasing exposure of energy infrastructure to compound hazards: Cascading wildfires and extreme rainfall. *Environmental Research Letters*, **14** (10), 104018. <https://doi.org/10.1088/1748-9326/ab41a6>
182. Hill, J., J. Kern, D.E. Rupp, N. Voisin, and G. Characklis, 2021: The effects of climate change on interregional electricity market dynamics on the U.S. West Coast. *Earth's Future*, **9** (12), e2021EF002400. <https://doi.org/10.1029/2021ef002400>
183. Zhang, W. and G. Villarini, 2020: Deadly compound heat stress-flooding hazard across the central United States. *Geophysical Research Letters*, **47** (15), e2020GL089185. <https://doi.org/10.1029/2020gl089185>
184. EIA, 2021: Today in Energy: Extreme Winter Weather Is Disrupting Energy Supply and Demand, Particularly in Texas. U.S. Energy Information Administration, Washington, DC, accessed February 19, 2021. <https://www.eia.gov/todayinenergy/detail.php?id=46836>
185. FERC, 2021: FERC, NERC and Regional Entity Staff Report: The February 2021 Cold Weather Outages in Texas and the South Central United States. Federal Energy Regulatory Commission, North American Electric Reliability Corporation. https://www.naesb.org/pdf4/ferc_nerc_regional_entity_staff_report_feb2021_cold_weather_outages_111621.pdf
186. Moreno, R., D.N. Trakas, M. Jamieson, M. Panteli, P. Mancarella, G. Strbac, C. Marnay, and N. Hatziaargyriou, 2022: Microgrids against wildfires: Distributed energy resources enhance system resilience. *IEEE Power and Energy Magazine*, **20** (1), 78–89. <https://doi.org/10.1109/mpe.2021.3122772>
187. Vazquez, D.A.Z., F. Qiu, N. Fan, and K. Sharp, 2022: Wildfire mitigation plans in power systems: A literature review. *IEEE Transactions on Power Systems*, **37** (5), 3540–3551. <https://doi.org/10.1109/tpwrs.2022.3142086>
188. Taylor, W.O., P.L. Watson, D. Cerrai, and E.N. Anagnostou, 2022: Dynamic modeling of the effects of vegetation management on weather-related power outages. *Electric Power Systems Research*, **207**, 107840. <https://doi.org/10.1016/j.epsr.2022.107840>
189. Perera, A.T.D., B. Zhao, Z. Wang, K. Soga, and T. Hong, 2023: Optimal design of microgrids to improve wildfire resilience for vulnerable communities at the wildland-urban interface. *Applied Energy*, **335**, 120744. <https://doi.org/10.1016/j.apenergy.2023.120744>
190. Gong, H. and D.M. Ionel, 2021: Improving the power outage resilience of buildings with solar PV through the use of battery systems and EV energy storage. *Energies*, **14** (18). <https://doi.org/10.3390/en14185749>
191. Katopodis, T. and A. Sfetsos, 2019: A review of climate change impacts to oil sector critical services and suggested recommendations for industry uptake. *Infrastructures*, **4** (4), 74. <https://doi.org/10.3390/infrastructures4040074>
192. Gerlak, A.K., J. Weston, B. McMahan, R.L. Murray, and M. Mills-Novoa, 2018: Climate risk management and the electricity sector. *Climate Risk Management*, **19**, 12–22. <https://doi.org/10.1016/j.crm.2017.12.003>
193. Jordan, D., T. Barnes, N. Haegel, and I. Repins, 2021: Build solar-energy systems to last—Save billions. *Nature*, **600** (7888), 215–217. <https://doi.org/10.1038/d41586-021-03626-9>

194. Zamuda, C.D., T. Wall, L. Guzowski, J. Bergerson, J. Ford, L.P. Lewis, R. Jeffers, and S. DeRosa, 2019: Resilience management practices for electric utilities and extreme weather. *The Electricity Journal*, **32** (9), 106642. <https://doi.org/10.1016/j.tej.2019.106642>
195. Caldwell, P.M., C.R. Terai, B. Hillman, N.D. Keen, P. Bogenschutz, W. Lin, H. Beydoun, M. Taylor, L. Bertagna, A.M. Bradley, T.C. Clevenger, A.S. Donahue, C. Eldred, J. Foucar, J.-C. Golaz, O. Guba, R. Jacob, J. Johnson, J. Krishna, W. Liu, K. Pressel, A.G. Salinger, B. Singh, A. Steyer, P. Ullrich, D. Wu, X. Yuan, J. Shpund, H.-Y. Ma, and C.S. Zender, 2021: Convection-permitting simulations with the E3SM global atmosphere model. *Journal of Advances in Modeling Earth Systems*, **13** (11), e2021MS002544. <https://doi.org/10.1029/2021ms002544>
196. Leung, L.R., D.C. Bader, M.A. Taylor, and R.B. McCoy, 2020: An introduction to the E3SM special collection: Goals, science drivers, development, and analysis. *Journal of Advances in Modeling Earth Systems*, **12** (11), e2019MS001821. <https://doi.org/10.1029/2019ms001821>
197. Mauree, D., E. Naboni, S. Coccolo, A.T.D. Perera, V.M. Nik, and J.-L. Scartezzini, 2019: A review of assessment methods for the urban environment and its energy sustainability to guarantee climate adaptation of future cities. *Renewable and Sustainable Energy Reviews*, **112**, 733–746. <https://doi.org/10.1016/j.rser.2019.06.005>
198. McGuire, M., S. Gangopadhyay, J. Martin, G.T. Pederson, C.A. Woodhouse, and J.S. Littell, 2021: Water Reliability in the West—Secure Water Act Section 9503(C). Technical Memorandum No. ENV-2021-001. U.S. Bureau of Reclamation, 60 pp. <http://pubs.er.usgs.gov/publication/70219467>
199. Balaguru, K., D.R. Judi, and L.R. Leung, 2016: Future hurricane storm surge risk for the U.S. gulf and Florida coasts based on projections of thermodynamic potential intensity. *Climatic Change*, **138** (1), 99–110. <https://doi.org/10.1007/s10584-016-1728-8>
200. Sippel, S., N. Meinshausen, E. Székely, E. Fischer, A.G. Pendergrass, F. Lehner, and R. Knutti, 2021: Robust detection of forced warming in the presence of potentially large climate variability. *Science Advances*, **7** (43), 4429. <https://doi.org/10.1126/sciadv.abh4429>
201. Tebaldi, C., R. Ranasinghe, M. Vourdoukas, D.J. Rasmussen, B. Vega-Westhoff, E. Kirezci, R.E. Kopp, R. Sriver, and L. Mentaschi, 2021: Extreme sea levels at different global warming levels. *Nature Climate Change*, **11** (9), 746–751. <https://doi.org/10.1038/s41558-021-01127-1>
202. Wang, J., W. Zuo, L. Rhode-Barbarigos, X. Lu, J. Wang, and Y. Lin, 2019: Literature review on modeling and simulation of energy infrastructures from a resilience perspective. *Reliability Engineering & System Safety*, **183**, 360–373. <https://doi.org/10.1016/j.res.2018.11.029>
203. Beswick, R.R., A.M. Oliveira, and Y. Yan, 2021: Does the green hydrogen economy have a water problem? *ACS Energy Letters*, **6** (9), 3167–3169. <https://doi.org/10.1021/acsenenergylett.1c01375>
204. Watson, E.B. and A.H. Etemadi, 2020: Modeling electrical grid resilience under hurricane wind conditions with increased solar and wind power generation. *IEEE Transactions on Power Systems*, **35** (2), 929–937. <https://doi.org/10.1109/tpwrs.2019.2942279>
205. Cohen, S.M., A. Dyreson, S. Turner, V. Tidwell, N. Voisin, and A. Miara, 2022: A multi-model framework for assessing long- and short-term climate influences on the electric grid. *Applied Energy*, **317**, 119193. <https://doi.org/10.1016/j.apenergy.2022.119193>
206. Miara, A., S.M. Cohen, J. Macknick, C.J. Vörösmarty, F. Corsi, Y. Sun, V.C. Tidwell, R. Newmark, and B.M. Fekete, 2019: Climate-water adaptation for future US electricity infrastructure. *Environmental Science & Technology*, **53** (23), 14029–14040. <https://doi.org/10.1021/acs.est.9b03037>
207. Ralston Fonseca, F., M. Craig, P. Jaramillo, M. Bergés, E. Severnini, A. Loew, H. Zhai, Y. Cheng, B. Nijssen, N. Voisin, and J. Yearsley, 2021: Effects of climate change on capacity expansion decisions of an electricity generation fleet in the southeast U.S. *Environmental Science & Technology*, **55** (4), 2522–2531. <https://doi.org/10.1021/acs.est.0c06547>
208. Wessel, J., J.D. Kern, N. Voisin, K. Oikonomou, and J. Haas, 2022: Technology pathways could help drive the U.S. West Coast grid's exposure to hydrometeorological uncertainty. *Earth's Future*, **10** (1), e2021EF002187. <https://doi.org/10.1029/2021ef002187>
209. Levi, P.J., S.D. Kurland, M. Carbajales-Dale, J.P. Weyant, A.R. Brandt, and S.M. Benson, 2019: Macro-energy systems: Toward a new discipline. *Joule*, **3** (10), 2282–2286. <https://doi.org/10.1016/j.joule.2019.07.017>

210. Reed, P.M., A. Hadjimichael, R.H. Moss, E. Monier, S. Alba, C. Brelsford, C. Burleyson, S. Cohen, A. Dyreson, D. Gold, R. Gupta, K. Keller, M. Konar, J. Macknick, J. Morris, V. Srikrishnan, N. Voisin, and J. Yoon, 2022: MultiSector Dynamics: Scientific Challenges and a Research Vision for 2030. U.S. Department of Energy, Office of Science. <https://doi.org/10.5281/zenodo.6144309>
211. Szinai, J.K., R. Deshmukh, D.M. Kammen, and A.D. Jones, 2020: Evaluating cross-sectoral impacts of climate change and adaptations on the energy-water nexus: A framework and California case study. *Environmental Research Letters*, **15** (12), 124065. <https://doi.org/10.1088/1748-9326/abc378>
212. Voisin, N., V. Tidwell, M. Kintner-Meyer, and F. Boltz, 2019: Planning for sustained water-electricity resilience over the U.S.: Persistence of current water-electricity operations and long-term transformative plans. *Water Security*, **7**, 100035. <https://doi.org/10.1016/j.wasec.2019.100035>
213. Yoon, J., P. Romero-Lankao, Y.C.E. Yang, C. Klassert, N. Urban, K. Kaiser, K. Keller, B. Yarlagadda, N. Voisin, P.M. Reed, and R. Moss, 2022: A typology for characterizing human action in multisector dynamics models. *Earth's Future*, **10** (8), e2021EF002641. <https://doi.org/10.1029/2021ef002641>
214. Bennett, J.A., C.N. Trevisan, J.F. DeCarolis, C. Ortiz-Garcia, M. Pérez-Lugo, B.T. Etienne, and A.F. Clarens, 2021: Extending energy system modelling to include extreme weather risks and application to hurricane events in Puerto Rico. *Nature Energy*, **6** (3), 240–249. <https://doi.org/10.1038/s41560-020-00758-6>
215. Ross, R., V. Pillitteri, R. Graubart, D. Bodeau, and R. McQuaid, 2021: Developing Cyber-Resilient Systems: A Systems Security Engineering Approach. NIST Special Publication, SP 800-160 Vol. 2 Rev. 1. U.S. Department of Commerce, National Institute of Standards and Technology. <https://doi.org/10.6028/nist.sp.800-160v2r1>
216. Tsvetanov, T. and S. Slaria, 2021: The effect of the Colonial Pipeline shutdown on gasoline prices. *Economics Letters*, **209**, 110122. <https://doi.org/10.1016/j.econlet.2021.110122>
217. AghaKouchak, A., L.S. Huning, F. Chiang, M. Sadegh, F. Vahedifard, O. Mazdiyasni, H. Moftakhari, and I. Mallakpour, 2018: How do natural hazards cascade to cause disasters? *Nature*, **561** (7724), 458–460. <https://doi.org/10.1038/d41586-018-06783-6>
218. Osman, A.I., L. Chen, M. Yang, G. Msigwa, M. Farghali, S. Fawzy, D.W. Rooney, and P.-S. Yap, 2023: Cost, environmental impact, and resilience of renewable energy under a changing climate: A review. *Environmental Chemistry Letters*, **21** (2), 741–764. <https://doi.org/10.1007/s10311-022-01532-8>
219. Dyreson, A., N. Devineni, S.W.D. Turner, T. De Silva M, A. Miara, N. Voisin, S. Cohen, and J. Macknick, 2022: The role of regional connections in planning for future power system operations under climate extremes. *Earth's Future*, **10** (6), e2021EF002554. <https://doi.org/10.1029/2021ef002554>
220. EIA, 2021: Today in Energy: U.S. Electric Power Sector's Use of Water Continued Its Downward Trend in 2020. U.S. Energy Information Administration, Washington, DC. <https://www.eia.gov/todayinenergy/detail.php?id=50698>
221. Bushnaq, O.M., A. Chaaban, and T.Y. Al-Naffouri, 2021: The role of UAV-IoT networks in future wildfire detection. *IEEE Internet of Things Journal*, **8** (23), 16984–16999. <https://doi.org/10.1109/jiot.2021.3077593>
222. OCM, 2022: Digital Coasts. National Oceanic and Atmospheric Administration, National Ocean Service, Office for Coastal Management. <https://coast.noaa.gov/digitalcoast/>
223. U.S. Federal Government, 2021: U.S. Climate Resilience Toolkit: Energy [Webpage]. <https://toolkit.climate.gov/topics/energy-supply-and-use>
224. GAO, 2019: Climate Resilience: A Strategic Investment Approach for High-Priority Projects Could Help Target Federal Resources. GAO-20-127. U.S. Government Accountability Office. <https://www.gao.gov/products/gao-20-127>
225. Hong, T., Z. Wang, X. Luo, and W. Zhang, 2020: State-of-the-art on research and applications of machine learning in the building life cycle. *Energy and Buildings*, **212**, 109831. <https://doi.org/10.1016/j.enbuild.2020.109831>
226. Kumbhar, A., P.G. Dhawale, S. Kumbhar, U. Patil, and P. Magdum, 2021: A comprehensive review: Machine learning and its application in integrated power system. *Energy Reports*, **7**, 5467–5474. <https://doi.org/10.1016/j.egy.2021.08.133>

227. Satchwell, A., M.A. Piette, A. Khandekar, J. Granderson, N.M. Frick, R. Hledik, A. Faruqui, L. Lam, S. Ross, J. Cohen, K. Wang, D. Urigwe, D. Delurey, M. Neukomm, and D. Nemtsov, 2021: A National Roadmap for Grid-Interactive Efficient Buildings. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. <https://gebroadmap.lbl.gov/>
228. Dragoña, J., J. Arroyo, I. Cupeiro Figueroa, D. Blum, K. Arendt, D. Kim, E.P. Ollé, J. Oravec, M. Wetter, D.L. Vrabie, and L. Helsen, 2020: All you need to know about model predictive control for buildings. *Annual Reviews in Control*, **50**, 190–232. <https://doi.org/10.1016/j.arcontrol.2020.09.001>
229. Wang, Z. and T. Hong, 2020: Reinforcement learning for building controls: The opportunities and challenges. *Applied Energy*, **269**, 115036. <https://doi.org/10.1016/j.apenergy.2020.115036>
230. Nubbe, V. and M. Yamada, 2019: Grid-Interactive Efficient Buildings Technical Report Series: Lighting and Electronics. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. <https://doi.org/10.2172/1580213>
231. Bistline, J.E.T., 2021: Roadmaps to net-zero emissions systems: Emerging insights and modeling challenges. *Joule*, **5** (10), 2551–2563. <https://doi.org/10.1016/j.joule.2021.09.012>
232. IEA, 2021: Net Zero by 2050: A Roadmap for the Global Energy Sector. International Energy Agency, Paris, France. <https://www.iea.org/reports/net-zero-by-2050>
233. IPCC, 2023: Summary for policymakers. In: *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Lee, H. and J. Romero, Eds. Intergovernmental Panel on Climate Change, Geneva, Switzerland, 1–34. <https://doi.org/10.59327/IPCC/AR6-9789291691647.001>
234. Murphy, C., T. Mai, Y. Sun, P. Jadun, P. Donohoo-Vallett, M. Muratori, R. Jones, and B. Nelson, 2020: High electrification futures: Impacts to the U.S. bulk power system. *The Electricity Journal*, **33** (10), 106878. <https://doi.org/10.1016/j.tej.2020.106878>
235. McLaughlin, K. and L. Bird, 2021: The US Set a Record for Renewables in 2020, but More Is Needed. World Resources Institute. <https://www.wri.org/insights/renewable-energy-2020-record-us>
236. EIA, 2022: Annual Energy Outlook 2022. U.S. Energy Information Administration, Washington, DC. <https://www.eia.gov/outlooks/aeo/narrative/introduction/sub-topic-02.php>
237. DOS and EOP, 2021: The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050. U.S. Department of State and U.S. Executive Office of the President, Washington, DC. <https://www.whitehouse.gov/wp-content/uploads/2021/10/us-long-term-strategy.pdf>
238. Larson, E., C. Greig, J. Jenkins, E. Mayfield, A. Pascale, C. Zhang, J. Drossman, R. Williams, S. Pacala, R. Socolow, E. Baik, R. Birdsey, R. Duke, R. Jones, B. Haley, E. Leslie, K. Paustian, and A. Swan, 2021: Final Report Summary—Net-Zero America: Potential Pathways, Infrastructure, and Impacts. Princeton University, Princeton, NJ. <https://netzeroamerica.princeton.edu/the-report>
239. Mueller, J.T. and M.M. Brooks, 2020: Burdened by renewable energy? A multi-scalar analysis of distributional justice and wind energy in the United States. *Energy Research & Social Science*, **63**, 101406. <https://doi.org/10.1016/j.erss.2019.101406>
240. FCAB, 2021: National Blueprint for Lithium Batteries 2021–2030. Federal Consortium for Advanced Batteries. https://www.energy.gov/sites/default/files/2021-06/FCAB%20National%20Blueprint%20Lithium%20Batteries%200621_0.pdf
241. DOE, 2021: Hydrogen Shot. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. <https://www.energy.gov/eere/fuelcells/hydrogen-shot>
242. NRC, 2021: Application Review Schedule for the NuScale US600 Design. U.S. Nuclear Regulatory Commission. <https://www.nrc.gov/reactors/new-reactors/smr/nuscale/review-schedule.html>
243. Carley, S. and D.M. Konisky, 2020: The justice and equity implications of the clean energy transition. *Nature Energy*, **5** (8), 569–577. <https://doi.org/10.1038/s41560-020-0641-6>
244. McNamara, W., H. Passell, M. Montes, R. Jeffers, and I. Gyuk, 2022: Seeking energy equity through energy storage. *The Electricity Journal*, **35** (1), 107063. <https://doi.org/10.1016/j.tej.2021.107063>

245. Widerynski, S., P. Schramm, K. Conlon, R. Noe, E. Grossman, M. Hawkins, S. Nayak, M. Roach, and A.S. Hiltz, 2017: The Use of Cooling Centers to Prevent Heat-Related Illness: Summary of Evidence and Strategies for Implementation. Centers for Disease Control and Prevention, National Center for Environmental Health. <https://www.cdc.gov/climateandhealth/docs/useofcoolingcenters.pdf>
246. STACCWG, 2021: The Status of Tribes and Climate Change Report. Marks-Marino, D., Ed. Northern Arizona University, Institute for Tribal Environmental Professionals, Flagstaff, AZ. <http://nau.edu/stacc2021>
247. Gallagher, C.L. and T. Holloway, 2020: Integrating air quality and public health benefits in U.S. decarbonization strategies. *Frontiers in Public Health*, **8**, 563358. <https://doi.org/10.3389/fpubh.2020.563358>
248. Markandya, A., J. Sampedro, S.J. Smith, R. Van Dingenen, C. Pizarro-Irizar, I. Arto, and M. González-Eguino, 2018: Health co-benefits from air pollution and mitigation costs of the Paris Agreement: A modelling study. *The Lancet Planetary Health*, **2** (3), e126–e133. [https://doi.org/10.1016/s2542-5196\(18\)30029-9](https://doi.org/10.1016/s2542-5196(18)30029-9)
249. Shindell, D., G. Faluvegi, K. Seltzer, and C. Shindell, 2018: Quantified, localized health benefits of accelerated carbon dioxide emissions reductions. *Nature Climate Change*, **8** (4), 291–295. <https://doi.org/10.1038/s41558-018-0108-y>
250. Vandyck, T., K. Keramidas, A. Kitous, J.V. Spadaro, R. Van Dingenen, M. Holland, and B. Saveyn, 2018: Air quality co-benefits for human health and agriculture counterbalance costs to meet Paris Agreement pledges. *Nature Communications*, **9** (1), 4939. <https://doi.org/10.1038/s41467-018-06885-9>
251. Carpenter, A. and M. Wagner, 2019: Environmental justice in the oil refinery industry: A panel analysis across United States counties. *Ecological Economics*, **159**, 101–109. <https://doi.org/10.1016/j.ecolecon.2019.01.020>
252. Elliott, M. and N. Kittner, 2022: Operational grid and environmental impacts for a V2G-enabled electric school bus fleet using DC fast chargers. *Sustainable Production and Consumption*, **30**, 316–330. <https://doi.org/10.1016/j.spc.2021.11.029>
253. Rowangould, G.M., 2013: A census of the US near-roadway population: Public health and environmental justice considerations. *Transportation Research Part D: Transport and Environment*, **25**, 59–67. <https://doi.org/10.1016/j.trd.2013.08.003>
254. Babaei, S., D.H. Loughlin, and P.O. Kaplan, 2020: Incorporating upstream emissions into electric sector nitrogen oxide reduction targets. *Cleaner Engineering and Technology*, **1**, 100017. <https://doi.org/10.1016/j.clet.2020.100017>
255. Gonzalez-Salazar, M.A., T. Kirsten, and L. Prchlik, 2018: Review of the operational flexibility and emissions of gas- and coal-fired power plants in a future with growing renewables. *Renewable and Sustainable Energy Reviews*, **82** (1), 1497–1513. <https://doi.org/10.1016/j.rser.2017.05.278>
256. Luderer, G., M. Pehl, A. Arvesen, T. Gibon, B.L. Bodirsky, H.S. de Boer, O. Fricko, M. Hejazi, F. Humpenöder, G. Iyer, S. Mima, I. Mouratiadou, R.C. Pietzcker, A. Popp, M. van den Berg, D. van Vuuren, and E.G. Hertwich, 2019: Environmental co-benefits and adverse side-effects of alternative power sector decarbonization strategies. *Nature Communications*, **10** (1), 5229. <https://doi.org/10.1038/s41467-019-13067-8>
257. Ou, Y., W. Shi, S.J. Smith, C.M. Ledna, J.J. West, C.G. Nolte, and D.H. Loughlin, 2018: Estimating environmental co-benefits of U.S. low-carbon pathways using an integrated assessment model with state-level resolution. *Applied Energy*, **216**, 482–493. <https://doi.org/10.1016/j.apenergy.2018.02.122>
258. Brown, M.A., A. Soni, M.V. Lapsa, K. Southworth, and M. Cox, 2020: High energy burden and low-income energy affordability: Conclusions from a literature review. *Progress in Energy*, **2** (4), 042003. <https://doi.org/10.1088/2516-1083/abb954>
259. Zamuda, C.D. and A. Ressler, 2020: Federal adaptation and mitigation programs supporting community investment in electricity resilience to extreme weather. *The Electricity Journal*, **33** (8), 106825. <https://doi.org/10.1016/j.tej.2020.106825>
260. DOE, 2021: Weatherization Assistance Program Fact Sheet. U.S. Department of Energy, 2 pp. https://www.energy.gov/sites/default/files/2021/01/f82/WAP-fact-sheet_2021_0.pdf
261. DOE, 2021: Equity in Energy: An Energy Economy for Everyone. U.S. Department of Energy, Office of Economic Impact and Diversity. https://www.energy.gov/sites/default/files/2021/01/f82/Equity_in_Energy_Booklet_1_11.pdf

262. Zeng, Z., A.D. Ziegler, T. Searchinger, L. Yang, A. Chen, K. Ju, S. Piao, L.Z.X. Li, P. Ciais, D. Chen, J. Liu, C. Azorin-Molina, A. Chappell, D. Medvigy, and E.F. Wood, 2019: A reversal in global terrestrial stilling and its implications for wind energy production. *Nature Climate Change*, **9** (12), 979–985. <https://doi.org/10.1038/s41558-019-0622-6>
263. Pryor, S.C., J.J. Coburn, R.J. Barthelmie, and T.J. Shepherd, 2023: Projecting future energy production from operating wind farms in North America. Part I: Dynamical downscaling. *Journal of Applied Meteorology and Climatology*, **62** (1), 63–80. <https://doi.org/10.1175/jamc-d-22-0044.1>
264. Yalaw, S.G., M.T.H. van Vliet, D.E.H.J. Gernaat, F. Ludwig, A. Miara, C. Park, E. Byers, E. De Cian, F. Piontek, G. Iyer, I. Mouratiadou, J. Glynn, M. Hejazi, O. Dessens, P. Rochedo, R. Pietzcker, R. Schaeffer, S. Fujimori, S. Dasgupta, S. Mima, S.R.S. da Silva, V. Chaturvedi, R. Vautard, and D.P. van Vuuren, 2020: Impacts of climate change on energy systems in global and regional scenarios. *Nature Energy*, **5** (10), 794–802. <https://doi.org/10.1038/s41560-020-0664-z>
265. Burleyson, C.D., G. Iyer, M. Hejazi, S. Kim, P. Kyle, J.S. Rice, A.D. Smith, Z.T. Taylor, N. Voisin, and Y. Xie, 2020: Future western U.S. building electricity consumption in response to climate and population drivers: A comparative study of the impact of model structure. *Energy*, **208**, 118312. <https://doi.org/10.1016/j.energy.2020.118312>
266. Marsooli, R., N. Lin, K. Emanuel, and K. Feng, 2019: Climate change exacerbates hurricane flood hazards along US Atlantic and Gulf Coasts in spatially varying patterns. *Nature Communications*, **10** (1), 3785. <https://doi.org/10.1038/s41467-019-11755-z>
267. Cohen, J., K. Pfeiffer, and J.A. Francis, 2018: Warm Arctic episodes linked with increased frequency of extreme winter weather in the United States. *Nature Communications*, **9** (1), 869. <https://doi.org/10.1038/s41467-018-02992-9>
268. Blackport, R., J.A. Screen, K. van der Wiel, and R. Bintanja, 2019: Minimal influence of reduced Arctic sea ice on coincident cold winters in mid-latitudes. *Nature Climate Change*, **9** (9), 697–704. <https://doi.org/10.1038/s41558-019-0551-4>
269. Cohen, J., X. Zhang, J. Francis, T. Jung, R. Kwok, J. Overland, T.J. Ballinger, U.S. Bhatt, H.W. Chen, D. Coumou, S. Feldstein, H. Gu, D. Handorf, G. Henderson, M. Ionita, M. Kretschmer, F. Laliberte, S. Lee, H.W. Linderholm, W. Maslowski, Y. Peings, K. Pfeiffer, I. Rigor, T. Semmler, J. Stroeve, P.C. Taylor, S. Vavrus, T. Vihma, S. Wang, M. Wendisch, Y. Wu, and J. Yoon, 2020: Divergent consensus on Arctic amplification influence on midlatitude severe winter weather. *Nature Climate Change*, **10** (1), 20–29. <https://doi.org/10.1038/s41558-019-0662-y>
270. Tian, Q., G. Huang, K. Hu, and D. Niyogi, 2019: Observed and global climate model based changes in wind power potential over the Northern Hemisphere during 1979–2016. *Energy*, **167**, 1224–1235. <https://doi.org/10.1016/j.energy.2018.11.027>
271. Craig, M.T., S. Cohen, J. Macknick, C. Draxl, O.J. Guerra, M. Sengupta, S.E. Haupt, B.M. Hodge, and C. Brancucci, 2018: A review of the potential impacts of climate change on bulk power system planning and operations in the United States. *Renewable and Sustainable Energy Reviews*, **98**, 255–267. <https://doi.org/10.1016/j.rser.2018.09.022>
272. Cronin, J., G. Anandarajah, and O. Dessens, 2018: Climate change impacts on the energy system: A review of trends and gaps. *Climatic Change*, **151** (2), 79–93. <https://doi.org/10.1007/s10584-018-2265-4>
273. Auffhammer, M., P. Baylis, and C.H. Hausman, 2017: Climate change is projected to have severe impacts on the frequency and intensity of peak electricity demand across the United States. *Proceedings of the National Academy of Sciences of the United States of America*, **114** (8), 1886–1891. <https://doi.org/10.1073/pnas.1613193114>
274. Martel, J.L., F.P. Brissette, P. Lucas-Picher, M. Troin, and R. Arsenault, 2021: Climate change and rainfall intensity-duration-frequency curves: Overview of science and guidelines for adaptation. *Journal of Hydrologic Engineering*, **26** (10), 03121001. [https://doi.org/10.1061/\(asce\)he.1943-5584.0002122](https://doi.org/10.1061/(asce)he.1943-5584.0002122)
275. Maxim, A. and E. Grubert, 2022: Anticipating climate-related changes to residential energy burden in the United States: Advance planning for equity and resilience. *Environmental Justice*, **15** (3), 139–148. <https://doi.org/10.1089/env.2021.0056>
276. Leon, W. and A. Ziai, 2023: Table of 100% Clean Energy States. Clean Energy Group, accessed April 5, 2023. <https://www.cesa.org/projects/100-clean-energy-collaborative/guide/table-of-100-clean-energy-states/>
277. McMahan, B. and A.K. Gerlak, 2020: Climate risk assessment and cascading impacts: Risks and opportunities for an electrical utility in the U.S. Southwest. *Climate Risk Management*, **29**, 100240. <https://doi.org/10.1016/j.crm.2020.100240>

278. EPA, 2022: State Energy and Environment Guide to Action: Electricity Resources Planning and Procurement. EPA-430-R-22-004. U.S. Environmental Protection Agency. https://www.epa.gov/system/files/documents/2022-08/Electricity%20Resource%20Planning%20and%20Procurement_508.pdf
279. Cooke, A., J.S. Homer, J. Lessick, D. Bhatnagar, and K. Kazimierczuk, 2021: A Review of Water and Climate Change Analysis in Electric Utility Integrated Resource Planning. PNNL-30910. U.S. Department of Energy, Pacific Northwest National Laboratory. <https://doi.org/10.2172/1906361>
280. Deser, C., A. Phillips, V. Bourdette, and H. Teng, 2012: Uncertainty in climate change projections: The role of internal variability. *Climate Dynamics*, **38** (3), 527–546. <https://doi.org/10.1007/s00382-010-0977-x>
281. Golaz, J.-C., L.P. Van Roekel, X. Zheng, A.F. Roberts, J.D. Wolfe, W. Lin, A.M. Bradley, Q. Tang, M.E. Maltrud, R.M. Forsyth, C. Zhang, T. Zhou, K. Zhang, C.S. Zender, M. Wu, H. Wang, A.K. Turner, B. Singh, J.H. Richter, Y. Qin, M.R. Petersen, A. Mametjanov, P.-L. Ma, V.E. Larson, J. Krishna, N.D. Keen, N. Jeffery, E.C. Hunke, W.M. Hannah, O. Guba, B.M. Griffin, Y. Feng, D. Engwirda, A.V. Di Vittorio, C. Dang, L.M. Conlon, C.-C.-J. Chen, M.A. Brunke, G. Bisht, J.J. Benedict, X.S. Asay-Davis, Y. Zhang, M. Zhang, X. Zeng, S. Xie, P.J. Wolfram, T. Vo, M. Veneziani, T.K. Tesfa, S. Sreepathi, A.G. Salinger, J.E.J. Reeves Eyre, M.J. Prather, S. Mahajan, Q. Li, P.W. Jones, R.L. Jacob, G.W. Huebler, X. Huang, B.R. Hillman, B.E. Harrop, J.G. Foucar, Y. Fang, D.S. Comeau, P.M. Caldwell, T. Bartoletti, K. Balaguru, M.A. Taylor, R.B. McCoy, L.R. Leung, and D.C. Bader, 2022: The DOE E3SM Model Version 2: Overview of the physical model and initial model evaluation. *Journal of Advances in Modeling Earth Systems*, **14** (12), e2022MS003156. <https://doi.org/10.1029/2022ms003156>
282. Kay, J.E., C. Deser, A. Phillips, A. Mai, C. Hannay, G. Strand, J.M. Arblaster, S.C. Bates, G. Danabasoglu, J. Edwards, M. Holland, P. Kushner, J.F. Lamarque, D. Lawrence, K. Lindsay, A. Middleton, E. Munoz, R. Neale, K. Oleson, L. Polvani, and M. Vertenstein, 2015: The Community Earth System Model (CESM) large ensemble Project: A community resource for studying climate change in the presence of internal climate variability. *Bulletin of the American Meteorological Society*, **96** (8), 1333–1349. <https://doi.org/10.1175/bams-d-13-00255.1>
283. Maher, N., S. Milinski, and R. Ludwig, 2021: Large ensemble climate model simulations: Introduction, overview, and future prospects for utilising multiple types of large ensemble. *Earth System Dynamics*, **12** (2), 401–418. <https://doi.org/10.5194/esd-12-401-2021>
284. Peng, W., G. Iyer, V. Bosetti, V. Chaturvedi, J. Edmonds, A.A. Fawcett, S. Hallegatte, D.G. Victor, D. van Vuuren, and J. Weyant, 2021: Climate policy models need to get real about people—Here's how. *Nature*, **594** (7862), 174–176. <https://doi.org/10.1038/d41586-021-01500-2>
285. Wise, M., P. Patel, Z. Khan, S.H. Kim, M. Hejazi, and G. Iyer, 2019: Representing power sector detail and flexibility in a multi-sector model. *Energy Strategy Reviews*, **26**, 100411. <https://doi.org/10.1016/j.esr.2019.100411>
286. IEA, 2021: About CCUS. International Energy Agency, accessed April 2021. <https://www.iea.org/reports/about-ccus>
287. IEA, 2021: Direct Air Capture: More Efforts Needed. International Energy Agency, Paris, France. <https://www.iea.org/reports/direct-air-capture>
288. Gohlke, D., Y. Zhou, X. Wu, and C. Courtney, 2022: Assessment of Light-Duty Plug-in Electric Vehicles in the United States, 2010–2021. ANL-22/71. U.S. Department of Energy, Argonne National Laboratory. <https://doi.org/10.2172/1898424>
289. National Academies of Sciences, Engineering, and Medicine, 2020: *Models to Inform Planning for the Future of Electric Power in the United States: Proceedings of a Workshop*. The National Academies Press, Washington, DC, 88 pp. <https://doi.org/10.17226/25880>
290. Tang, Q., S.A. Klein, S. Xie, W. Lin, J.C. Golaz, E.L. Roesler, M.A. Taylor, P.J. Rasch, D.C. Bader, L.K. Berg, P. Caldwell, S.E. Giangrande, R.B. Neale, Y. Qian, L.D. Riihimaki, C.S. Zender, Y. Zhang, and X. Zheng, 2019: Regionally refined test bed in E3SM atmosphere model version 1 (EAMv1) and applications for high-resolution modeling. *Geoscientific Model Development*, **12** (7), 2679–2706. <https://doi.org/10.5194/gmd-12-2679-2019>
291. Macknick, J., A. Kandt, P. Kurup, X. Li, J. McCall, A. Miara, J. Sperling, and A. de Fontaine, 2019: Water Security Grand Challenge Workshop Outcomes. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. <https://www.energy.gov/eere/analysis/articles/water-security-grand-challenge-workshop-outcomes>
292. Mouratiadou, I., M. Bevione, D.L. Bijl, L. Drouet, M. Hejazi, S. Mima, M. Pehl, and G. Luderer, 2018: Water demand for electricity in deep decarbonisation scenarios: A multi-model assessment. *Climatic Change*, **147** (1), 91–106. <https://doi.org/10.1007/s10584-017-2117-7>

293. Hadjimichael, A., J. Quinn, E. Wilson, P. Reed, L. Basdekas, D. Yates, and M. Garrison, 2020: Defining robustness, vulnerabilities, and consequential scenarios for diverse stakeholder interests in institutionally complex river basins. *Earth's Future*, **8** (7), e2020EF001503. <https://doi.org/10.1029/2020ef001503>
294. Shindell, D., M. Ru, Y. Zhang, K. Seltzer, G. Faluvegi, L. Nazarenko, G.A. Schmidt, L. Parsons, A. Challapalli, L. Yang, and A. Glick, 2021: Temporal and spatial distribution of health, labor, and crop benefits of climate change mitigation in the United States. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (46), e2104061118. <https://doi.org/10.1073/pnas.2104061118>
295. Oke, D., J.B. Dunn, and T.R. Hawkins, 2022: The contribution of biomass and waste resources to decarbonizing transportation and related energy and environmental effects. *Sustainable Energy & Fuels*, **6** (3), 721–735. <https://doi.org/10.1039/d1se01742j>
296. Lamers, P., T. Ghosh, S. Upasani, R. Sacchi, and V. Daioglou, 2023: Linking life cycle and integrated assessment modeling to evaluate technologies in an evolving system context: A power-to-hydrogen case study for the United States. *Environmental Science & Technology*, **57** (6), 2464–2473. <https://doi.org/10.1021/acs.est.2c04246>