4 Energy Supply, Delivery, and Demand

Federal Coordinating Lead Author
Craig D. Zamuda
U.S. Department of Energy, Office of Policy

Chapter Lead
Craig D. Zamuda
U.S. Department of Energy, Office of Policy

Chapter Authors
Daniel E. Bilello
National Renewable Energy Laboratory

Guenter Conzelmann
Argonne National Laboratory

Ellen Mecray
National Oceanic and Atmospheric Administration

Ann Satsangi
U.S. Department of Energy, Office of Fossil Energy

Vincent Tidwell
Sandia National Laboratories

Brian J. Walker
U.S. Department of Energy, Office of Energy
Efficiency and Renewable Energy

Review Editor
Sara C. Pryor
Cornell University

Recommended Citation for Chapter

Zamuda, C., D.E. Bilello, G. Conzelmann, E. Mecray, A. Satsangi, V. Tidwell, and B.J. Walker, 2018: 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.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 174–201. doi: 10.7930/NCA4.2018.CH4

On the Web: https://nca2018.globalchange.gov/chapter/energy

Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II

4 Energy Supply, Delivery, and Demand

Linemen working to restore power in Puerto Rico after Hurricane Maria in 2017

Key Message 1

Nationwide Impacts on Energy

The Nation’s energy system is already affected by extreme weather events, and due to climate change, it is projected to be increasingly threatened by more frequent and longer-lasting power outages affecting critical energy infrastructure and creating fuel availability and demand imbalances. The reliability, security, and resilience of the energy system underpin virtually every sector of the U.S. economy. Cascading impacts on other critical sectors could affect economic and national security.

Key Message 2

Changes in Energy System Affect Vulnerabilities

Changes in energy technologies, markets, and policies are affecting the energy system’s vulnerabilities to climate change and extreme weather. Some of these changes increase reliability and resilience, while others create additional vulnerabilities. Changes include the following: natural gas is increasingly used as fuel for power plants; renewable resources are becoming increasingly cost competitive with an expanding market share; and a resilient energy supply is increasingly important as telecommunications, transportation, and other critical systems are more interconnected than ever.

Key Message 3

Improving Energy System Resilience

Actions are being taken to enhance energy security, reliability, and resilience with respect to the effects of climate change and extreme weather. This progress occurs through improved data collection, modeling, and analysis to support resilience planning; private and public–private partnerships supporting coordinated action; and both development and deployment of new, innovative energy technologies for adapting energy assets to extreme weather hazards. Although barriers exist, opportunities remain to accelerate the pace, scale, and scope of investments in energy systems resilience.

Executive Summary

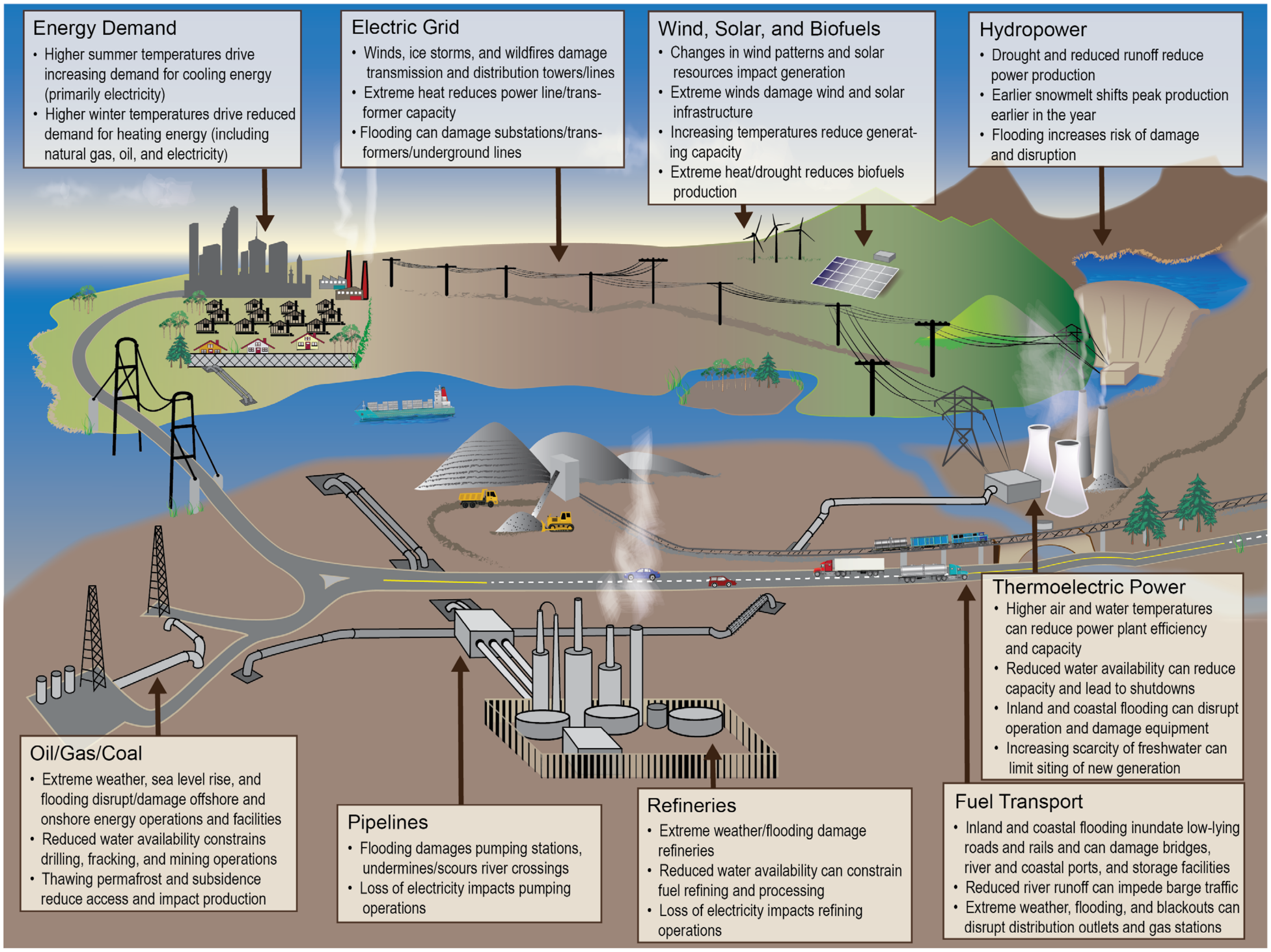
The Nation's economic security is increasingly dependent on an affordable and reliable supply of energy.[1,2] Every sector of the economy depends on energy, from manufacturing to agriculture, banking, healthcare, telecommunications, and transportation. Increasingly, climate change and extreme weather events are affecting the energy system, threatening more frequent and longer-lasting power outages and fuel shortages. Such events can have cascading impacts on other critical sectors, potentially affecting the Nation's economic and national security. At the same time, the energy sector is undergoing substantial policy, market, and technology-driven changes that are projected to affect these vulnerabilities.

The impacts of extreme weather and climate change on energy systems will differ across the United States.[3] Low-lying energy facilities and systems located along inland waters or near the coasts are at elevated risk of flooding from more intense precipitation, rising sea levels, and more intense hurricanes.[4,5,6,7,8] Increases in the severity and frequency of extreme precipitation are projected to affect inland energy infrastructure in every region. Rising temperatures and extreme heat events are projected to reduce the generation capacity of thermoelectric power plants and decrease the efficiency of the transmission grid.[9,10] Rising temperatures are projected to also drive greater use of air conditioning and increase electricity demand, likely resulting in increases in electricity costs.[8,11,12,13,14,15,16,17,18,19] The increase in annual electricity demand across the country for cooling is offset only marginally by the relatively small decline in electricity demand for heating. Extreme cold events, including ice and snow events, can damage power lines and impact fuel supplies.[20] Severe drought, along with changes in evaporation, reductions in mountain snowpack, and shifting mountain snowmelt timing, is projected to reduce hydropower production and threaten oil and gas drilling and refining, as well as thermoelectric power plants that rely on surface water for cooling.[3,21,22,23,24] Drier conditions are projected to increase the risk of wildfires and damage to energy production and generation assets and the power grid.[3,8]

At the same time, the nature of the energy system itself is changing.[1,2,22,25,26,27,28,29,30,31,32,33,34] Low carbon-emitting natural gas generation has displaced coal generation due to the rising production of low-cost, unconventional natural gas, in part supported by federal investment in research and development.[35] In the last 10 years, the share of generation from natural gas increased from 20% to over 30%, while coal has declined from nearly 50% to around 30%.[36] Over this same time, generation from wind and solar has grown from less than 1% to over 5% due to a combination of technological progress, dramatic cost reductions, and federal and state policies.[2,33]

It is possible to address the challenges of a changing climate and energy system, and both industry and governments at the local, state, regional, federal, and tribal levels are taking actions to improve the resilience of the Nation's energy system. These actions include planning and operational measures that seek to anticipate climate impacts and prevent or respond to damages more effectively, as well as hardening measures to protect assets from damage during extreme events.[3,37,38,39,40,41,42] Resilience actions can have co-benefits, such as developing and deploying new innovative energy technologies that increase resilience and reduce emissions. While steps are being taken, an escalation of the pace, scale, and scope of efforts is needed to ensure the safe and reliable provision of energy and to establish a climate-ready energy system to address present and future risks.

Potential Impacts from Extreme Weather and Climate Change



Energy Demand
- Higher summer temperatures drive increasing demand for cooling energy (primarily electricity)
- Higher winter temperatures drive reduced demand for heating energy (including natural gas, oil, and electricity)

Electric Grid
- Winds, ice storms, and wildfires damage transmission and distribution towers/lines
- Extreme heat reduces power line/transformer capacity
- Flooding can damage substations/transformers/underground lines

Wind, Solar, and Biofuels
- Changes in wind patterns and solar resources impact generation
- Extreme winds damage wind and solar infrastructure
- Increasing temperatures reduce generating capacity
- Extreme heat/drought reduces biofuels production

Hydropower
- Drought and reduced runoff reduce power production
- Earlier snowmelt shifts peak production earlier in the year
- Flooding increases risk of damage and disruption

Thermoelectric Power
- Higher air and water temperatures can reduce power plant efficiency and capacity
- Reduced water availability can reduce capacity and lead to shutdowns
- Inland and coastal flooding can disrupt operation and damage equipment
- Increasing scarcity of freshwater can limit siting of new generation

Oil/Gas/Coal
- Extreme weather, sea level rise, and flooding disrupt/damage offshore and onshore energy operations and facilities
- Reduced water availability constrains drilling, fracking, and mining operations
- Thawing permafrost and subsidence reduce access and impact production

Pipelines
- Flooding damages pumping stations, undermines/scours river crossings
- Loss of electricity impacts pumping operations

Refineries
- Extreme weather/flooding damage refineries
- Reduced water availability can constrain fuel refining and processing
- Loss of electricity impacts refining operations

Fuel Transport
- Inland and coastal flooding inundate low-lying roads and rails and can damage bridges, river and coastal ports, and storage facilities
- Reduced river runoff can impede barge traffic
- Extreme weather, flooding, and blackouts can disrupt distribution outlets and gas stations

Extreme weather and climate change can potentially impact all components of the Nation's energy system, from fuel (petroleum, coal, and natural gas) production and distribution to electricity generation, transmission, and demand. *From Figure 4.1 (Source: adapted from DOE 2013* [23]*).*

State of the Sector

The Nation's economic security is increasingly dependent on an affordable and reliable supply of energy. Every sector of the economy depends on energy, from manufacturing to agriculture, banking, healthcare, telecommunications, and transportation.[2] Increasingly, climate change and extreme weather events are affecting the energy system (including all components related to the production, conversion, delivery, and use of energy), threatening more frequent and longer-lasting power outages and fuel shortages.[3] Such events can have cascading impacts on other critical sectors[43,44] and potentially affect the Nation's economic and national security (Ch. 17: Complex Systems). At the same time, the energy sector is undergoing substantial policy-, market-, and technology-driven changes.[2,31] Natural gas and renewable resources are moving to the forefront as energy sources and energy efficiency efforts continue to expand, forcing changes to the design and operation of the Nation's gas infrastructure and electrical grid. Beyond these changes, deliberate actions are being taken to enhance energy security, reliability, and resilience with respect to the effects of climate change through integrated planning, innovative energy technologies, and public–private partnerships;[1,2,31,45] however, much work remains to establish a climate-ready energy system that addresses present and future risks.

Regional Summary

Energy systems and the impacts of climate change differ across the United States, but all regions will be affected by a changing climate. The petroleum, natural gas, and electrical infrastructure along the East and Gulf Coasts are at increased risk of damage from rising sea levels and hurricanes of greater intensity (Ch. 18: Northeast, KM 3; Ch. 19: Southeast, KM 1 and 2). This vulnerable infrastructure serves other parts of the country, so regional disruptions are projected to have national implications. Hawai‘i and the U.S. Caribbean (Ch. 27: Hawai‘i & Pacific Islands, KM 3; Ch. 20: U.S. Caribbean, KM 3 and 5) are especially vulnerable to sea level rise and extreme weather, as they rely on imports of petroleum through coastal infrastructure, ports, and storage facilities. Oil and gas operations in Alaska are vulnerable to thawing permafrost, which, together with sea level rise and dwindling protective sea ice, is projected to damage existing infrastructure and restrict seasonal access; however, a longer ice-free season may enhance offshore energy exploration and transport (Ch. 26: Alaska, KM 5). More frequent and intense extreme precipitation events are projected to increase the risk of floods for coastal and inland energy infrastructure, especially in the Northeast and Midwest (Ch. 18: Northeast, KM 1 and 3; Ch. 21: Midwest, KM 5). Temperatures are rising in all regions, and these increases are expected to drive greater use of air conditioning. The increase in annual electricity demand across the country for cooling is offset only marginally by the relatively small decline in heating demand that is met with electric power.[11] In addition, higher temperatures reduce the thermal efficiency and generating capacity of thermoelectric power plants and reduce the efficiency and current-carrying capacity of transmission and distribution lines.

Energy systems in the Northwest and Southwest are likely to experience the most severe impacts of changing water availability, as reductions in mountain snowpack and shifts in snowmelt timing affect hydropower production (Ch. 24: Northwest, KM 3; Ch. 25: Southwest, KM 5). Drought will likely threaten fuel production, such as fracking for natural gas and shale oil; enhanced oil recovery in the Northeast, Midwest, Southwest, and Northern and Southern Great Plains; oil refining; and thermoelectric power generation that relies on surface water for cooling. In the Midwest, Northern Great Plains, and Southern Great Plains, higher temperatures and reduced soil moisture will likely make it more difficult to grow biofuel crops and impact the availability of wood and wood waste products for heating, fuel production, and electricity generation (Ch. 22: N. Great Plains, KM 4; Ch. 23: S. Great Plains, KM 1 and 2).

Key Message 1

Nationwide Impacts on Energy

The Nation's energy system is already affected by extreme weather events, and due to climate change, it is projected to be increasingly threatened by more frequent and longer-lasting power outages affecting critical energy infrastructure and creating fuel availability and demand imbalances. The reliability, security, and resilience of the energy system underpin virtually every sector of the U.S. economy. Cascading impacts on other critical sectors could affect economic and national security.

The principal contributor to power outages, and their associated costs, in the United States is extreme weather.[2,8,46] Extreme weather includes high winds, thunderstorms, hurricanes, heat waves, intense cold periods, intense snow events and ice storms, and extreme rainfall. Such events can interrupt energy generation, damage energy resources and infrastructure, and interfere with fuel production and distribution systems, causing fuel and electricity shortages or price spikes (Figure 4.1). Many extreme weather impacts are expected to continue growing in frequency and severity over the coming century,[8] affecting all elements of the Nation's complex energy supply system and reinforcing the energy supply-and-use findings of prior National Climate Assessments.[9]

Extreme weather can damage energy assets—a broad suite of equipment used in the production, generation, transmission, and distribution of energy—and cause widespread energy disruption that can take weeks to fully resolve, at sizeable economic costs.[2,3] High winds threaten damage to electricity transmission and distribution lines (Box 4.1), buildings, cooling towers, port facilities, and other onshore and offshore structures associated with energy infrastructure and operations.[3] Extreme rainfall (including extreme precipitation events, hurricanes, and atmospheric river events) can lead to flash floods that undermine the foundations of power line and pipeline crossings and inundate common riverbank energy facilities such as power plants, substations, transformers, and refineries.[3] River flooding can also shut down or damage fuel transport infrastructure such as railroads, fuel barge ports, pipelines, and storage facilities.[3]

Box 4.1: Economic Impacts to Electricity Systems

Repairs to electricity generation, transmission, and distribution systems from recent hurricane events are costing billions of dollars. Con Edison and Public Service Electric and Gas invested over $2 billion (in 2014 dollars) in response to Superstorm Sandy.[50,51] An estimate to build back Puerto Rico's electricity systems in response to Hurricanes Irma and Maria is approximately $17 billion (in 2017 dollars).[52]

Coastal flooding threatens much of the Nation's energy infrastructure, especially in regions with highly developed coastlines.[4,5,6] Coastal flooding, including wave action and storm surge (where seawater moves inland, often at levels above typical high tides due to strong winds), can affect gas and electric asset performance, cause asset damage and failure,

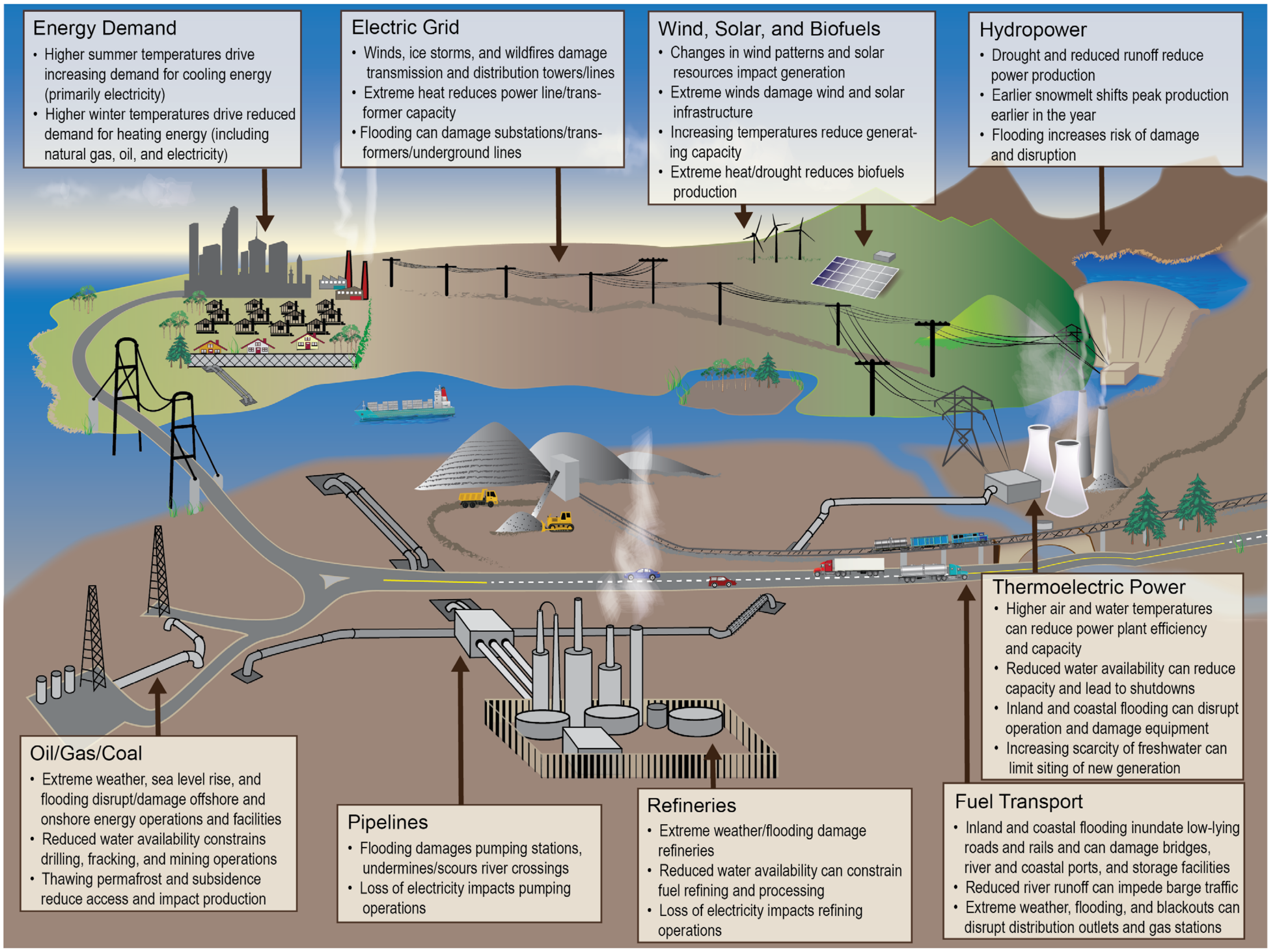

Potential Impacts from Extreme Weather and Climate Change

Figure 4.1: Extreme weather and climate change can potentially impact all components of the Nation's energy system, from fuel (petroleum, coal, and natural gas) production and distribution to electricity generation, transmission, and demand. Source: adapted from DOE 2013.[23]

and disrupt energy generation, transmission, and delivery. In addition, flooding can cause large petroleum storage tanks to float, destroying the tanks and potentially creating hazardous spills.[3] Any significant increase in hurricane intensities would greatly exacerbate exposure to storm surge and wind damage.

In the Southeast (Atlantic and Gulf Coasts), power plants and oil refineries are especially vulnerable to flooding. The number of electricity generation facilities in the Southeast potentially exposed to hurricane storm surge is estimated at 69 and 291 for Category 1 and Category 5 storms, respectively.[4] Nationally, a sea level rise of 3.3 feet (1 m; at the high end of the very likely range under a lower scenario [RCP4.5] for 2100) (for more on RCPs, see the Scenario Products section in App. 3)[47] could expose dozens of power plants that are currently out of reach to the risks of a 100-year flood (a flood having a 1% chance of occurring in a given year). This would put an additional cumulative total of 25 gigawatts (GW) of operating or proposed power capacities at risk.[48] In Florida and Delaware, sea level rise of 3.3 feet (1 m) would double the number of vulnerable plants (putting an additional 11 GW and 0.8 GW at risk in the two states, respectively); in Texas, vulnerable capacity would more than triple (with an additional 2.8 GW at risk).[48] Sea level rise and storm surge already pose a risk to coastal substations; this risk is projected to increase as sea levels continue to rise. For example, in southeastern Florida the number of major substations exposed to flooding from a Category 3 storm could more than double by 2050 and triple by 2070 under the higher scenario (RCP8.5).[49] Under RCP8.5, the projected number of electricity substations in the Gulf of Mexico exposed to storm surge from Category 1 hurricanes could increase by over 30% and nearly 60% by 2030 and 2050, respectively.[1] Increases in baseline sea levels expose many more Gulf Coast refineries to flooding risk during extreme weather events. For example, given a Category 1 hurricane, a sea level rise of less than 1.6 feet (0.5 m)[47] doubles the number of refineries in Texas and Louisiana vulnerable to flooding by 2100 under the lower scenario (RCP4.5).[4]

Rising air and water temperatures and extreme heat events[53,54,55] drive increases in demand for cooling while simultaneously resulting in reduced capacity and increased disruption of power plants and the electric grid, and potentially increasing electricity prices to consumers. Increased demand for cooling will likely also increase energy-related emissions of criteria air pollutants (for example, nitrogen oxide and sulfur dioxide), presenting an additional challenge to meet national ambient air quality standards, which are particularly important in the summer, when warmer temperatures and more direct sunlight can exacerbate the formation of photochemical smog (Ch. 13: Air Quality, KM 1 and 4). Unless other mitigation strategies are implemented, more frequent, severe, and longer-lasting extreme heat events are expected to make blackouts and power disruptions more common, increase the potential for electricity infrastructure to malfunction, and result in increased risks to public health and safety.[2,3,8,15,56]

If greenhouse gas emissions continue unabated (as with the higher scenario [RCP8.5]), rising temperatures are projected to drive up electricity costs and demand. Despite anticipated gains in end use and building and appliance efficiencies, higher temperatures are projected to drive up electricity costs not only by increasing demand but also by reducing the efficiency of power generation and delivery, and by requiring new generation capacity costing residential and commercial ratepayers by some estimates up to $30 billion per year by mid-century.[3,57] By 2040, nationwide, residential and commercial electricity expenditures are projected to increase by 6%–18% under a higher scenario (RCP8.5), 4%–15% under a lower scenario (RCP4.5), and 4%–12% under an even lower scenario (RCP2.6).[13] By the end of the century, an increase in average annual energy expenditures from increased energy demand under the higher scenario is estimated at $32–$87 billion (Figure 4.2; in 2011 dollars for GAO 2017[12] and in 2013 dollars for Rhodium Group LLC 2014, Larsen et al. 2017, Hsiang et al. 2017[16,13,14]). Nationwide, electricity demand is projected to increase by 3%–9% by 2040 under the higher scenario and 2%–7% under the lower scenario.[13] This projection includes the reduction in electricity used for space heating in states with warming winters, the associated decrease in heating degree days, and the increase in electricity demand associated with increases in cooling degree days.

In a lower scenario (RCP4.5), temperatures remain on an upward trajectory that could increase net electricity demand by 1.7%–2.0%.[15] To ensure grid reliability, enough generation and storage capacity must be available to meet the highest peak load demand. Rising temperatures could necessitate the construction

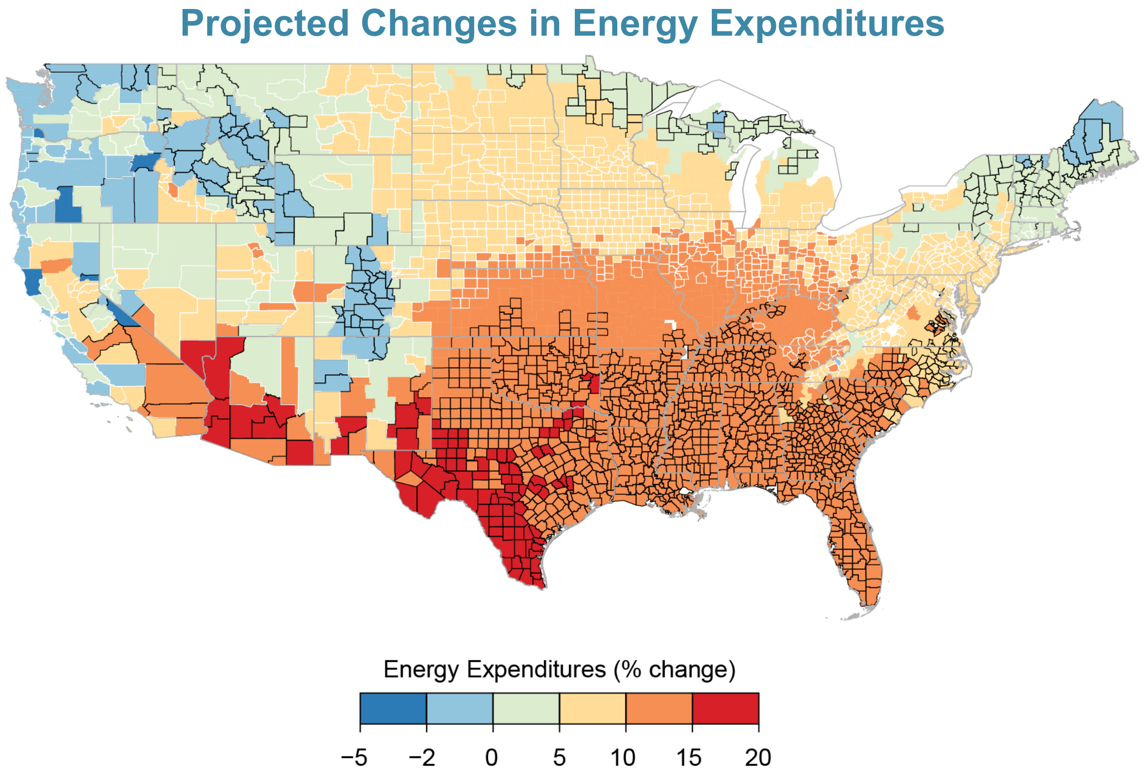


Figure 4.2: This figure shows county-level median projected increases in energy expenditures for average 2080–2099 impacts under the higher scenario (RCP8.5). Impacts are changes relative to no additional change in climate. Color indicates the magnitude of increases in energy expenditures in median projection; outline color indicates level of agreement across model projections (thin white outline, inner 66% of projections disagree in sign; no outline, more than 83% of projections agree in sign; black outline, more than 95% agree in sign; thick gray outline, state borders). Data were unavailable for Alaska, Hawai‘i and the U.S.-Affiliated Pacific Islands, and the U.S. Caribbean regions. Source: Hsiang et al. 2017.[14]

of up to 25% more power plant capacity by 2040, compared to a scenario without a warming climate.[13]

Most U.S. power plants, regardless of fuel source (for example, coal, natural gas, nuclear, concentrated solar, and geothermal), rely on a steady supply of water for cooling, and operations are projected to be threatened when water availability decreases or water temperatures increase (Ch. 3: Water; Ch. 17: Complex Systems, Box 17.3).[3] Elevated water temperatures reduce power plant efficiency; in some cases, a plant could have to shut down to comply with discharge temperature regulations designed to avoid damaging aquatic ecosystems.[3] In North America, the output potential of power plants cooled by river water could fall by 7.3% and 13.1% by 2050 under the RCP2.6 and RCP8.5 scenarios, respectively.[21]

A changing climate also threatens hydropower production, especially in western snow-dominated watersheds, where declining mountain snowpack affects river levels (Ch. 24: Northwest, KM 3; Ch. 25: Southwest, KM 5). For example, severe, extended drought caused California's hydropower output to decline 59% in 2015 compared to the average annual production over the two prior decades.[22]

Reduced water availability also affects the production and refining of petroleum, natural gas, and biofuels. During droughts, hydraulic fracturing and fuel refining operations will likely need alternative water supplies (such as brackish groundwater) or to shut down temporarily.[3,23,24] Shutdowns and the adoption of emergency measures and backup systems can increase refinery costs, raising product prices for the consumer.[23] Drought can reduce the cultivation of biofuel feedstocks (Ch. 10: Ag & Rural) and increase the risk of wildfires that threaten transmission lines and other energy infrastructure.[3,8]

Key Message 2

Changes in Energy System Affect Vulnerabilities

Changes in energy technologies, markets, and policies are affecting the energy system's vulnerabilities to climate change and extreme weather. Some of these changes increase reliability and resilience, while others create additional vulnerabilities. Changes include the following: natural gas is increasingly used as fuel for power plants; renewable resources are becoming increasingly cost competitive with an expanding market share; and a resilient energy supply is increasingly important as telecommunications, transportation, and other critical systems are more interconnected than ever.

The energy sector is undergoing a transformation driven by technology, markets, and policies that will change the sector's vulnerability to extreme weather and climate hazards. New drilling technologies and methods are enabling increased natural gas production, lower prices, and greater consumption. For example, in 2016 for the first time, natural gas replaced coal as the leading source of electricity generation in the United States (Figure 4.3).[22,31] In addition, U.S. net imports of petroleum reached a new low (Box 4.2). Likewise, dramatic reductions in the cost of renewable generation sources have led to the rapid growth of solar and wind installations.[32,58] Solar and wind generation in the United States grew by 44% and 19% during 2016, respectively.[25] These changes offer the opportunity to diversify the energy generation portfolio and require planning for operation and reliability of power generation, transmission, and delivery to maximize the positive effects and avoid unintended consequences. For example, natural gas generation generally improves electric system flexibility and reliability, as gas-fired power plants can quickly ramp output up and down,[2] but gas supplies

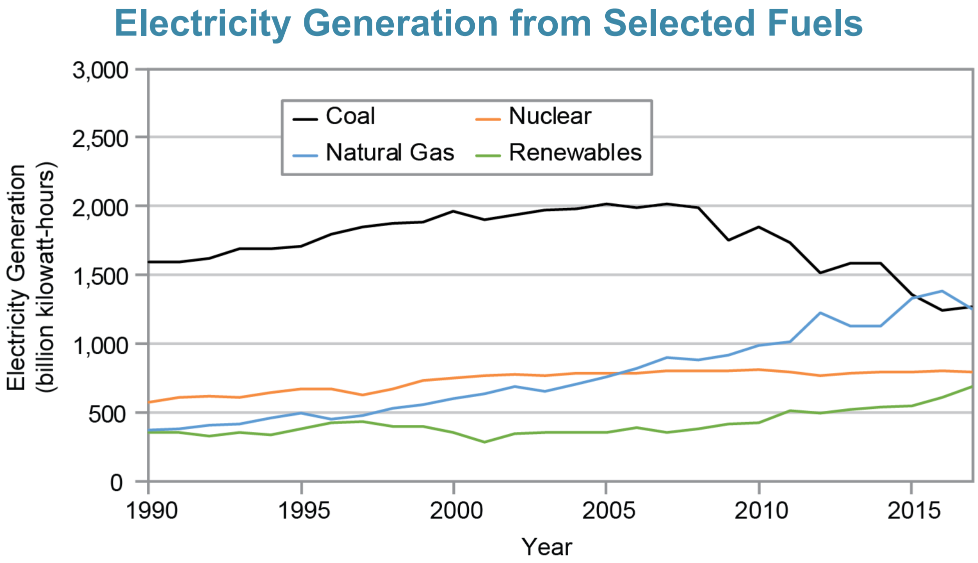


Figure 4.3: This figure shows electric power generation from different fuel sources and technologies. Since 2010, the declining market share from coal has been filled largely by natural gas and, to a lesser extent, renewables. Renewables include: conventional hydroelectric, geothermal, wood, wood waste, biogenic municipal waste, landfill gas, other biomass, solar, and wind power. Source: EIA/AEO 2018.[59]

and midstream infrastructure are vulnerable to disruption as noted previously. The flexible dispatch of gas generation can partially address the intermittency introduced by wide-scale deployment of solar and wind generation, which can be impacted by extreme weather as described earlier.[2] In addition, the growing adoption of energy efficiency programs, demand response programs, transmission capacity increases, and microgrids with energy storage technologies is enhancing system flexibility, reliability, and resilience.[31]

Energy efficiency has been remarkably successful over several decades in helping control energy costs to homes, buildings, and industry, while also contributing to enhanced resilience through reduced energy demand.[2] A number of actions are contributing to the increases in energy efficiency, significant energy savings, and improved resilience, including: the use of tax policy and other financial incentives to lower the cost of deploying efficient energy technologies, the development of building energy codes and appliance and equipment standards, the encouragement of voluntary actions to improve energy efficiency, and the continued growth of the broader energy efficiency and energy management industry.[60] The grid is changing with the adoption of new technologies. For example, grid operators are improving system resilience and reliability by installing advanced communications and control technologies as well as automation systems that can detect and react to local changes in usage. On distribution grids, smart meter infrastructure and communication-enabled devices give utilities new abilities to monitor—and potentially lower—electricity usage in real time. These technologies provide operators with access to real-time communications for outages and better tools to prevent outages and manage restoration efforts.

Although most electric service disruptions are caused by transmission and distribution

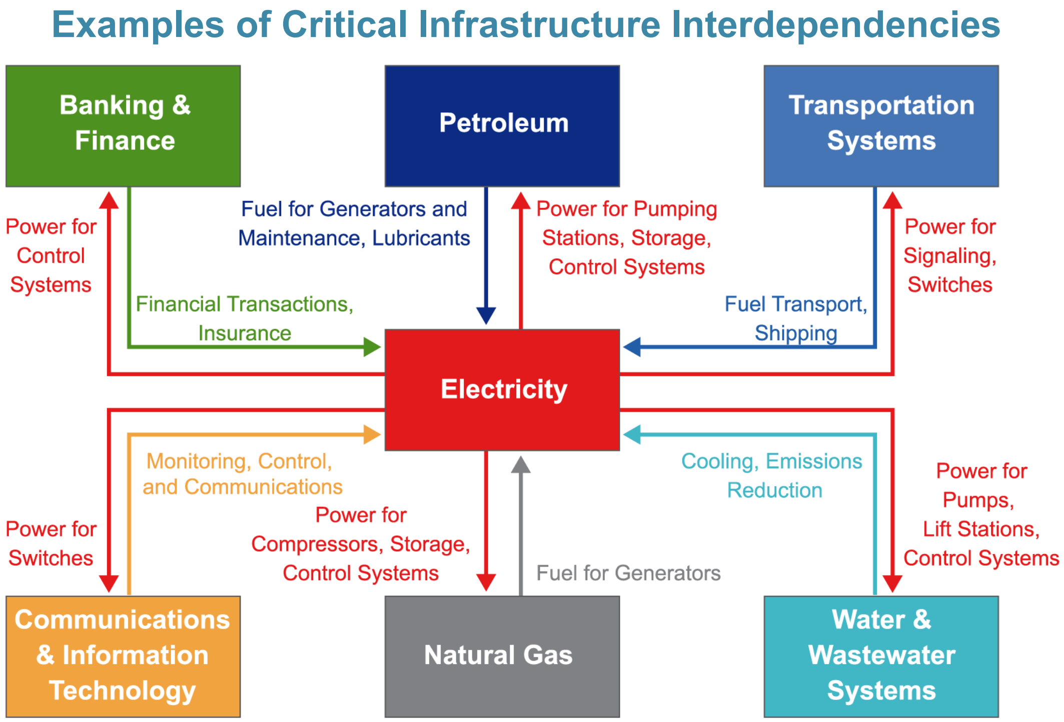


Figure 4.4: The interdependence of critical infrastructure systems increases the importance of electricity resilience, as disruptions to energy services are projected to affect other sectors. Shown above is a representative set of connections, and the complex relationships are analogous to other systems (Ch. 17: Complex Systems). A more complete listing of these linkages can be found at DOE.[2] Source: adapted from DOE 2017.[2]

outages,[1] it is possible for fuel availability to affect electricity generation reliability and resilience. Most generation technologies have experienced fuel deliverability challenges in the past.[31] Coal facilities typically store enough fuel onsite to last for 30 days or more, but extreme cold can lead to frozen fuel stockpiles and disruptions in train deliveries. Natural gas is delivered by pipeline on an as-needed basis. Capacity challenges on existing pipelines, combined with the difficulty in some areas of siting and constructing new natural gas pipelines, along with competing uses for natural gas such as for home heating, have created supply constraints in the past.[31] Renewables supplies are not immune from storage issues, as hydropower is particularly sensitive to water availability and reservoir levels, the magnitude and timing of which will be influenced by a changing climate. Management of the myriad fuel storage challenges and their relation to climate change is a subject that would benefit from improved understanding.

Box 4.2: Changing Dimensions of Energy Security

There is a trend of decreasing net imports (imports minus exports) of petroleum. In 2016, U.S. net imports reached a new low equal to about 25% of U.S. petroleum consumption, down from 60% in 2005.[59,61] This significant decline is the result of several factors, including the exploitation of vast domestic shale oil reserves and, to a lesser extent, reduced demand levels and expanded biofuel production. While this shift has potential national security benefits, there is an accompanying altered geographic distribution of our energy production assets and activities that could result in changes in exposure to the effects of extreme weather and climate change.

Increasing electrification in other sectors—such as telecommunications, transportation (including electric vehicles), banking and finance, healthcare and emergency response, and manufacturing—can exacerbate and compound the impacts of future power outages (Figure 4.4).[2] Like other complex systems (Boxes 4.1 and 4.3) (Ch. 17: Complex Systems), disruptions in other sectors also affect the energy system. For instance, communication architectures, including supervisory control and data acquisition, are often used in power delivery. While increasing automation of these systems on the grid can help mitigate the impact of extreme weather, without appropriate preventive measures, these systems are expected to increase system vulnerabilities to cyberattacks and other systemic risks.[2,31]

Given the interdependencies, resilience actions taken by other sectors to address climate change and extreme weather can have implications for the energy sector. For example, reductions in urban water consumption can result in reductions in electricity use to treat and convey both water and wastewater. California's mandate to reduce urban water consumption to address drought conditions in 2015 resulted in significant reductions in both water use and associated electricity use.[62] Exploring the resilience nexus between sectors can identify the co-benefits of resilience solutions and inform cost-effective resilience strategies.

While the Nation's energy system is changing, it is also aging, with the majority of energy infrastructure dating to the 20th century: 70% of the grid's transmission lines and power transformers are over 25 years old, and the average age of power plants is over 30 years old.[63] The components of the energy system are of widely varying ages and conditions and were not engineered to serve under the extreme weather conditions projected for this century. Aging, leak-prone natural gas distribution pipelines and associated infrastructures prompt safety and environmental concerns.[1]

Without greater attention to aging equipment as well as increasing storm and climate impacts, the U.S. will likely experience longer and more frequent power interruptions.[64]

Key Message 3

Improving Energy System Resilience

Actions are being taken to enhance energy security, reliability, and resilience with respect to the effects of climate change and extreme weather. This progress occurs through improved data collection, modeling, and analysis to support resilience planning; private and public–private partnerships supporting coordinated action; and both development and deployment of new, innovative energy technologies for adapting energy assets to extreme weather hazards. Although barriers exist, opportunities remain to accelerate the pace, scale, and scope of investments in energy systems resilience.

Industry and governments at the local, state, regional, and federal levels are taking actions to improve the resilience of the Nation's energy system and to develop quantitative metrics to assess the economic and energy security benefits associated with these measures. Current efforts include planning and operational measures that seek to anticipate climate impacts and prevent or respond to damages more effectively, as well as hardening measures (including physical barriers, protective casing, or other upgrades) to protect assets from damage, multi-institutional and public–private partnerships for coordinated action, and development and deployment of new technologies to enhance system resilience (Figure 4.5).[3,37,38,39,40,41,42,65]

Energy companies, utilities, and system operators are increasingly employing advanced data, modeling, and analysis to support a range of assessment and planning activities. Accurate load forecasting and generation planning now require considering both extreme weather and climate change. These are also essential considerations for planning and deploying energy infrastructure with a useful service life of decades. Coastal infrastructure plans are beginning to take into account rising sea levels and the associated increased risk of flooding. Resource plans for new thermoelectric power plants and fuel refineries are considering potential changes to fuel and water supplies. For example, the inability of natural gas-fired power plants to store fuel on site is leading energy providers to explore various resilience options, such as co-firing with fuel oil, which can be more readily stored; improving information sharing and coordination between electric generators, gas suppliers, and pipeline operators; and, ensuring the availability of more flexible resources for use to mitigate the uncertainties associated with natural gas fuel risks.[31,66] Advanced tools and techniques are helping planners understand how changes in extreme weather and in the energy system will affect future vulnerabilities and identify the actions necessary to establish a climate-ready energy system.

For the electric grid, improved modeling and analysis of changing generation resources, electricity demand, and usage patterns are helping industry, utilities, and other stakeholders plan for future changes, such as the role of increased storage, demand response, smart grid technologies, energy efficiency, and distributed generation including solar and fuel cells.[67,68] Energy companies, utilities, and system operators are increasingly evaluating long-term capital expansion strategies, their system operations, the resilience of supply chains, and the potential of mutual assistance efforts.[3,29,69]

For example, electricity demand response programs and energy efficiency programs are helping shift or reduce electricity usage during peak periods, improving grid reliability without increasing power generation. A central challenge to such planning is dealing with the broad range of uncertainties inherent to infrastructure investment planning (for example, climate, technology, and load). Advanced tools are being developed that help inform

Energy Sector Resilience Solutions

Flood Protection

- Building/strengthening berms, levees, and floodwalls
- Elevating substations, control rooms, and pump stations
- Expanding wetlands restoration
- Installing flood monitors

Wind Protection

- Inspecting and upgrading poles and structures
- Burying power lines underground
- Improving vegetation management efforts

Drought Protection

- Adopting water efficient thermoelectric cooling
- Utilizing non-freshwater sources
- Expanding low water-use generation

Modernization

- Deploying sensors and control technology
- Installing asset databases/tools, including supervisory control and data acquisition (SCADA) system redundancies
- Deploying energy storage and microgrid infrastructure (distributed energy resources, demand response programs, islanding capabilities)

Advanced Planning and Preparedness

- Conducting extreme weather risk assessment planning, preparedness, and training
- Participating in mutual assistance groups and public–private partnerships
- Purchasing or leasing mobile transformers and substations
- Utilizing geographic information systems (GIS) analysis to help identify vulnerabilities and plan for new builds and relocations

Storm-Specific Readiness

- Coordinating priority restoration and waivers
- Securing emergency fuel contracts
- Improving communication during outages to assist customers

Figure 4.5: Solutions are being deployed in the energy sector to enhance resilience to extreme weather and climate impacts across a spectrum of energy generation technologies, infrastructure, and fuel types. The figure illustrates resilience investment opportunities addressing specific extreme weather threats, as well as broader resilience actions that include grid modernization and advanced planning and preparedness. Photo credits (from top): Todd Plain, U.S. Army Corps of Engineers; Program Executive Office, Assembled Chemical Weapons Alternative; Lance Cheung, USDA; Idaho National Laboratory (CC BY 2.0); Darin Leach, USDA; Master Sgt. Roy Santana, U.S. Air Force.

investment decisions that balance costs as well as risk exposure[70,71,72] in an uncertain future.

Box 4.3: Rebuilding and Enhancing Energy System Resilience: Lessons Learned

While Superstorm Sandy and Hurricanes Harvey, Irma, and Maria caused significant damages to energy infrastructure, these storms also provided an opportunity to rebuild in ways that will enhance resilience to such storms in the future. For example, Superstorm Sandy caused 8.7 million customers to lose power, and utility companies in New York and New Jersey invested billions of dollars in upgrades to protect assets from projected extreme weather and climate change, including installing submersible equipment and floodwalls, elevating equipment, redesigning underground electrical networks, and installing smart switches to isolate and clear trouble on lines.[3,50] These actions have prevented outages to hundreds of thousands of customers and have reduced recovery times.[50] Emerging networks of expert practitioners (such as the National Adaptation Forum), foundation-supported initiatives focusing on cities, and regional events targeting counties and multi-jurisdictional audiences are also providing new forums for information sharing across impacted communities on best practices and low-cost interventions to enhance resilience.

Private and public–private partnerships are increasingly being used to share lessons learned and to coordinate action. Municipal, state, and tribal communities (Ch. 15: Tribes, KM 1) are working together to address climate change related risks,[3,73] as in the case of the Rockefeller Foundation's 100 Resilient Cities and C40 Cities partnerships, which are empowering communities to collaborate, share knowledge, and drive meaningful, measurable, and sustainable action on resilience.[74,75] By way of the U.S. Department of Energy's (DOE) Partnership for Energy Sector Climate Resilience, a number of utilities from across the country are collaborating with the DOE to develop resilience planning guidance, conduct climate change vulnerability assessments, and develop and implement cost-effective resilience solutions.[76] Additionally, the Administration established the Build America Investment Initiative as an interagency effort led by the Departments of Treasury and Transportation to promote increased investment in U.S. infrastructure, particularly through public–private partnerships.

Hardening measures protect energy systems from extreme weather hazards. Measures being adopted include, but are not limited to, adding natural or physical barriers to elevate, encapsulate, waterproof, or protect equipment vulnerable to flooding; reinforcing assets vulnerable to wind damage; adding or improving cooling or ventilation equipment to improve system performance during drought or extreme heat conditions; adding redundancy to increase a system's resilience to disruptions; and deploying distributed generation equipment (such as solar, fuel cells, or small combined-heat-and-power generators), energy storage, and microgrids with islanding capabilities (the ability to isolate a local, self-sufficient power grid during outages) to protect critical services from widespread outages while promoting improved energy efficiency and associated appliance standards. While hardening assets in place may be effective, in other situations, relocating assets may be more cost effective in the longer term.

One key category of hardening measures is addressing the vulnerability of the Nation's energy systems in water-constrained areas (Ch. 3: Water, KM 1). Technologies and practices are available to help address these vulnerabilities (Ch. 17: Complex Systems, KM 3) to thermoelectric power plants, including alternative cooling systems that reduce water withdrawals; nontraditional water sources, including brackish or municipal wastewater;

and power generation technologies that greatly reduce freshwater use, such as wind, photovoltaic solar, and natural gas combined-cycle technologies.[77,78,79,80,81] Technology is also enabling the growing use of produced water (water produced as a byproduct with oil and gas extraction) and brackish groundwater for water-intensive oil and gas drilling techniques.[82] However, expanding the use of non-freshwater sources puts a greater demand on the energy sector to provide the power to capture, treat, and deliver these water supplies.[83,84] Research on innovative future biofuels that are adapted to local climates can also reduce the water needs of biofuels and the possible impacts of a changing climate on the suitability of land for biofuels production.

The current pace, scale, and scope of efforts to improve energy system resilience are likely to be insufficient to fully meet the challenges presented by a changing climate and energy sector, as several key barriers exist. Among these impediments is a lack of reliable projections of climate change at a local level and the associated risks to energy assets, as well as a lack of a national, regional, or local cost-effective risk reduction strategy. This includes a consideration of where adaptation measures are pursued, thereby addressing the uncertainty concerning their effectiveness and the need for additional resilience investments. Addressing these obstacles would benefit from improved awareness of energy asset vulnerability and performance, cost-effective resilience-enhancing energy technologies and operations plans, standardized methodologies and metrics for assessing the benefits of resilience measures, and expanded public–private partnerships to address vulnerabilities collaboratively.[1,2,3,45] Ensuring that poor and marginalized populations, who often face a higher risk from climate change and energy system vulnerabilities, are part of the planning process can help lead to effective resilience actions and provide ancillary co-benefits to society. Energy infrastructure is long-lived and, as a result, today's decisions about how to locate, expand, and modify the Nation's energy system will influence system reliability, resilience, and economic security for decades.[1,2] In addition, without substantial and sustained mitigation efforts to reduce global greenhouse gas emissions, the need for adaptation and resilience investments to address the impacts of climate change on the energy sector is expected to increase if the most severe consequences are to be avoided in the long term.

Acknowledgments

USGCRP Coordinators

Natalie Bennett
Adaptation and Assessment Analyst

Christopher W. Avery
Senior Manager

Opening Image Credit

Linemen: © Jeff Miller/Western Area Power Administration/Flickr (CC BY 2.0). Adaptation: cropped top and bottom to conform to the size needed for publication.

Traceable Accounts

Process Description

We sought an author team that could bring diverse experience, expertise, and perspectives to the chapter. Some members have participated in past assessment processes. The team's diversity adequately represents the spectrum of current and projected impacts on the various components that compose the Nation's complex energy system and its critical role to national security, economic well-being, and quality of life. The author team has demonstrated experience in the following areas:

- characterizing climate risks to the energy sector—as well as mitigation and resilience opportunities—at national, regional, and state levels;
- developing climate science tools and information for characterizing energy sector risks;
- supporting local, state, and federal stakeholders with integrating climate change issues into long-range planning;
- analyzing technological, economic, and business factors relevant to risk mitigation and resilience; and
- analyzing energy system sensitivities to drivers such as policy, markets, and physical changes.

In order to develop Key Messages, the author team characterized current trends and projections based on wide-ranging input from federal, state, local, and tribal governments; the private sector, including investor-owned, state, municipal, and cooperative power companies; and state-of-the-art models developed by researchers in consultation with industry and stakeholders. Authors identified recent changes in the energy system (that is, a growing connectivity and electricity dependence that are pervasive throughout society) and focused on how these transitions could affect climate impacts, including whether the changes were likely to exacerbate or reduce vulnerabilities. Using updated assessments of climate forecasts, projections, and predictions, the team identified key vulnerabilities that require near-term attention and highlighted the actions being taken to enhance energy security, reliability, and resilience.

Key Message 1

Nationwide Impacts on Energy

The Nation's energy system is already affected by extreme weather events, and due to climate change, it is projected to be increasingly threatened by more frequent and longer-lasting power outages affecting critical energy infrastructure and creating fuel availability and demand imbalances (*high confidence*). The reliability, security, and resilience of the energy system underpin virtually every sector of the U.S. economy (*high confidence*). Cascading impacts on other critical sectors could affect economic and national security (*high confidence*).

Description of evidence

The energy system's vulnerability to climate change impacts is evidenced through two sources: 1) the historical experience of damage and disruption to energy assets and systems, using data and case studies from events such as Superstorm Sandy and Hurricanes Harvey, Irma, and Maria, as well as the 2011–2016 California drought, and 2) a growing base of scientific literature assessing and projecting the past and future role of climate change in driving damage and disruption to the energy sector. Federal government and international scientific efforts have documented the scope and scale of a changing climate's effects on the U.S. energy system—factors that will need to be considered in long-term planning, design, engineering, operations, and maintenance of energy assets and supply chains if current standards of reliability are to be maintained or improved.[1,2,3,15,23,29,85,86]

This Key Message claims that damage and/or disruption to energy systems is more likely in the future. This claim is based on the following specific climate change projections and their expected impacts on energy systems:

- higher maximum air temperatures during heat waves and associated impacts on energy generation, delivery, and load (*very likely*, *very high confidence*)[3,53]
- higher average air temperatures and associated increases in energy demand for cooling (*very likely*, *very high confidence*)[11,12,13,14,15,16,17,18,19,53]
- higher surface water temperatures and associated impacts on thermoelectric power generation (*very likely*, *very high confidence*)[3,87]
- shifts in streamflow timing in snow-dominated watersheds to earlier in the year[8] and associated impacts on hydropower generation (*very likely*, *very high confidence*)[86,88]
- increased frequency and intensity of drought (*very likely*, *high confidence*)[54] and associated impacts on biofuels production[3]
- more frequent, intense, and longer-duration drought, particularly in snow-dominated watersheds in the western United States,[54] and associated threat to hydropower production, oil and gas extraction and refining, and thermoelectric cooling[3,21,22,24,88]
- increased wind intensity from Atlantic and eastern Pacific hurricanes (*medium confidence*)[55] and associated impacts on coastal energy infrastructure[3]
- increased rain intensity for hurricanes (*high confidence*) and increased frequency and intensity of heavy precipitation events (*high confidence*), including West Coast atmospheric river events (*medium confidence*),[89] and associated impacts on energy infrastructure[3]
- increased relative sea level rise (*very high confidence*)[47] and associated risk of enhanced flooding of coastal infrastructure as well as inland energy infrastructure along rivers[3]
- increased frequency and intensity of heavy precipitation (*very likely*)[89] and associated impacts to inland flooding of energy assets[3,15]

- increased frequency of occurrence of conditions that support the formation of convective storms (thunderstorms, tornadoes, and high winds)[55] and associated damage to electricity transmission and distribution lines (*low confidence*)[1,3]

The effects of extreme weather on energy system infrastructure have been well documented by researchers and synthesized into several assessment reports produced by federal agencies.[2,3,15,23] The link between extreme weather and power outages is strongest: extreme weather is the leading cause of power outages in the United States.[2] Increased wind speeds and precipitation have been correlated with increased outage duration, and wind speeds have also been correlated with outage frequency.[90] Claims regarding fuel shortages are also based on historical experience; Superstorm Sandy led to local fuel distribution shortages, while Hurricane Katrina led to fuel production and refining shortages with national impacts.[3] The claim that energy system outages can increase energy prices, negatively affect economic growth, and disrupt critical services essential for health and safety is likewise substantiated by the historical experience of severe storms, flooding, and widespread power outages.[23]

Major uncertainties

The inability to predict future climate parameters with complete accuracy is one primary uncertainty that hinders energy asset owners, operators, and planners from anticipating, planning for, and acting on vulnerabilities to climate change and extreme weather. All climate change projections include a degree of uncertainty, owing to a variety of factors, including incomplete historical data, constraints on modeling methodologies, and uncertainty about future emissions. For some climate parameters, confidence in both the direction and magnitude of projected change is high, so expected impacts to the energy sector are well understood. For example, projected temperature changes across the United States uniformly indicate that the demand for cooling energy is projected to increase and the demand for heating energy is projected to decrease.[8,15]

However, confidence is generally lower for other climate parameters projections, making it difficult to understand and prioritize the risks associated with climate hazards and lowering confidence levels in related energy sector impacts. There is uncertainty in projections regarding changes in the frequency and intensity of hurricanes and convective storms, the magnitude and timing of sea level rise, the connection between projected changes in precipitation and the likelihood of droughts and flooding, and the potential increased seasonal variability in wind and solar resources. Hurricanes and convective storms represent major threats to energy infrastructure in general and to electricity transmission and distribution grids in particular.[1,3] However, historical data for hurricanes and convective storms (including tornadoes, hail, and thunderstorms) are lacking and inconsistent over different time periods and regions, and they can be biased based on population density and shifting populations.[55] Furthermore, for convective storms, most global climate models are not capable of modeling the atmosphere at a small enough scale to directly simulate storm formation.[8] Projections of changes in sea level rise and impacts on coastal energy infrastructure are improving, but significant uncertainty regarding the magnitude of long-term sea level rise impedes energy system planners' ability to make decisions about infrastructure with useful lifetimes of 50 years or more.[47] Global climate models are also insufficient to project future hydrological changes, as these projections lack sufficient spatial and temporal resolution and lack detail about other factors important to local hydrology, including changes to soil, groundwater, and water withdrawal and consumption. A lack of hydrological projections increases uncertainty about water availability consequences for hydropower and thermoelectric power plants and oil and gas extraction.

Description of confidence and likelihood

Climate change is projected to affect the energy sector in many ways, but the overall effect of rising temperatures, changing precipitation patterns, and increases in the frequency and/or severity of extreme weather is to increase the risk of damage or disruption to energy sector assets and energy systems. The combined projection of increasing risk of damage or disruption is *very likely*, with *high confidence*.

Key Message 2

Changes in Energy System Affect Vulnerabilities

> Changes in energy technologies, markets, and policies are affecting the energy system's vulnerabilities to climate change and extreme weather. Some of these changes increase reliability and resilience, while others create additional vulnerabilities (*very likely, very high confidence*). Changes include the following: natural gas is increasingly used as fuel for power plants; renewable resources are becoming increasingly cost competitive with an expanding market share; and a resilient energy supply is increasingly important as telecommunications, transportation, and other critical systems are more interconnected than ever.

Description of evidence

Large-scale changes in the energy sector are primarily evidenced through the U.S. Energy Information Administration's (EIA) data collection and analysis. EIA collects monthly and annual surveys from every U.S. power plant; findings include the types of fuel each plant uses.[22] Several sources support claims that renewable technology deployment is growing while costs are falling: EIA data,[22,25] National Renewable Energy Laboratory research,[26] and multiple studies.[27,28,30,32,33] The U.S. Department of Energy's *Quadrennial Energy Review*[1,2] and other reviews[31] provide analysis that supports the growing integration of energy systems into other sectors of the economy.

Major uncertainties

Future changes in the energy system, and the effect on energy system vulnerabilities to extreme weather and climate change, are uncertain and will depend on numerous factors that are difficult to predict, including macroeconomic and population growth; financial, economic, policy, and regulatory changes; and technological progress. Each of these factors can affect the cost of technologies, the growth in energy demand, the rate of deployment of new technologies, and the selection of sites for deployment.

Description of confidence and likelihood

The reliable production and delivery of power enables modern electricity-dependent critical infrastructures to support American livelihoods and the national economy. There is *very high confidence* that a deepening dependence on electric power and increasing interdependencies within the energy system can increase the vulnerabilities and risks associated with extreme weather and climate hazards in some situations (*very likely*, *very high confidence*).

There is *very high confidence* that many trends in the changing energy system are *very likely* to continue and that changes will have potential effects on reliability and resilience. A primary factor affecting the increased use of natural gas and the deployment of renewable resources is the relative price of these generation sources. Existing proven resources of natural gas are sufficient to supply current demand for several decades.[91] Renewable technologies are *very likely* to continue falling in price, as manufacturers continue to improve their processes and take advantage of economies of scale.[92] The degree of interconnection of critical systems is also *very likely* to increase. The continued deployment of smart grid devices, microgrids, and energy storage will *likely* provide multiple reliability and resilience benefits.[2]

Key Message 3

Improving Energy System Resilience

Actions are being taken to enhance energy security, reliability, and resilience with respect to the effects of climate change and extreme weather *(very high confidence)*. This progress occurs through improved data collection, modeling, and analysis to support resilience planning; private and public–private partnerships supporting coordinated action; and both development and deployment of new, innovative energy technologies for adapting energy assets to extreme weather hazards. Although barriers exist, opportunities remain to accelerate the pace, scale, and scope of investments in energy systems resilience *(very high confidence)*.

Description of evidence

Several entities have identified evidence for the planning and deployment of resilience solutions in the energy sector. Support comes from both industry and federal agencies, including the U.S. Department of Energy (DOE), the U.S. Environmental Protection Agency (EPA), and the Department of Homeland Security (DHS).[3,37,38,39,40,41,42] For example, the DOE's recent efforts, reflected in the *Quadrennial Energy Review*[1,2] and the *Quadrennial Technology Review*,[45] examine how to modernize our Nation's energy system and technologies to promote economic competitiveness, energy security and reliability, and environmental responsibility. Through the Partnership for Energy Sector Climate Resilience, the DOE and partner utilities provide examples of plans and implementation of resilience solutions, as well as barriers to expanded investments in resilience.[3,76] This Key Message gains further support from the EPA's work with industry and local and state governments through its Creating Resilient Water Utilities program,[93] as well as from the collaboration of the DHS with private sector critical infrastructure owners and operators through its National Infrastructure Protection Plan Security and Resilience Challenge.[94] In addition, a growing constituency of cities, municipalities, states, and tribal communities are dedicating resources and personnel toward identifying, quantifying, and responding to climate change related risks to energy system reliability and the social services that depend on those systems.[3,73] For example, the Rockefeller Foundation's 100 Resilient Cities and C40 Cities are both networks of the world's cities committed to addressing resilience. These coalitions, including multiple U.S. cities, support cities in their efforts to collaborate effectively, share knowledge, and drive meaningful, measurable, and sustainable action on resilience.[74,75]

Major uncertainties

The most significant uncertainties affecting future investments in climate resilience are related to evaluating the costs, benefits, and performance of resilience investments—and the costs of inaction. To make informed investments, decision-makers need standardized cost–benefit frameworks and methodologies, as well as reliable, high-resolution (temporal and spatial) climate change projections of critical weather and climate parameters.[1,2,3,76]

The high complexity of the energy system introduces uncertainty in whether particular actions could yield unintended consequences. Using the examples above, energy storage, distributed generation, microgrids, and other technologies and practices can contribute to resilience. However, unless evaluated in a systematic manner, the adoption of technologies and practices will likely lead to unintended consequences, including environmental (such as air quality), economic, and policy impacts.

Significant uncertainty is also found in the future pace of mitigation efforts that will, in turn, influence the need for resilience investments. Some level of climate change will continue, given past and current emissions of heat-trapping greenhouse gases. However, without an effective mitigation strategy, the need for additional adaptation and resilience investments becomes greater. Uncertainty about the rate of stabilizing and reducing greenhouse gas emission levels (mitigation) compounds the challenge of characterizing the magnitude and timing of additional resilience investments.

The pace of development and deployment of resilient cost-effective energy technologies are also uncertain and will likely be critical to implementing resilience strategies at scale. These technologies will likely include improvements in areas such as energy storage, distributed generation, microgrids, and cooling for thermoelectric power plants.[1,2,3,31,76]

Description of confidence and likelihood

There is *very high confidence* that many of the technologies and planning or operational measures necessary to respond to climate change exist and that their implementation is in progress.[29] Although federal, state, local, and tribal governments and the private sector are already responding, there is *very high confidence* that the pace, scale, and scope of combined public and private efforts to improve preparedness and resilience of the energy sector are likely to be insufficient, given the nature of the challenge[1,2,3,29,31] presented by a changing climate and energy sector.

References

1. DOE, 2015: Transforming U.S. Energy Infrastructures in a Time of Rapid Change: The First Installment of the Quadrennial Energy Review. U.S. Department of Energy (DOE), Washington, DC. https://energy.gov/epsa/downloads/quadrennial-energy-review-first-installment

2. DOE, 2017: Transforming the Nation's Electricity System: The Second Installment of the QER. DOE/EPSA-0008. U.S. Department of Energy (DOE), Washington, DC https://energy.gov/epsa/quadrennial-energy-review-second-installment

3. DOE, 2015: Climate Change and the U.S. Energy Sector: Regional Vulnerabilities and Resilience Solutions DOE/EPSA-0005. U.S. Department of Energy (DOE), Washington, DC, 189 pp. https://energy.gov/sites/prod/files/2015/10/f27/Regional_Climate_Vulnerabilities_and_Resilience_Solutions_0.pdf

4. Maloney, M.C. and B.L. Preston, 2014: A geospatial dataset for U.S. hurricane storm surge and sea-level rise vulnerability: Development and case study applications. *Climate Risk Management*, **2**, 26-41. http://dx.doi.org/10.1016/j.crm.2014.02.004

5. GAO, 2014: Climate Change: Energy Infrastructure Risks and Adaptation Efforts. GAO-14-74. Government Accounting Office (GAO), Washington, DC, 68 pp. https://www.gao.gov/assets/670/660558.pdf

6. DOE, 2014: Effect of Sea Level Rise on Energy Infrastructure in Four Major Metropolitan Areas. U.S. Department of Energy, Washington, DC, 44 pp. https://www.energy.gov/sites/prod/files/2014/10/f18/DOE-OE_SLR%20Public%20Report_Final%20_2014-10-10.pdf

7. Kinniburgh, F., M.G. Simonton, and C. Allouch, 2015: Come Heat and High Water: Climate Risk in the Southeastern U.S. and Texas. Gordon, K. Ed. Risky Business Project, New York, 109 pp. https://riskybusiness.org/site/assets/uploads/2015/09/Climate-Risk-in-Southeast-and-Texas.pdf

8. USGCRP, 2017: Climate Science Special Report: Fourth National Climate Assessment, Volume I. Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA, 470 pp. http://dx.doi.org/10.7930/J0J964J6

9. Dell, J., S. Tierney, G. Franco, R.G. Newell, R. Richels, J. Weyant, and T.J. Wilbanks, 2014: Ch. 4: Energy supply and use. *Climate Change Impacts in the United States: The Third National Climate Assessment*. Melillo, J.M., Terese (T.C.) Richmond, and G.W. Yohe, Eds. U.S. Global Change Research Program, Washington, DC, 113-129. http://dx.doi.org/10.7930/J0BG2KWD

10. 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. http://dx.doi.org/10.1088/1748-9326/11/11/114008

11. Clarke, L., J. Eom, E.H. Marten, R. Horowitz, P. Kyle, R. Link, B.K. Mignone, A. Mundra, and Y. Zhou, 2018: Effects of long-term climate change on global building energy expenditures. *Energy Economics*, **72**, 667-677. http://dx.doi.org/10.1016/j.eneco.2018.01.003

12. GAO, 2017: Climate Change: Information on Potential Economic Effects Could Help Guide Federal Efforts to Reduce Fiscal Exposure. GAO-17-720. Government Accounting Office (GAO), Washington, DC, 45 pp. https://www.gao.gov/products/GAO-17-720

13. Larsen, K., J. Larsen, M. Delgado, W. Herndon, and S. Mohan, 2017: Assessing the Effect of Rising Temperatures: The Cost of Climate Change to the U.S. Power Sector. Rhodium Group, New York, NY, 27 pp. https://rhg.com/wp-content/uploads/2017/01/RHG_PowerSectorImpactsOfClimateChange_Jan2017-1.pdf

14. Hsiang, S., R. Kopp, A. Jina, J. Rising, M. Delgado, S. Mohan, D.J. Rasmussen, R. Muir-Wood, P. Wilson, M. Oppenheimer, K. Larsen, and T. Houser, 2017: Estimating economic damage from climate change in the United States. *Science*, **356** (6345), 1362-1369. http://dx.doi.org/10.1126/science.aal4369

15. EPA, 2017: Multi-model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment. EPA 430-R-17-001. U.S. Environmental Protection Agency (EPA), Washington, DC, 271 pp. https://cfpub.epa.gov/si/si_public_record_Report.cfm?dirEntryId=335095

16. Rhodium Group LLC, 2014: American Climate Prospectus: Economic Risks in the United States. Prepared as input to the Risky Business Project Rhodium Group, New York, NY, 201 pp. http://www.impactlab.org/wp-content/uploads/2017/10/AmericanClimateProspectus_v1.2.pdf

17. McFarland, J., Y. Zhou, L. Clarke, P. Sullivan, J. Colman, W.S. Jaglom, M. Colley, P. Patel, J. Eom, S.H. Kim, G.P. Kyle, P. Schultz, B. Venkatesh, J. Haydel, C. Mack, and J. Creason, 2015: Impacts of rising air temperatures and emissions mitigation on electricity demand and supply in the United States: A multi-model comparison. *Climatic Change*, **131** (1), 111-125. http://dx.doi.org/10.1007/s10584-015-1380-8

18. Dirks, J.A., W.J. Gorrissen, J.H. Hathaway, DC Skorski, M.J. Scott, T.C. Pulsipher, M. Huang, Y. Liu, and J.S. Rice, 2015: Impacts of climate change on energy consumption and peak demand in buildings: A detailed regional approach. *Energy*, **79**, 20-32. http://dx.doi.org/10.1016/j.energy.2014.08.081

19. Jaglom, W.S., J.R. McFarland, M.F. Colley, C.B. Mack, B. Venkatesh, R.L. Miller, J. Haydel, P.A. Schultz, B. Perkins, J.H. Casola, J.A. Martinich, P. Cross, M.J. Kolian, and S. Kayin, 2014: Assessment of projected temperature impacts from climate change on the U.S. electric power sector using the Integrated Planning Model®. *Energy Policy*, **73**, 524-539. http://dx.doi.org/10.1016/j.enpol.2014.04.032

20. EIA, 2018: Energy Market Alerts: Northeastern Winter Energy Alert. U.S. Energy Information Administration, Washington, DC. https://www.eia.gov/special/alert/east_coast/

21. van Vliet, M.T.H., D. Wiberg, S. Leduc, and K. Riahi, 2016: Power-generation system vulnerability and adaptation to changes in climate and water resources. *Nature Climate Change*, **6** (4), 375-380. http://dx.doi.org/10.1038/nclimate2903

22. EIA, 2017: Electric Power Monthly: Table 1.1. Net Generation by Energy Source: Total (All Sectors), 2008-April 2018. U.S. Energy Information Administration (EIA), Washington, DC. https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_1_01

23. DOE, 2013: U.S. Energy Sector Vulnerabilities to Climate Change and Extreme Weather. DOE/PI-0013. U.S. Department of Energy (DOE), Washington, DC, 73 pp. http://www.energy.gov/downloads/us-energy-sector-vulnerabilities-climate-change-and-extreme-weather

24. Galbraith, K., 2012: "Conservation a growing focus for industrial plants as drought stirs fears." *The Texas Tribune*. https://www.texastribune.org/2012/02/27/texas-drought-sparked-water-worries-industry/

25. EIA, 2017: Electric Power Monthly: Table 1.1A. Net Generation From Renewable Sources. U.S. Energy Information Administration (EIA), Washington, DC. https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_1_01_a

26. NREL, 2014: Distributed Solar PV for Electricity System Resiliency: Policy and Regulatory Considerations. NREL/BR-6A20-62631. National Renewable Energy Laboratory, Denver, CO, 12 pp. https://www.nrel.gov/docs/fy15osti/62631.pdf

27. Barbose, G.L. and N.R. Darghouth, 2016: Tracking the Sun IX: The Installed Price of Residential and Non-Residential Photovoltaic Systems in the United States. LBNL-1006036. Berkeley Lab, Berkeley, CA, 52 pp. https://emp.lbl.gov/publications/tracking-sun-ix-installed-price

28. Bolinger, M. and J. Seel, 2016: Utility-Scale Solar 2015: An Empirical Analysis of Project Cost, Performance, and Pricing Trends in the United States. LBNL-1006037. Berkeley Lab, Berkeley, CA. https://emp.lbl.gov/publications/utility-scale-solar-2015-empirical

29. DOE, 2016: Climate Change and the Electricity Sector: Guide for Climate Change Resilience Planning. U.S. Department of Energy (DOE), Washington, DC, 100 pp. https://www.energy.gov/epsa/downloads/climate-change-and-electricity-sector-guide-climate-change-resilience-planning

30. DOE, 2016: Solid-State Lighting: R&D Plan. DOE/EE-1418. U.S. Department of Energy (DOE). Office of Energy Efficiency and Renewable Energy, Washington, DC, 100 pp. https://energy.gov/sites/prod/files/2016/06/f32/ssl_rd-plan_%20jun2016_2.pdf

31. DOE, 2017: Staff Report to the Secretary on Electricity Markets and Reliability. U.S. Department of Energy (DOE), Washington, DC, 181 pp. https://energy.gov/staff-report-secretary-electricity-markets-and-reliability

32. Wise, R. and M. Bolinger, 2017: 2016 Wind Technologies Market Report. DOE, Office of Energy Efficiency and Renewable Energy, Washington, DC, 82 pp. https://www.energy.gov/sites/prod/files/2017/10/f37/2016_Wind_Technologies_Market_Report_101317.pdf

33. Mone, C., M. Hand, M. Bolinger, J. Rand, D. Heimiller, and J. Ho, 2017: 2015 Cost of Wind Energy Review. NREL/TP-6A20-66861. National Renewable Energy Laboratory, Golden, CO, 97 pp. https://www.nrel.gov/docs/fy17osti/66861.pdf

34. Lantz, E., T. Mai, R.H. Wiser, and V. Krishnan, 2016: Long-term implications of sustained wind power growth in the United States: Direct electric system impacts and costs. *Applied Energy*, **179**, 832-846. http://dx.doi.org/10.1016/j.apenergy.2016.07.023

35. Feng, K., S.J. Davis, L. Sun, and K. Hubacek, 2016: Correspondence: Reply to "Reassessing the contribution of natural gas to US CO_2 emission reductions since 2007." *Nature Communications*, **7**, 10693. http://dx.doi.org/10.1038/ncomms10693

36. EIA, 2017: Electric Power Monthly: Table 7.2b. Electricity Net Generation: Electric Power Sector. U.S. Energy Information Administration (EIA), Washington, DC https://www.eia.gov/totalenergy/data/monthly/pdf/sec7_6.pdf

37. Con Edison, 2013: Storm Hardening and Resiliency Collaborative Report. Consolidated Edison Company, New York, 162 pp.

38. Entergy, 2010: Building a Resilient Energy Gulf Coast: Executive Report. America's Wetlands Foundation and America's Energy Coast and Entergy, 11 pp. http://www.entergy.com/content/our_community/environment/GulfCoastAdaptation/Building_a_Resilient_Gulf_Coast.pdf

39. Exelon, 2017: Exelon Corporation Sustainability Report 2016. Exelon Corporation, Chicago, IL, 127 pp. http://www.exeloncorp.com/sustainability

40. PG&E, 2016: Climate Change Vulnerability Assessment and Resilience Strategies. Pacific Gas and Electric Company (PG&E), San Francisco, CA, 69 pp. http://www.pgecurrents.com/wp-content/uploads/2016/12/PGE_climate_resilience_report.pdf

41. Seattle City Light, 2015: Climate Change Vulnerability: Assessment and Adaptation Plan. Seattle City Light, Seattle, WA, 97 pp. http://www.seattle.gov/light/enviro/docs/Seattle_City_Light_Climate_Change_Vulnerability_Assessment_and_Adaptation_Plan.pdf

42. TVA, 2014: Climate Change Adaptation Action Plan. Tennessee Valley Authority (TVA), Knoxville, TN, 43 pp. https://www.tva.gov/file_source/TVA/Site%20Content/About%20TVA/Guidelines%20and%20Reports/Sustainability%20Plans%20and%20Performance/TVA_Climate_Change_Adaptation_Plan_2014.pdf

43. Horton, R., C. Rosenzweig, W. Solecki, D. Bader, and L. Sohl, 2016: Climate science for decision-making in the New York metropolitan region. *Climate in Context: Science and Society Partnering for Adaptation*. Parris, A.S., G.M. Garfin, K. Dow, R. Meyer, and S.L. Close, Eds. Wiley, New York, 51-72.

44. Rosenzweig, C., W.D. Solecki, P. Romeo-Lankao, S. Mehrotra, S. Dhakal, and S.A. Ibrahim, Eds., 2017: *Climate Change and Cities: Second Assessment Report of the Urban Climate Change Research Network*. Cambridge University Press, 350 pp.

45. DOE, 2015: An Assessment of Energy Technologies and Research Opportunities: Quadrennial Technology Review. U.S. Department of Energy (DOE), Washington, DC, 489 pp. https://energy.gov/sites/prod/files/2015/09/f26/Quadrennial-Technology-Review-2015_0.pdf

46. NCEI, 2018: Billion-Dollar Weather and Climate Disasters [web page]. NOAA National Centers for Environmental Information (NCEI), Asheville, NC. https://www.ncdc.noaa.gov/billions/

47. Sweet, W.V., R. Horton, R.E. Kopp, A.N. LeGrande, and A. Romanou, 2017: Sea level rise. *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA, 333-363. http://dx.doi.org/10.7930/J0VM49F2

48. Bierkandt, R., M. Auffhammer, and A. Levermann, 2015: US power plant sites at risk of future sea-level rise. *Environmental Research Letters*, **10** (12), 124022. http://dx.doi.org/10.1088/1748-9326/10/12/124022

49. McNamara, J., S. Clemmer, K. Dahl, and E. Spanger-Siegfried, 2015: Lights Out? Storm Surge, Blackouts, and How Clean Energy Can Help. Union of Concerned Scientists, Cambridge, MA, 40 pp. https://www.ucsusa.org/sites/default/files/attach/2015/10/lights-out-full-report.pdf

50. Con Edison, 2016: Con Edison Close To Completing $1 Billion In Post-Sandy Storm Protections. Consolidated Edison Company, New York. https://www.coned.com/en/about-con-edison/media/news/20161029/post-sandy

51. Wernsing, R., 2014: Reliability and resiliency in New Jersey. In *IEEE Power & Energy Society General Meeting*, National Harbor, MD, 30 July. IEEE. https://www.ieee-pes.org/presentations/gm2014/IEEE2014-Energy-StrongRWWv3.pdf

52. PRERWG, 2017: Build Back Better: Reimagining and Strengthening the Power Grid of Puerto Rico. Puerto Rico Energy Resiliency Working Group (PRERWG), various pp. https://www.governor.ny.gov/sites/governor.ny.gov/files/atoms/files/PRERWG_Report_PR_Grid_Resiliency_Report.pdf

53. Vose, R.S., D.R. Easterling, K.E. Kunkel, A.N. LeGrande, and M.F. Wehner, 2017: Temperature changes in the United States. *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA, 185-206. http://dx.doi.org/10.7930/J0N29V45

54. Wehner, M.F., J.R. Arnold, T. Knutson, K.E. Kunkel, and A.N. LeGrande, 2017: Droughts, floods, and wildfires. *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA, 231-256. http://dx.doi.org/10.7930/J0CJ8BNN

55. Kossin, J.P., T. Hall, T. Knutson, K.E. Kunkel, R.J. Trapp, D.E. Waliser, and M.F. Wehner, 2017: Extreme storms. *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA, 257-276. http://dx.doi.org/10.7930/J07S7KXX

56. 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. http://dx.doi.org/10.1073/pnas.1613193114

57. Gordon, K. and the Risky Business Project, 2014: The Economic Risks of Climate Change in the United States: A Climate Risk Assessment for the United States. Risky Business Project, New York, 51 pp. https://riskybusiness.org/site/assets/uploads/2015/09/RiskyBusiness_Report_WEB_09_08_14.pdf

58. DOE, 2016: Revolution...Now: The Future Arrives for Five Clean Energy Technologies—2016 Update. DOE/EE-1478. U.S. Department of Energy (DOE), Washington, DC, 25 pp. https://www.energy.gov/sites/prod/files/2016/09/f33/Revolutiona%CC%82%E2%82%ACNow%202016%20Report_2.pdf

59. EIA, 2018: Annual Energy Outlook 2018. AEO2018. U.S. Energy Information Administration (EIA), Washington, DC, 146 pp. https://www.eia.gov/outlooks/aeo/

60. Schwartz, L., M. Wei, W. Morrow, J. Deason, S.R. Schiller, G. Leventis, S. Smith, W.L. Leow, T. Levin, S. Plotkin, Y. Zhou, and J. Teng, 2017: Electricity End Uses, Energy Efficiency, and Distributed Energy Resources Baseline LBNL-1006983. Lawrence Berkeley National Laboratory, Berkeley, CA, 370 pp. http://eta-publications.lbl.gov/sites/default/files/lbnl-1006983.pdf

61. EIA, 2018: Frequently Asked Questions: How Much Oil Consumed by the United States Comes from Foreign Countries? U.S. Energy Information Administration (EIA), Washington, DC. https://www.eia.gov/tools/faqs/faq.php?id=32&t=6

62. Spang, E., S., A.J. Holguin, and F.J. Loge, 2018: The estimated impact of California's urban water conservation mandate on electricity consumption and greenhouse gas emissions. *Environmental Research Letters*, **13** (1), 014016. http://dx.doi.org/10.1088/1748-9326/aa9b89

63. DOE, 2014: INFOGRAPHIC: Understanding the Grid. U.S. Department of Energy, Washington, DC. https://www.energy.gov/articles/infographic-understanding-grid

64. ASCE, 2017: 2017 Infrastructure Report Card: Energy. American Society of Civil Engineers (ASCE), Reston, VA, 6 pp. https://www.infrastructurereportcard.org/wp-content/uploads/2017/01/Energy-Final.pdf

65. Zamuda, C., 2016: A Review of Climate Change Vulnerability Assessments: Current Practices and Lessons Learned from the U.S. Department of Energy's *Partnership for Energy Sector Climate Resilience*. U.S. Department of Energy, Office of Energy Policy and Systems Analysis, Washington, DC, 35 pp. https://www.energy.gov/epsa/downloads/review-climate-change-vulnerability-assessments-current-practices-and-lessons-learned

66. NERC, 2013: Special Reliability Assessment: Accommodating an Increased Dependence on Natural Gas for Electric Power. Phase II: A Vulnerability and Scenario Assessment for the North American Bulk Power System North American Electric Reliability Corporation (NERC), Atlanta, GA, 114 pp. https://www.nerc.com/pa/RAPA/ra/Reliability%20Assessments%20DL/NERC_PhaseII_FINAL.pdf

67. Sullivan, P., J. Colman, and E. Kalendra, 2015: Predicting the Response of Electricity Load to Climate Change. NREL/TP-6A20-64297 National Renewable Energy Laboratory, Denver, CO, 18 pp. https://www.nrel.gov/docs/fy15osti/64297.pdf

68. Chang, J.W., M.G. Aydin, J. Pfeifenberger, K. Spees, and J.I. Pedtke, 2017: Advancing Past "Baseload" to a Flexible Grid: How Grid Planners and Power Markets Are Better Defining System Needs to Achieve a Cost-Effective and Reliable Supply Mix. The Brattle Group, Boston, MA, 35 pp. http://files.brattle.com/system/publications/pdfs/000/005/456/original/advancing_past_baseload_to_a_flexible_grid.pdf?1498482432

69. EEI, 2014: Before and After the Storm—Update. Edison Electric Institute, Washington, DC, 133 pp. http://www.eei.org/issuesandpolicy/electricreliability/mutualassistance/Documents/BeforeandAftertheStorm.pdf

70. Chen, B., J. Wang, L. Wang, Y. He, and Z. Wang, 2014: Robust optimization for transmission expansion planning: Minimax cost vs. minimax regret. *IEEE Transactions on Power Systems*, **29** (6), 3069-3077. http://dx.doi.org/10.1109/TPWRS.2014.2313841

71. Jin, S., S.M. Ryan, J.-P. Watson, and D.L. Woodruff, 2011: Modeling and solving a large-scale generation expansion planning problem under uncertainty. *Energy Systems*, **2** (3), 209-242. http://dx.doi.org/10.1007/s12667-011-0042-9

72. Chiara, N., M.J. Garvin, and J. Vecer, 2007: Valuing simple multiple-exercise real options in infrastructure projects. *Journal of Infrastructure Systems*, **13** (2), 97-104. http://dx.doi.org/10.1061/(ASCE)1076-0342(2007)13:2(97)

73. DOE, 2015: Tribal Energy System Vulnerabilities to Climate Change and Extreme Weather. U.S. Department of Energy (DOE). Office of Indian Energy, Washington, DC, 489 pp. https://energy.gov/sites/prod/files/2015/09/f26/Tribal%20Energy%20Vulnerabilities%20to%20Climate%20Change%208-26-15b.pdf

74. Rockerfeller Foundation, 2017: 100 Resilient Cities, New York. https://www.rockefellerfoundation.org/our-work/initiatives/100-resilient-cities/

75. C40 Cities, 2017: C40 Cities [web page]. http://www.c40.org/about

76. DOE, 2016: A Review of Climate Change Vulnerability Assessments: Current Practices and Lessons Learned from DOE's *Partnership for Energy Sector Climate Resilience*. U.S. Department of Energy (DOE). Office of Energy Policy and System Analysis, Washington, DC, 89 pp. https://www.energy.gov/epsa/downloads/review-climate-change-vulnerability-assessments-current-practices-and-lessons-learned

77. EIA, 2017: Form EIA-860 Detailed Data: Generator-Level Specific Information. U.S. Energy Information Administration (EIA), Washington, DC. https://www.eia.gov/electricity/data/eia860/

78. EIA, 2017: Form EIA-923 Detailed Data: Electric Power Data. U.S. Energy Information Administration (EIA), Washington, DC. https://www.eia.gov/electricity/data/eia923/

79. EIA, 2014: Many Newer Power Plants Have Cooling Systems That Reuse Water. U.S. Energy Information Administration (EIA), Washington, DC. https://www.eia.gov/todayinenergy/detail.php?id=14971

80. Macknick, J., R. Newmark, G. Heath, and K.C. Hallett, 2012: Operational water consumption and withdrawal factors for electricity generating technologies: A review of existing literature. *Environmental Research Letters*, **7** (4), 045802. http://dx.doi.org/10.1088/1748-9326/7/4/045802

81. Peer, R.A.M. and K.T. Sanders, 2016: Characterizing cooling water source and usage patterns across US thermoelectric power plants: A comprehensive assessment of self-reported cooling water data. *Environmental Research Letters*, **11** (12), 124030. http://dx.doi.org/10.1088/1748-9326/aa51d8

82. Veil, J., 2015: U.S. Produced Water Volumes and Management Practices in 2012. Groundwater Protection Council, Oklahoma City, OK. http://www.veilenvironmental.com/publications/pw/prod_water_volume_2012.pdf

83. Sanders, K.T. and M.E. Webber, 2012: Evaluating the energy consumed for water use in the United States. *Environmental Research Letters*, **7** (3), 034034. http://dx.doi.org/10.1088/1748-9326/7/3/034034

84. Tidwell, V.C., B. Moreland, and K. Zemlick, 2014: Geographic footprint of electricity use for water services in the western U.S. *Environmental Science & Technology*, **48** (15), 8897-8904. http://dx.doi.org/10.1021/es5016845

85. Arent, D.J., R.S.J. Tol, E. Faust, J.P. Hella, S. Kumar, K.M. Strzepek, F.L. Tóth, and D. Yan, 2014: Key economic sectors and services. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change*. Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 659-708.

86. Kao, S.-C., M. Ashfaq, B.S. Naz, R.U. Martínez, D. Rastogi, R. Mei, Y. Jager, N.M. Samu, and M.J. Sale, 2016: Transforming the Nation's Electricity System: The Second Installment of the Quadrennial Energy Review (QER 1.2). ORNL/SR-2015/357. U.S. Department of Energy. Oak Ridge National Laboratory, Washington, DC, 100 pp. https://nhaap.ornl.gov/sites/default/files/9505_FY16_Assessment_Report.pdf

87. Jiménez Cisneros, B.E., T. Oki, N.W. Arnell, G. Benito, J.G. Cogley, P. Döll, T. Jiang, and S.S. Mwakalila, 2014: Freshwater resources. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change*. Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 229-269.

88. DOE, 2013: Effects of Climate Change on Federal Hydropower: Report to Congress. U.S. Department of Energy (DOE), Washington, DC, 29 pp. https://energy.gov/sites/prod/files/2013/12/f5/hydro_climate_change_report.pdf

89. Easterling, D.R., K.E. Kunkel, J.R. Arnold, T. Knutson, A.N. LeGrande, L.R. Leung, R.S. Vose, D.E. Waliser, and M.F. Wehner, 2017: Precipitation change in the United States. *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA, 207-230. http://dx.doi.org/10.7930/J0H993CC

90. Larsen, P.H., K.H. LaCommare, J.H. Eto, and J.L. Sweeney, 2015: Assessing Changes in the Reliability of the U.S. Electric Power System. LBNL-188741. Lawrence Berkeley National Laboratory, Berkeley, CA, 68 pp. https://emp.lbl.gov/sites/all/files/lbnl-188741.pdf

91. EIA, 2016: Frequently Asked Questions: How Much Natural Gas Does the United States Have, and How Long Will It Last? U.S. Energy Information Administration (EIA), Washington, DC. https://www.eia.gov/tools/faqs/faq.php?id=58&t=8

92. IRENA, 2016: The Power to Change: Solar and Wind Cost Reduction Potential to 2025. International Renewable Energy Agency (IRENA), Bonn, Germany, 108 pp. http://www.irena.org/DocumentDownloads/Publications/IRENA_Power_to_Change_2016.pdf

93. EPA, 2017: Creating Resilient Water Utilities (CRWU). U.S. Environmental Protection Agency (EPA), Washington, DC. https://www.epa.gov/crwu

94. DHS, 2017: Regional Resiliency Assessment Program. U.S. Department of Homeland Security (DHS), Washington, DC. https://www.dhs.gov/regional-resiliency-assessment-program#