U.S. DEPARTMENT OF
ENERGY

Climate Change and the U.S. Energy Sector:

Regional Vulnerabilities and Resilience Solutions

October 2015

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Office of Energy Policy and Systems Analysis

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Cover photo credits

Top row: photovoltaic panels and transmission towers (dollarphotoclub.com); wind turbine in wheat field (istockphoto)

Middle row: aerial view of New Jersey refinery (istockphoto)

Map: ice road in Arctic Alaska (NETL 2015); Grand Coulee Dam in Washington state (USBR 2011); residential photovoltaic panels in Castro Valley, California (APS 2010); coal train in South Dakota (LOC 2015); drilling rig in Texas (Luck 2009); coal plant cooling tower on Lake Michigan coast in Michigan City, Indiana (USGS 2002); window air conditioning units in New York City (Rothamel 2008); Port Fourchon in Louisiana (Gringo 2013); San Juan Port in Puerto Rico (USACE 2007)

Executive Summary

Changes in climate create diverse challenges across the U.S. energy system. Some energy infrastructure assets have already suffered damage or disruption in services from a variety of climate-related impacts, such as higher temperatures, rising sea levels, and more severe weather events. In the absence of concerted action to improve resilience, energy system vulnerabilities pose a threat to America's national security, energy security, economic well-being, and quality of life.

Building climate change resilience into our energy infrastructure planning is a challenging and complex undertaking. Planning horizons can span several decades (the typical service life of most energy assets), associated investments can extend into the billions of dollars, and relevant technologies can change rapidly. Some climate change impacts may trigger cascading effects on natural resources, energy demand, and supply chains. Challenges are compounded when addressing climate risks at the regional or local level, where climate change projections are subject to less certainty than at the national scale.

The U.S. Department of Energy (DOE) has proactively launched numerous initiatives to support and facilitate energy sector climate preparedness and resilience at national, regional, and local levels. In addition to enhancing resilience to climate change, these actions may also have co-benefits that accommodate non-climate resilience needs (e.g., aging infrastructure, cybersecurity, physical attacks, geomagnetic storms). To assist infrastructure owners and utility planners, DOE has compiled this report on region-specific energy vulnerabilities to climate change (see Figure ES-1) and current resilience solutions.

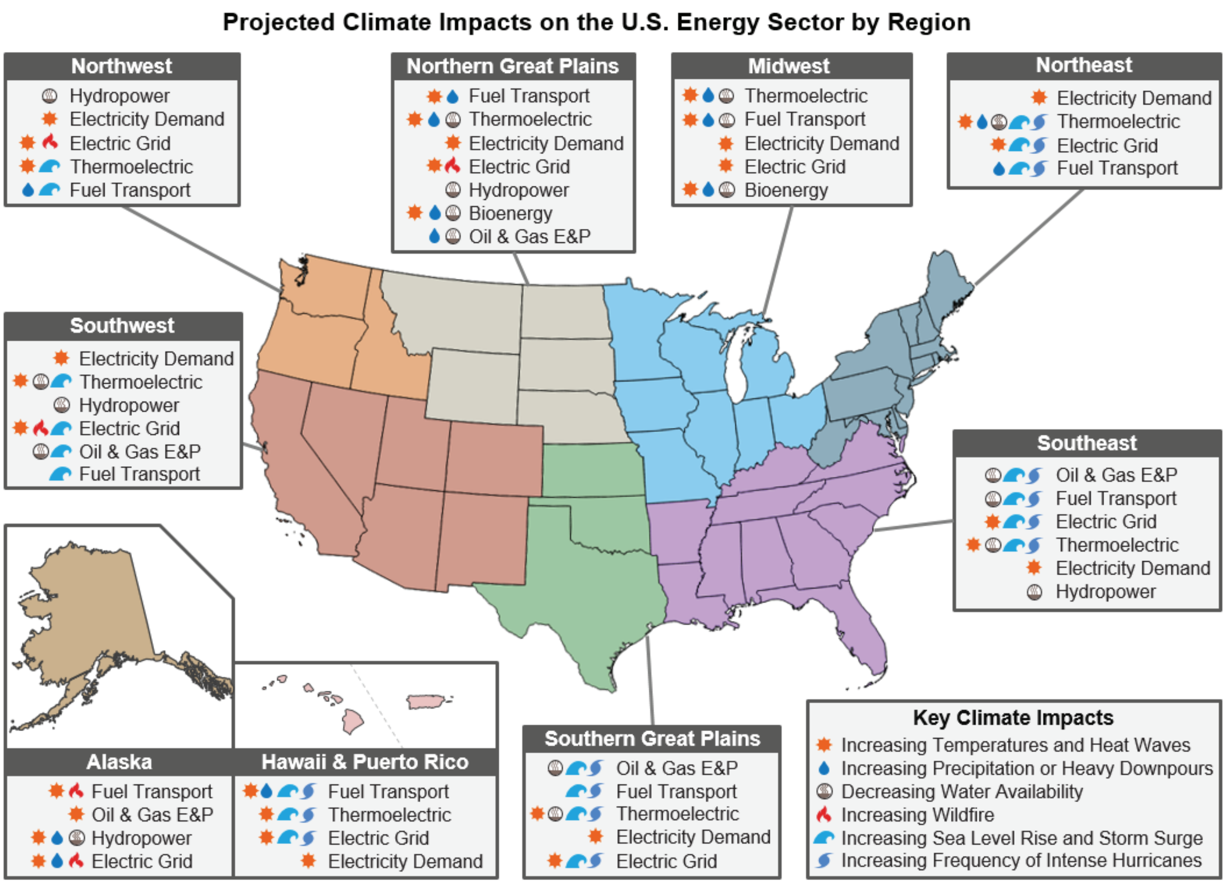


Figure ES-1. Potential climate change impacts on the U.S. energy infrastructure vary by region. Energy subsectors considered most vulnerable to projected climate impacts are listed first for each region.[1]

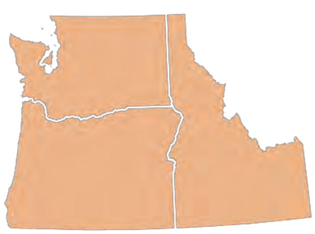
[1] "Thermoelectric" generally refers to power plants that use a steam turbine to generate electricity. Examples of thermoelectric power plant fuel sources include coal, natural gas, oil, nuclear, biomass, geothermal, and concentrated solar power. "Oil & Gas E&P" refers to upstream oil and gas operations, primarily exploration and production (E&P). "Fuel Transport" refers to movements of energy resources by rail, truck, marine vessel, and pipeline, and it includes associated facilities such as ports, pumping stations, terminals, and storage facilities. Hurricane impacts in Hawaii refer to a projected increase in the frequency of all hurricanes striking the islands, not just intense hurricanes; see Chapter 10 for specific projections. The order of subsector vulnerabilities shown in the figure is based on judgments by the report authors as well as experts from government agencies, national laboratories, and private sector energy companies.

Key Climate Impacts and Regional Vulnerabilities

Vulnerabilities to climate change vary across regions depending upon the nature of the climate impacts (see text box), the types and age of energy systems present, and the projected combined impacts on operations, energy demand, and energy supply chains. Major energy systems affected by regional climate impacts include the following:

- Oil and gas upstream operations are most vulnerable in the Southeast, Southern Great Plains, and Alaska.
- Fuel transport in every region is vulnerable to a variety of climate impacts, including increasing heavy precipitation, heat waves, drought, hurricanes, and sea level rise-enhanced storm surge.
- Thermoelectric power generation is vulnerable to increasing temperatures and reduced water availability in most regions, particularly in the Midwest, Great Plains, and southern regions.
- Hydropower is vulnerable to reduced snowpack, earlier melting, and changes to precipitation patterns, mainly in western regions.
- Bioenergy crops in the Midwest and Northern Great Plains may be harmed by higher temperatures and more frequent droughts and floods.
- Electric grid operations and infrastructure in every region is vulnerable to a variety of climate impacts, including increasing temperatures, heavy rainfall events, wildfire, hurricanes, and storm surge.
- Electricity demand is affected by increasing temperatures and is a key vulnerability in nearly every region.

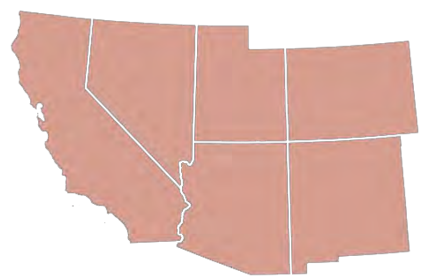
Critical regional vulnerabilities are summarized below.



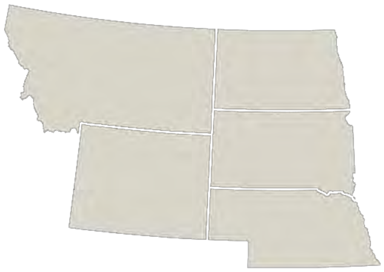
Northwest: Hydropower provides more than 70% of the Northwest's electricity and is an important export to California and Canada (EIA 2014a, EIA 2014b). Warmer temperatures and less mountain snowpack will shift peak streamflow in the region from summer toward spring (BPA 2011, CIG 2009, DOE 2012, Doppelt 2009, USGCRP 2014). Meanwhile, warmer temperatures will likely increase electricity demand for cooling in the summer, when available hydropower generation is reduced (BPA 2011, DOE 2012, DOE 2013, USGCRP 2014). Warmer and drier summers may also increase the threat of wildfires, which have the potential to disrupt electricity transmission (DOE 2013, USGCRP 2014).

Key climate impacts projected by region

Climate impact	Regions with energy systems that are most affected
Increasing temperatures and heat waves	All regions
Increasing heavy downpours	Northern regions
Decreasing water availability	Western and southern regions
Increasing wildfire	Western regions
Increasing sea level rise and storm surge	Nearly all coastal regions
Increasing frequency of intense hurricanes	Gulf and Atlantic regions, including Puerto Rico
Permafrost thaw	Alaska



Southwest: Many energy systems in the Southwest are already designed for hot and arid conditions, but system reliability is increasingly threatened by higher temperatures, declining water availability, and greater risk of wildfire (DOE 2013, NOAA 2013, USGCRP 2014). More frequent and severe heat waves are likely to amplify demand for cooling energy (NOAA 2013, Sathaye et al. 2012, USGCRP 2014). Higher temperatures and reduced water availability may limit the ability of natural gas-fired, coal-fired, and other thermoelectric power plants in the region to meet demand (DOE 2013, Sathaye et al. 2012). Hydropower resources will be affected by reductions in streamflow and shifts in streamflow timing (AEG and Cubed 2005, Cayan et al. 2013, NOAA 2013, USGCRP 2014). Electricity transmission lines essential to connecting remote generation assets to demand centers are vulnerable to projected increases in wildfire as forests and shrub lands become drier (DOE 2013, Sathaye et al. 2012, USGCRP 2014).

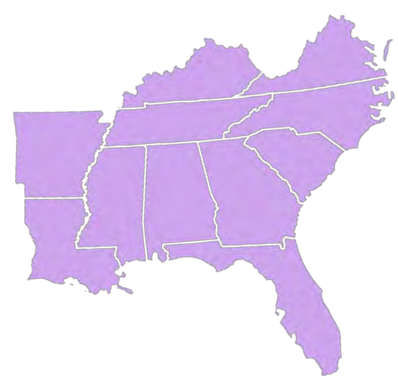


Northern Great Plains: The Northern Great Plains produces coal, crude oil, and biofuel for use across the nation (EIA 2012, EIA 2014c). Delivery is mainly by railroad and pipeline, which are vulnerable to damage or disruption from increasing heavy precipitation events and associated flooding and erosion (USGCRP 2014). Summer heat waves could also damage railroad tracks and are likely to reduce thermoelectric power plant and transmission line capacity (DOE 2013, USGCRP 2014). Higher temperatures could lower the yields of crops used for biofuels while expanding northward the range in which certain biofuel crops (e.g., corn) can be cultivated (NOAA 2013, Roberts and Schlenker 2011, USGCRP 2014).

Southern Great Plains: The Southern Great Plains is home to substantial oil and gas production, refining, and transportation assets, with an especially high concentration near the Gulf Coast. Projected increases in the intensity of Atlantic hurricanes and associated rainfall, combined with rising global sea levels and subsiding coastlines, escalate the risk of coastal flooding and wind damage to many of these assets (DOE 2013, USGCRP 2014, DOE 2015). Heat waves and higher temperatures are also projected for the region, increasing electricity demand for cooling while reducing the generation capacity of thermoelectric power plants and the transmission capacity of power lines (DOE 2013, NOAA 2013, USGCRP 2014). Drought and increased competition for water could limit the water available for power plant cooling and oil and gas operations (Cook et al. 2013, DOE 2013, USGCRP 2014).

Midwest: More than 90% of the region's electricity is generated by coal-fired and other thermoelectric power plants, which are vulnerable to increasing temperatures (DOE 2013, EIA 2013). Warmer temperatures reduce the generation capacity of power plants and the transmission capacity of power lines, while simultaneously increasing electricity demand for cooling (DOE 2013, USGCRP 2014). Energy-related infrastructure, including roads, railroads, and electric grid equipment, may also be at increased risk of damage due to flooding, as heavy precipitation events are projected to occur more frequently (DOE 2013, NOAA 2013, USGCRP 2014). Increased risk of floods and droughts may disrupt fuel transport on inlands waterways. Changing water availability and increasing temperatures may also affect biofuel production and refining capacity in the Midwest (NOAA 2013, USGCRP 2014).

Northeast: The Northeast region is comparatively cool, so as temperatures rise, increased electricity demand for cooling is likely to be driven in part by increasing market penetration of air conditioners (Auffhammer 2011, DOE 2013, NOAA 2013, USGCRP 2014). Warmer temperatures and more intense heat waves also reduce the capacity of thermoelectric power plants and electric grid transmission during periods of peak electricity demand (DOE 2013, USGCRP 2014). Sea level rise and storm surge increasingly threaten coastal energy infrastructure, including ports, electric grid equipment, and power plants (DOE 2013, USGCRP 2014). Farther inland, low-lying infrastructure, such as roads, railroads, refineries, and power lines, is vulnerable to more frequent flooding from heavy precipitation events (DOE 2013, NOAA 2013, USGCRP 2014).



Southeast: The Southeast, especially the northern Gulf Coast, hosts a large amount of energy infrastructure in low-lying coastal plains that are vulnerable to increases in flooding (DOE 2013, USGCRP 2014). High winds, coastal erosion, flooding, and large waves from hurricanes and sea level rise-enhanced storm surge threaten oil and gas production, ports, pipelines, refineries, and storage facilities, as well as electricity generation and transmission assets (DOE 2013, USGCRP 2014, DOE 2015). Higher temperatures and more frequent, severe, and longer-lasting heat waves are also projected for the Southeast, potentially increasing peak electricity demand for cooling while reducing the capacity of the thermoelectric generation and transmission systems needed to meet the increased demand (DOE 2013, NOAA 2013, USGCRP 2014).

Alaska: Northern latitudes, including all of Alaska, are warming faster than temperate regions, and the permafrost underlying much of Alaska's interior and northern coastlines is at risk of thawing (USGCRP 2014). Thawing permafrost causes underlying land to shift and soften. These structural changes can potentially damage the foundations of pipelines as well as roads and airstrips used for fuel shipments to Alaska's remote rural communities (USGCRP 2014). Thawing permafrost and declining sea ice have already accelerated the erosion of coastlines in rural communities, resulting in damaged or destroyed infrastructure for fuel transfer and storage (Alaska AAG 2010, DOE 2013, USGCRP 2014). Warmer temperatures are likely to shorten the season during which ice roads can be used to reach oil and gas operations in the North Slope (DOE 2013). Alaska's extensive energy assets may also be vulnerable to projected increases in wildfire (USGCRP 2014).

Islands: Hawaii and Puerto Rico share many similarities in their energy systems, including reliance on imported petroleum and other fuels. In both of the island regions, projected sea level rise and hurricane-driven storm surge threaten ports and other essential coastal energy infrastructure with flooding, wave damage, and erosion, while hurricane winds pose a danger to structures and power lines (DOE 2013, Murakami et al. 2013, PRCCC 2013, USGCRP 2014). Higher temperatures reduce the efficiency of oil-fired and other thermoelectric power plants, significantly restricting electricity supply if such losses are not offset by reduced demand or supplies added elsewhere in the system (DOE 2013). Other U.S. islands in the Pacific and in the Caribbean are not separately examined in this report but are likely to have climate impacts and resilience solutions similar to those in Hawaii and Puerto Rico.

Challenges and Opportunities to Accelerate and Expand Resilience

Building a reliable and resilient 21st century U.S. energy sector will require a concerted effort to overcome an array of challenges, including those that are technological and financial, informational and behavioral, institutional, and policy-related. Informational shortcomings, for example, may prevent energy sector owners from making an attractive business case for resilience actions. The public and private sectors are working together to overcome these challenges and better understand the implications of projected climate impacts and the suitability of various resilience solutions.

The private sector, which owns and operates the majority of energy assets, holds central responsibility for identifying and implementing appropriate measures to ensure the climate resilience of those assets. However, DOE fills an important role by facilitating basic scientific discovery; enhancing research, development, demonstration, and deployment; providing technical information and assistance; designing, analyzing, recommending, and fostering enabling policies; and convening and partnering with stakeholders. As a result, a range of organizations are sharing their experiences, conducting research to identify vulnerabilities and evaluate resilience strategies, and incorporating projected climate impacts into risk management decision making.

While government, academia, and technical institutions continue to provide supporting research, data, and tools, energy system planners, owners, and operators are already identifying vulnerabilities, monitoring resources, investing in resilient technology, and planning for rapid recovery. Continued and expanded efforts by states, localities, and tribes will build regional energy resilience capabilities. This proactive approach will improve access to critical information for decision making and assist in building the body of knowledge required to cope effectively. Smart decisions today will help to provide a robust and resilient energy system for tomorrow. Working together, the private and public sectors can make sure that the United States continues to deliver the reliable, affordable, and increasingly clean power and fuels required to maintain a healthy economy and comfortable standard of living.

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Preface

Changes in the global climate system will profoundly affect the U.S. energy sector, which powers the nation's economy. The energy sector provides the electricity and fuels that underpin every facet of the economy, including commerce, manufacturing, transportation, communications, health care, water supply and treatment, and other critical infrastructure and systems. The clear potential for disruptions to the energy sector raises concern for normal economic operations and American's quality of life.

In addition to efforts to reduce the greenhouse gas emissions that cause climate change, the Administration recognizes the importance of adapting to and preparing for climate impacts that can no longer be avoided (see sidebar). This report is part of a broad U.S. Department of Energy (DOE) effort to inform preparedness, resilience planning, and response initiatives (see sidebar on following page).

While this report focuses on resilience to climate change impacts, DOE is also pursuing resilience initiatives that address other energy sector risks not related to climate change (e.g., aging infrastructure, cybersecurity, physical attacks, geomagnetic storms, etc.) that will increase resilience, reliability, safety, and asset security of U.S. energy infrastructure. For example, the Administration recently released the first installment of the Quadrennial Energy Review (QER) that addresses this broader set of challenges and recommends policies and investments to modernize energy transmission, storage, and distribution infrastructure that will promote economic competitiveness, energy security, and environmental responsibility.[1]

Previously, DOE's 2013 report *U.S. Energy Sector Vulnerabilities to Climate Change and Extreme Weather* provided a national perspective on U.S. energy system vulnerabilities to potential climate impacts, including increasing temperatures, decreasing water availability, and increasing storms, flooding, and sea level rise (as summarized in Table P-1).[2] That report identified vulnerabilities in the system and highlighted opportunities to enhance preparedness and resilience at a national level.

Federal leadership on climate change resilience initiatives

In June of 2013, President Obama announced the *Climate Action Plan,* which identifies activities to prepare for a changing climate—impacts of which are already evident across the country. Executive Order (EO) 13653: *Preparing the United States for the Impacts of Climate Change* (November 2013) directs federal agencies to take steps to help American communities strengthen their resilience to extreme weather and prepare for other impacts of climate change. EO 13653 also instructs agencies to provide the information, data, and tools that local, state, and private sector leaders need to take timely and informed actions to improve preparedness and resilience in critical systems, including energy systems.

EO 13653 created the Council on Climate Preparedness and Resilience, which led to the development of national principles for adaptation and is leading to crosscutting and government-wide adaptation policies. The Council is also facilitating development of information, data, and tools for climate change preparedness and resilience to support federal, regional, state, local, tribal, private sector, and nonprofit sector efforts to prepare for the impacts of climate change. For example, see http://www.data.gov/climate/energy-infrastructure/.

EO 13653 also established a short-term task force of state, local, and tribal officials to advise on key actions the federal government can take to better support local preparedness and resilience-building efforts. In the fall of 2014, this task force recommended removing barriers to resilient investments, modernizing grant and loan programs, and developing information and tools to better serve communities.

This new report builds upon the 2013 report, the QER, and other DOE preparedness and resilience initiatives by examining energy sector vulnerabilities to climate impacts at the regional level. To improve understanding of the vulnerabilities in each region, this document reviews the composition, operation, and management of regional energy systems—including regional energy resources, private and public infrastructure, imports and exports, and energy consumption patterns. It also examines regional energy planning efforts, state and local regulations, and measures taken by energy sector owners and operators to enhance climate resilience.

[1] *Quadrennial Energy Review: Energy Transmission, Storage, and Distribution Infrastructure.* U.S. Department of Energy. http://energy.gov/sites/prod/files/2015/04/f22/QER-ALL%20FINAL_0.pdf.

[2] *U.S. Energy Sector Vulnerabilities to Climate Change and Extreme Weather*. U.S. Department of Energy. http://www.energy.gov/downloads/us-energy-sector-vulnerabilities-climate-change-and-extreme-weather.

Energy infrastructure has always been vulnerable to many natural phenomena, such as earthquakes, extreme heat, thunderstorms, high winds, ice storms, landslides, erosion, and floods. This report focuses on potential energy infrastructure impacts of weather-related hazards that are *likely to worsen because of climate change*. These hazards include changes in average and extreme temperatures; changes in average, seasonal, and extreme precipitation and hydrology; more intense hurricanes; increasing sea level rise and storm surge; and changes to ecosystems, which could increase the risk of wildfire. Some of these phenomena have already become more frequent or severe because of climate change—and these trends are expected to continue. The introduction of this report describes these trends, and their national and regional implications in more detail.

Analyses of the changing climate and impacts on energy systems at the regional level are valuable for several reasons:

- Energy systems are designed for and often depend upon regional features, such as the historical climate and presence of natural resources.
- Projected near- and long-term climate change threats and vulnerabilities to energy systems vary considerably by region.
- Interdependencies between regions and energy subsectors may exacerbate or, conversely, reduce energy sector vulnerabilities.
- Appropriate resilience strategies for energy systems depend on regional and local circumstances, such as available resources, population trends, energy demand, and the mix of projected climate impacts.

This report is intended as a resource for private entities, institutions, governments, and other decision makers in need of regional and localized information and insights to assist in assessing risks and developing effective resilience strategies for energy systems vulnerable to climate impacts. The aim is to provide decision makers with a base of regional information that they can use to (1) further explore what the projected changes in climate might mean for their specific energy assets and (2) evaluate a range of strategies for effectively increasing local, regional, and national energy system resilience to climate change.

Examples of DOE initiatives that address preparedness, resilience planning, and response

- **Climate Action Champions:** DOE conducted a national competition to identify local and tribal community organizations pursuing preparedness and resilience activities that can serve as models for other communities. The agency initially selected 16 organizations working on a range of ambitious activities at the frontier of climate action—from creating climate-smart building codes to installing green infrastructure. Federal agencies facilitate peer-to-peer learning and mentorship, provide targeted support, and foster coordination and communication across agencies and organizations. See http://www.energy.gov/epsa/climate-action-champions.
- **Preparedness Pilots:** In cooperation with the State of Colorado, DOE and the National Renewable Energy Laboratory are leading a pilot program that connects local communities with key federal agencies (e.g., NASA, U.S. Army Corps of Engineers, Departments of Defense, Interior, and Agriculture) to assess and plan for region-specific interdependencies and climate change vulnerabilities. This effort promotes preparedness planning and helps create models for other communities.
- **State Energy Assurance Plan Assistance and Risk Assessment Initiative:** DOE works with state and local governments on energy resilience, developing information and tools and conducting forums, training, and tabletop exercises with energy officials, emergency managers, policy makers, and industry asset owners and operators. DOE initiatives include support to State Energy Emergency Assurance Coordinators (EEACs) on information sharing and coordination protocols, as well as grants to help state and local governments develop or refine their energy assurance plans and develop in-house expertise on infrastructure interdependencies and related vulnerabilities. DOE is also leading a State Energy Risk Assessment Initiative, in collaboration with the National Association of State Energy Officials, National Association of Regulatory Utility Commissioners, National Conference of State Legislatures, and National Governors Association, to increase state officials' awareness of risk considerations and be prepared to make informed decisions related to energy systems and infrastructure investments, energy assurance planning, resilience strategies, and asset management. See http://www.energy.gov/indianenergy/downloads/tribal-energy-system-vulnerabilities-climate-change-and-extreme-weather.
- **Strengthening Tribal Energy Systems:** In September 2015, DOE released a report on *Tribal Energy System Vulnerabilities to Climate Change and Extreme Weather* (DOE 2015b). The report describes climate-related events that threaten the economic and energy security of Indian Tribes, who are among the nation's most impoverished communities. The report is part of a broad DOE effort to support tribal climate preparedness that includes technical assistance to help tribes identify, assess, and respond to specific vulnerabilities and resilience options.
- **Partnership for Energy Sector Climate Resilience:** On April 21, 2015, the White House and DOE announced the establishment of the Partnership for Energy Sector Climate Resilience with initially 17 companies representing a range of utilities, including investor-owned as well as federal, state, municipal, and cooperative organizations. Through the Partnership, DOE works with the private sector to develop and deploy effective strategies for enhancing resilience to extreme weather and climate change. The Partnership will assist in the dissemination of user-friendly climate data and decision tools; assessment of costs and benefits of climate resilience actions; and identification of gaps, opportunities and metrics for developing and deploying climate-resilient energy technologies, practices, and policies. See http://www.energy.gov/epsa/partnership-energy-sector-climate-resilience.

Table P-1. Potential effects of climate change on the energy sector

Energy sector	Climate projection	Potential implication
Oil and gas exploration and production	▪ Thawing permafrost in Arctic Alaska	▪ Damaged infrastructure and changes to existing operations
	▪ Longer sea ice-free season in Arctic Alaska	▪ Limited use of ice-based infrastructure; longer drilling season; new shipping routes
	▪ Decreasing water availability	▪ Impacts on drilling, production, and refining
	▪ Increasing frequency of intense hurricanes, and increasing sea level rise and storm surge	▪ Increased risk of physical damage and disruption to offshore and coastal facilities
	▪ Increasing intensity and frequency of flooding	▪ Increased risk of physical damage and disruption to inland facilities
Fuel transport	▪ Reduction in river levels	▪ Disruption of barge transport of crude oil, petroleum products, and coal
	▪ Increasing intensity and frequency of flooding	▪ Disruption of rail and barge transport of crude oil, petroleum products, and coal
Thermoelectric power generation (Coal, natural gas, nuclear, geothermal, and solar CSP)	▪ Increasing air temperatures	▪ Reduction in plant efficiencies and available generation capacity
	▪ Increasing water temperatures	▪ Reduction in plant efficiencies and available generation capacity; increased risk of exceeding thermal discharge limits
	▪ Decreasing water availability	▪ Reduction in available generation capacity; impacts on coal, natural gas, and nuclear fuel supply chains
	▪ Increasing frequency of intense hurricanes, and increasing sea level rise and storm surge	▪ Increased risk of physical damage and disruption to coastal facilities
	▪ Increasing intensity and frequency of flooding	▪ Increased risk of physical damage and disruption to inland facilities
Hydropower	▪ Increasing temperatures and evaporative losses	▪ Reduction in available generation capacity and changes in operations
	▪ Changes in precipitation and decreasing snowpack	▪ Reduction in available generation capacity and changes in operations
	▪ Increasing intensity and frequency of flooding	▪ Increased risk of physical damage and changes in operations
Bioenergy and biofuel production	▪ Increasing air temperatures	▪ Increased irrigation demand and risk of crop damage from extreme heat events
	▪ Extended growing season	▪ Increased production
	▪ Decreasing water availability	▪ Decreased production
	▪ Sea level rise and increasing intensity and frequency of flooding	▪ Increased risk of crop damage
Wind energy	▪ Potential variation in wind patterns	▪ Uncertain impact on resource potential
Solar energy	▪ Increasing air temperatures	▪ Reduction in potential generation capacity
	▪ Decreasing water availability	▪ Reduction in concentrated solar power (CSP) potential generation capacity
Electric grid	▪ Increasing air temperatures	▪ Reduction in transmission efficiency and available transmission capacity
	▪ More frequent and severe wildfires	▪ Increased risk of physical damage and decreased transmission capacity
	▪ Increasing frequency of intense hurricanes, and increasing sea level rise and storm surge	▪ Increased risk of physical damage
Energy demand	▪ Increasing air temperatures	▪ Increased electricity demand for cooling; decreased fuel oil and natural gas demand for heating[3]
	▪ Increasing magnitude and frequency of extreme heat events	▪ Increased peak electricity demand

Source: Adapted from DOE 2013

[3] Energy demand is often reported as a function of heating degree days (HDDs) and cooling degree days (CDDs). Degree days measure the difference between mean air temperature and a standard baseline temperature at which buildings would begin using air conditioning on warm days and heating on cool days; this standard baseline temperature is typically 65°F. On an annual basis, HDDs and CDDs measure the time-integrated difference over a year between the mean daily temperature and the baseline temperature (DOE 2013).

1. Introduction

Across the country, energy systems are increasingly vulnerable to the effects of a changing climate. This section describes the key climate change trends, including rising temperatures and sea levels, changing precipitation patterns, and more frequent and severe episodes of extreme weather, that are already forcing energy systems to operate outside of the conditions for which they were designed and are threatening to damage or disrupt critical energy infrastructure.

Climate change and extreme weather can damage equipment and facilities, disrupt supply chains and operations, and cause shifts in energy supply and demand. Disruptions in energy services can have serious consequences at the local and regional level and can hurt the national economy. U.S. competitiveness and economic health depend upon an energy system that is prepared to meet the demands and threats of the 21st century. The climate and weather impacts that are evident today are expected to become more frequent and more intense in the decades ahead. Planning and investment will be required to ensure that the nation’s energy systems can continue to deliver high performance while anticipating and reducing vulnerabilities to climate change and extreme weather.

Influence of climate on energy systems

Energy production, transport, and delivery infrastructure and operations are typically tailored either to take advantage of or to address regional differences in climate conditions, available resources, and demand for energy (see Figure 1-1). A region’s **resources**, including water availability and energy resources (fossil and renewable resources), are primary considerations in the design of energy systems. For example, the Northwest has high volumes of water flowing through mountainous terrain, making the region well-suited for hydroelectric power generation. Similarly, the Southeast, Midwest, and Northeast are served by navigable waterways, so marine vessels are used extensively in these regions to transport energy products such as petroleum and coal. Regional differences in water availability are also reflected in technologies used in power plant cooling water systems. In the Southeast, many large generating stations incorporate once-through cooling technologies that rely on an abundant supply of fresh surface water. In the Southwest, where fresh surface water is scarce, most power plants rely on alternative sources of water (e.g., municipal waste water), or they use water-efficient cooling systems (e.g., recirculating systems or dry cooling). In fact, less than 1% of Southwest generating capacity uses once-through surface water for cooling (UCS 2012).

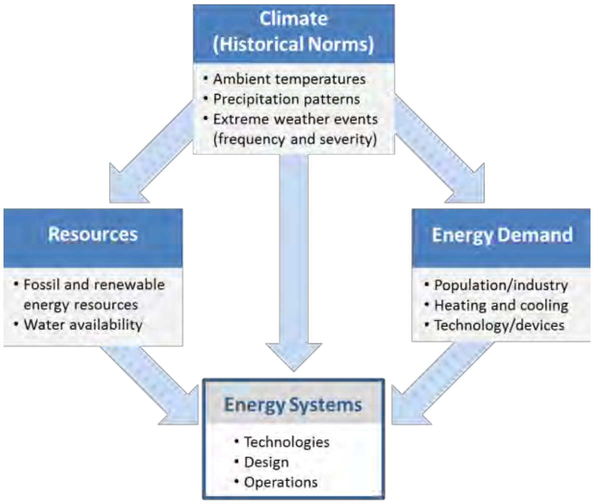

Figure 1-1. Energy systems are designed for regional climate conditions, resources, and energy demand

Beyond the available resources, which tend to influence the *type* of energy systems used, **energy demand** typically drives the *amount* of energy system infrastructure needed in an area. High demand centers require numerous high-voltage transmission lines. Across the country, natural gas and crude oil pipelines have been built to serve energy supply centers such as power plants and refineries, which, in turn, are located in proximity to large demand centers for electricity and fuel.

The **climate** (historical norms) influences multiple factors, including many of the resources that are available for generating energy (e.g., water, solar, wind, and biomass) as well as the level of energy demand (e.g., requirements for heating and cooling). For example, precipitation patterns and temperatures affect the amount of water and biomass resources available for bioenergy. Additionally, ambient temperatures and humidity are among the biggest factors in determining energy demand; more than 40% of U.S. household energy is used for heating and cooling (EIA 2013).

In addition to influencing natural resources and energy demand, **climate** also directly influences the technology, design, and operations of regional energy systems. For example, thermoelectric power plants design and operate their cooling water intakes and effluent systems based, in part, on an expected range of air and water temperatures. In addition, utilities typically equip their transformers with cooling systems that are adequate to prevent overheating in regions that historically experience extremely hot weather. Similarly, pipelines constructed on permafrost in Arctic Alaska are designed for an expected range of historic temperatures.

The energy used for space heating and cooling is also affected by climate and varies by region. In the northern states, more energy is used for winter heating (often in the form of natural gas or oil) than for cooling; in the southern states, the opposite typically holds true. In parts of the Northeast, many homes use electric window air conditioners to address the limited need for cooling but rely on natural gas for heat. In the Southeast, by contrast, many homes are equipped with electric heat pumps for efficient summer cooling and rely on electricity for winter heat (EIA 2013).

Weather and climate patterns—including the prevalence of storms, wildfires, floods, and drought—have long shaped energy system design and operations. Hurricanes can have devastating impacts on local or regional energy systems. Companies operating oil and gas infrastructure along the Gulf Coast in the Southern Great Plains and Southeast, for example, typically incorporate the historical likelihood of severe hurricanes into risk management planning. Transmission line operators in wildfire areas incorporate vegetation management and other techniques to mitigate fire risk. Utilities in tornado-prone regions are commonly prepared with emergency response and recovery plans. The QER examines these and other hazards that impact energy transmission, storage, and distribution systems. Figure 1-2 from the QER shows the regional distribution of certain natural hazards.

The annual frequency of billion-dollar weather events and associated costs from these events has increased during the last 30 years (Figure 1-3). These storm-related damages affect the energy sector and many other sectors.

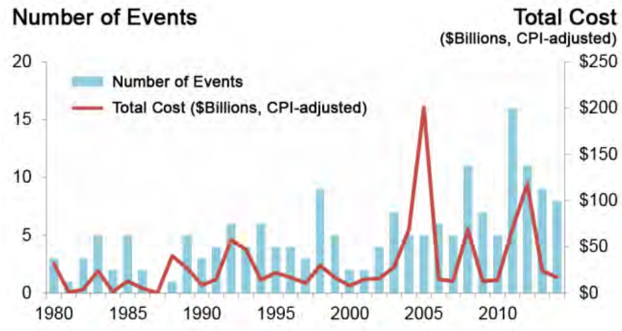

Figure 1-3. Billion-dollar disaster events and aggregate costs by year[4]
Data source: NOAA 2015

As climate change progresses, energy infrastructure that has been designed to perform across the known range of historical conditions in a region may not be designed to withstand the projected changes to temperatures, precipitation, hurricanes, wildfire, and sea level rise. A regional climate's departure from the historical averages could significantly impede energy system performance and expose the system to much greater risks, particularly with aging energy infrastructure. Geographic variations in climate change and energy infrastructure underscore the value of a regional approach to analyzing infrastructure

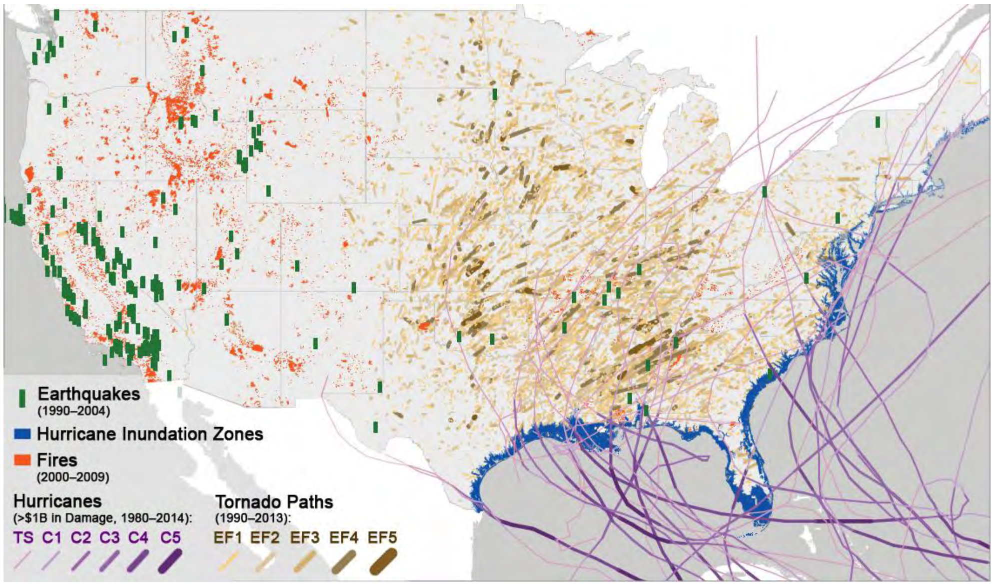

Figure 1-2. Regional distribution of hazards, of which fires, hurricane intensity, and storm surge are projected to intensify because of climate change
Source: DOE 2015a

[4] Number of events exceeding $1 billion using 2014 consumer price index (CPI) adjustment

vulnerabilities and developing and implementing effective climate resilience solutions.

Regional variations in projected climate impacts

Projected changes to local and regional climates differ from national or global average projections. In general, the United States is expected to become warmer, and periods of extreme heat are likely to become more severe, more frequent, and more extended. However, the degree of projected warming varies; Alaska and the northern and interior areas of the nation are expected to experience more rapid warming, while the Pacific, South Atlantic, and Gulf coastal areas are likely to see their warming trends moderated by the oceans (Figure 1-4) (NOAA 2013, USGCRP 2014).

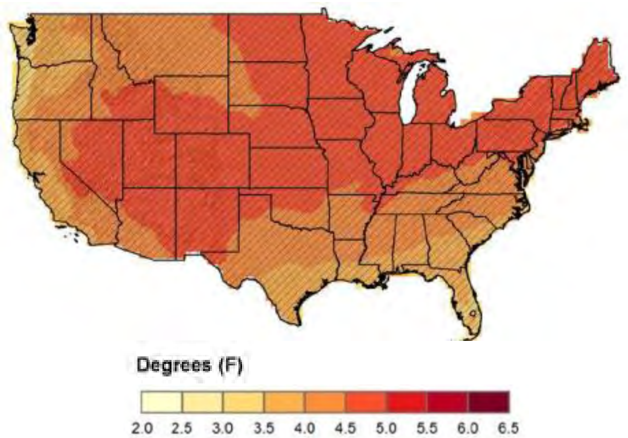

Figure 1-4. Increase in annual mean temperature by mid-century[5]
Source: NOAA 2013

Annual average precipitation is generally expected to increase across the northern United States but decline in the southern states (NOAA 2013, USGCRP 2014). Other changes in precipitation patterns, such as increased frequency or severity of heavy precipitation events and changes in the length of dry spells, are also projected to vary across regions. The largest increases in heavy precipitation events are projected for the northern regions, including the Northern Great Plains and the Northeast, as well as interior areas of the West (Figure 1-5), while the largest increases in consecutive dry days are anticipated in the Southern Great Plains and Southwest (Figure 1-6) (NOAA 2013).

Certainty of regional climate projections

Climate models have improved dramatically over the last several decades, particularly at a national or global scale. However, the complexity of climate systems and scientific uncertainty about some aspects of climate mean that small variations in inputs and assumptions can produce a range of outcomes. Small differences at the global scale can create large changes to projected climate impacts for a region. Figure 1-4, Figure 1-5, and Figure 1-6 show averages from multiple models. Hatched lines indicate areas with the greatest agreement among models.

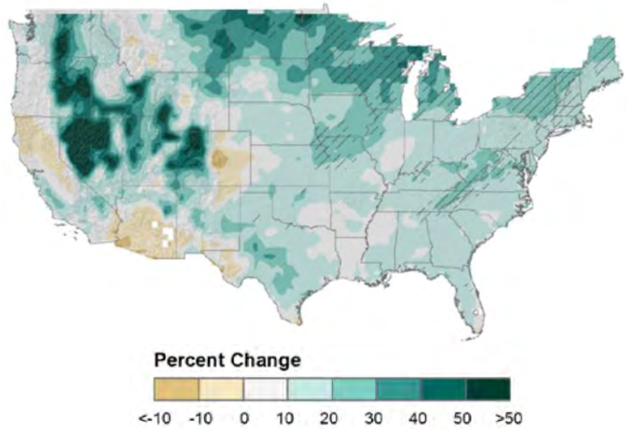

Figure 1-5. Change in annual heavy precipitation events by mid-century[6]
Source: NOAA 2013

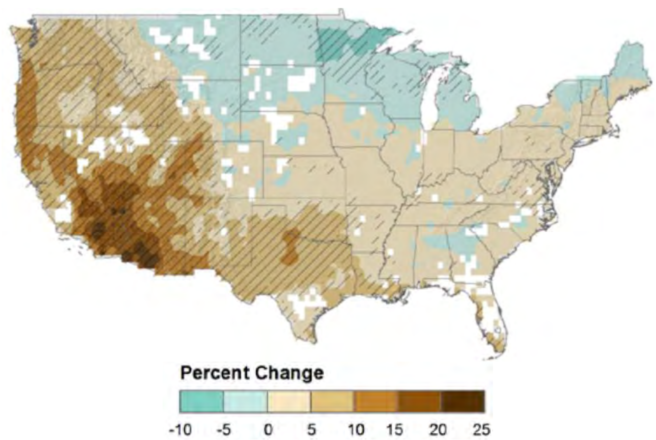

Figure 1-6. Change in consecutive days with minimal precipitation by mid-century[7]
Source: NOAA 2013

[5] Simulated difference in annual mean temperature (°F) for 2041–2070 compared to 1971–2000 under a high (A2) emissions scenario. Climate projections for Alaska, Hawaii, and Puerto Rico are based on different sources and can be found in Chapters 9 and 10.

[6] Simulated percentage difference in the mean annual number of days with precipitation of greater than one inch for 2041–2070 compared to 1980–2000 under a high (A2) emissions scenario. Climate projections for Alaska, Hawaii, and Puerto Rico are based on different sources and can be found in Chapters 9 and 10.

[7] Simulated difference in the mean annual maximum number of consecutive days with precipitation of less than 0.1 inches for 2041-2070 compared to 1980-2000 under a high (A2) emissions scenario. Climate projections for Alaska, Hawaii, and Puerto Rico are based on different sources and can be found in Chapters 9 and 10.

The severity of climate change impacts on a region or locality will depend on baseline climate conditions as well as the scale of the projected change. In colder parts of the country, for example, higher winter temperatures may reduce net energy consumption, as reductions in energy demand for winter heating may more than offset increases in energy demand for summer cooling, at least in the near term. In western forests, higher temperatures and reduced precipitation are projected to increase the risk of wildfire, while forests in the East are less likely to see an immediate increase in fires than those in the West—despite also experiencing increases in temperatures and summer drying (USGCRP 2014).[8] Increases in sea level rise and hurricane intensity are most likely to affect regions with low-lying coastal energy infrastructure, high rates of land subsidence, and gently sloping continental shelves, such as parts of the Gulf and Mid-Atlantic Coasts (USGCRP 2014). Figure 1-7 illustrates the projected exposure of a portion of the Gulf Coast to sea-level rise and storm surge from a Category 1 hurricane.

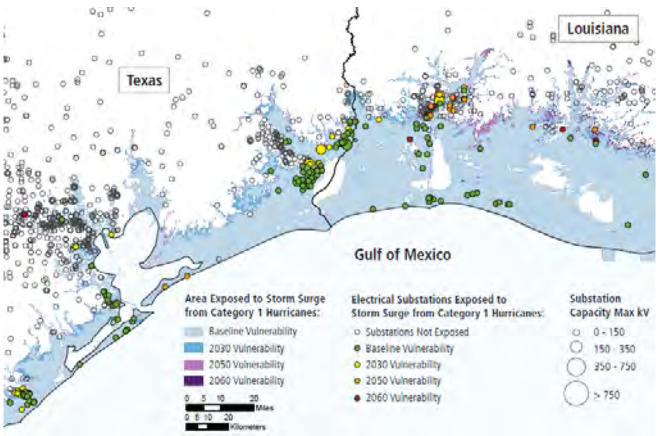

Figure 1-7. Storm surge inundation zones from a Category 1 hurricane under different sea level rise scenarios; exposure to electrical substations shown[9]
Source: DOE 2015a

Key sources

Projected climate impacts in this report are primarily based on assessments by the U.S. Global Change Research Program (USGCRP) and the National Oceanic and Atmospheric Administration (NOAA). The projections represent an average of multiple climate models, as presented in in the 2014 *Third National Climate Assessment* (NCA) and its supporting analyses. The NCA, conducted under the auspices of the Global Change Research Act of 1990, assesses the effects of global climate change on human and natural systems, analyzes current trends in global change, and projects major trends for the next 25 to 100 years. The NCA provides the United States' most comprehensive scientific assessment of how climate change affects each region of the country.

This report also draws upon valuable studies and resources from several federal agencies, including the U.S. Department of Energy (DOE), U.S. Department of Transportation (DOT), U.S. Environmental Protection Agency (EPA), U.S. Geological Survey (USGS), U.S. Army Corps of Engineers (USACE), and NOAA, among others. Supplemental resources used in this report include state, regional, and local publications and planning documents; regulatory filings; and peer-reviewed studies and datasets published in major scientific journals. News articles and press releases are used to illustrate climate change impacts and resilience solutions.

Using this report

Each of the next nine chapters of this report focuses on a single region of the United States. These nine regions broadly correspond with the geographic breakdown used in the *Third National Climate Assessment* (Figure 1-8).[10] By aligning the regional boundaries of this report with the NCA, this report is able to better leverage the scientific findings of the authoritative NCA and its series of supportive analyses. Each of the chapters in this report is structured as a stand-alone regional profile and includes a brief overview of the regional energy infrastructure and key vulnerabilities, a more detailed description of the critical energy subsectors that are most vulnerable to the impacts of climate change, a one-page description of regional climate change trends and projections, and its own references section. The final chapter provides crosscutting observations relevant to multiple regions.

Figure 1-8. Regions of the United States addressed in this report

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[8] Although both western and eastern forests may experience increasing disturbances caused by climate change, western forests are already more vulnerable to large-scale die-offs resulting from drought, disease, and pests than eastern forests, so climate impacts on western forests are expected to be more severe.

[9] Baseline vulnerability corresponds with sea level in 1992. Future vulnerabilities correspond with a high-end sea level rise scenario of 10 inches in 2030, 23 inches in 2050, and 32 inches in 2060.

[10] Report chapters correspond to the regions in the *Third National Climate Assessment* with two main exceptions: the Great Plains region, which is separated into two regions in this report, and the Islands region, which discusses Hawaii and Puerto Rico.

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Chapter 2: **Northwest**

Climate Change and the Energy Sector

Overview

The Northwest has a diverse topography with rocky shorelines, lush forests, mountains, farmlands, and arid regions. Major climate change impacts projected to increasingly threaten the region's energy infrastructure include the following:

- **Higher temperatures may increase the amount of precipitation falling as rain rather than as snow and cause mountain snowpack to melt earlier in the spring. Combined with projected declines in summer precipitation, these changes may lead to reduced summer streamflow.**[a] The Northwest is highly dependent on hydroelectric power to supply its electricity. Together, these changes may contribute to higher streamflows in the winter and spring and decreased streamflows and hydropower generation in the summer.[b]
- **Average temperatures are projected to increase by 3°F–10°F over the course of the century, and annual cooling degree days (CDDs) for some areas could increase by 400 by mid-century. The region is also projected to experience longer and more severe heat waves and higher overnight low temperatures**.[c] Greater seasonal demand for electricity for cooling could occur simultaneously with reduced availability of hydropower in the summer.[d]
- **Wildfire activity is projected to increase, with median burn area projected to quadruple by the 2080s.**[e] Wildfires in the region's forests threaten to disrupt or damage critical transmission infrastructure. Fires can burn poles, and smoke and fire retardants can foul lines, increasing the chance of arcing to ground.[f]
- **Sea levels are projected to rise more slowly in the Northwest than in other regions because of tectonic uplift, which has elevated much of the Northwestern coast.**[g] The uplift is not consistent, however, and infrastructure in the Puget Sound may be more vulnerable than in other areas.

QUICK FACTS

Northwest States:	Washington, Oregon, Idaho
Population (2013)	13,000,000 (4% of U.S.)
Area (square miles)	245,000 (7% of U.S.)
Energy Expenditures	$49 billion

ENERGY SUPPLY & DEMAND		**Annual Production**	**Annual Consumption**	***% for electric power***
Electric power	*TWh*	193	163	*n/a*
Petroleum	*million barrels*	0	232	*<1%*
Coal	*million tons*	0	5	*89%*
Natural gas	*Bcf*	1	569	*24%*

ELECTRIC POWER	**Annual Production (TWh)**	***% of Total Production***	**Capacity (GW)**	**Power plants >1 MW***
Natural gas	19	*10%*	9	39
Coal	6	*3%*	2	4
Nuclear	9	*5%*	1	1
Hydroelectric	140	*72%*	32	209
Wind	15	*8%*	7	87
Biomass	3	*2%*	1	48
Solar	<1	*<1%*	<1	6

CRITICAL INFRASTRUCTURE

Petroleum		**Electric Power**	
Wells (>1 boe/d):	0	Power plants (> 1 MW):	394
Refineries:	5	Interstate transmission lines:	10
Liquids pipelines:	5	**Coal**	
Ports (>200 tons/yr):	6	Mines:	0
Natural Gas		**Waterways**	
Wells:	27	Coal and petroleum routes:	10
Interstate pipelines:	3	**Railroads**	
Market hubs:	3	Miles of freight track:	7,200

Note: Table presents 2012 data except number of oil wells, which is 2009 data.
*Some plants use multiple fuels, and individual generating units may be <1 MW.
Sources: AAR 2014, EIA 2011, EIA 2013b, EIA 2013d, EIA 2013f, EIA 2014a, EIA 2014e, EIA 2014f, EIA 2014g, EIA 2014h, EIA 2014i, EIA 2014j, USACE 2014, U.S. Census Bureau 2014

Table 2-1. Examples of important energy sector vulnerabilities and climate resilience solutions in the Northwest

Subsector	Vulnerability	Magnitude	Illustrative Resilience Solutions
Hydroelectric Power	Reduced availability of summer power generation due to declining summer streamflow[h]	Summer hydropower generation may decrease by 18%–21% by the 2080s[i]	Water conservation, integrated water management, water availability forecasting, energy storage[j]
Electricity Demand	Increased summer demand due to warmer air temperatures[k]	Peak load may increase by almost 3,200 MW (about 8%) by 2030 due to temperature alone[l]	Capacity expansion, energy efficiency, demand management, energy storage[m]
Electric Grid	Increased risk of damage from more frequent and severe wildfires[n]	Recent wildfires have burned through transmission and distribution lines[o] and threatened the critical Pacific Intertie[p]	Vegetation management, improved design standards for transmission equipment, redundant systems[q]
Coastal Infrastructure	Threats from rising sea levels to power plants, terminals, and other low-lying assets[r]	Four power plants are at or below four feet above sea level[s]	Hardening and elevating structures, incorporating sea-level rise projections into infrastructure project planning

Regional Energy Sector Vulnerabilities and Resilience Solutions

Key energy subsectors and illustrative examples of resilience solutions in the Northwest are discussed below. System components that are most vulnerable to climate change are described first.

Hydroelectric Power

Subsector Vulnerabilities

Hydroelectric power dominates the Northwest's electricity generation mix, providing 72% of the region's power (Table 2-2). Washington is the leading producer of hydroelectric power in the United States, followed by Oregon. The region supplies both Canada and U.S. markets[1] with significant electricity (EIA 2014l). Oregon and Washington both produce more electricity than they consume, while Idaho is a net power importer and dependent on interstate transmission lines (EIA 2014a).

Table 2-2. 2012 net electricity generation (percentage of total electricity generated)

Generation Type	OR	WA	ID	Total Region
Natural Gas	19%	5%	12%	10%
Coal	4%	3%	-	3%
Nuclear	-	8%	-	5%
Hydroelectric	**65%**	**77%**	**71%**	**72%**
Other Renewables	12%	7%	16%	9%

Source: EIA 2013f

Federal agencies—including the U.S. Bureau of Reclamation, the U.S. Army Corps of Engineers, and the Bonneville Power Administration (BPA)—and private owners operate 203 hydroelectric facilities in the region, which produced almost 140 TWh in 2012. Hydroelectric power is generated from multiple dams in the Columbia River Basin, which provides more than 40% of the nation's total hydropower (Figure 2-1) (EIA 2014k). The Grand Coulee Dam in Washington is the largest electric power plant in the United States and sixth largest in the world, with a capacity of over 6,800 MW (EIA 2014k). The nation's largest privately owned hydroelectric facility is located in Idaho, at the Hells Canyon complex on the Snake River (EIA 2013a, EIA 2014a).

Climate change is expected to affect hydropower in the Northwest in a number of ways, including:

- Decrease in summer hydropower production from a combination of earlier spring snowmelt, reduced snowpack, and declining summer precipitation (BPA 2011a, CIG 2009, DOE 2012a, Doppelt 2009, USGCRP 2014).

Figure 2-1. Federal and non-federal dams in the Columbia River Basin

Source: EIA 2014k

- Increase in winter/early spring hydropower production and spills at dams (BPA 2011a, USGCRP 2014).
- Decrease in water available for hydropower production as competition for water increases (USGCRP 2014).

Climate change is affecting the supply of water for hydropower. Projected changes in the timing of snowmelt and streamflow in the summer would reduce hydropower generating capacity due to reduced available water (see Figure 2-2 for one scenario's projection of changes in streamflow). One recent study simulated streamflows in the Columbia River watershed for historical and future climates under two scenarios,[2] and found that annual hydropower production could decrease by 3.0%–3.5% by the 2080s compared to 20th century levels. This is the net effect of a projected increase of 7%–10% in the winter and a projected decrease of 18%–21% in the summer (CIG 2009).

At the same time, increasing temperatures are causing larger percentages of precipitation to fall as rain instead of snow, reducing snow water equivalent in mountain snowpacks (CIG 2009, Doppelt 2009, USGCRP 2014). For the winter through early spring (January through April), increased winter rainfall would provide more power generation due to increased streamflows, but also increase occurrences of dam spilling due to exceeding available generation, most notably in April and May (BPA 2011a, BPA 2011c). Streamflows in some watersheds are expected to increasingly be driven by rainfall rather than snowmelt (CIG 2009), and with summer precipitation expected to decline

[1] Three Northwest states are discussed here; however, it is recognized that the vulnerabilities could substantially affect the electricity supply in Canada and California.

[2] B1 (low emissions) scenario and A1B (medium emissions) scenario

by as much as 30% by the end of the century (USGCRP 2014), the availability of hydropower at periods of higher demand could be further diminished.

Reduced availability of hydropower generation in the summer coincides with anticipated greater demand for cooling energy due, in part, to temperature increases during the same period (see Electricity Demand section).

Abundant and low-cost hydropower has helped maintain what have been historically low regional wholesale power prices. If hydropower becomes less dominant, prices in the region may be increasingly determined by the cost of natural gas generation (EIA 2014c).

Changes to the supply of water in the Northwest due to climate change not only affect hydropower but other competing consumers of water reservoir supplies, including irrigation, municipal, and industrial uses; flood control; water quality; navigation; recreation; and aquatic species habitat preservation. In the summer (especially during drier years), not all competing water needs can be met all of the time. By the 2080s, it is projected that hydropower production could be reduced by as much as 20% in order to preserve Columbia River Basin in-stream flow for fish (USGCRP 2014).

Hydroelectric Power

Resilience Solutions

A comprehensive resilience approach to climate change will need to include strategies for optimized hydropower production as part of an integrated water management plan. The approach should also consider options for electricity supply diversification and demand management to reduce reliance on hydropower.

Actions to enhance resilience will need to take into account formal agreements, such as those regarding hydropower in the Northwest, including the Columbia River Treaty and the agreement between Canada and the United States that addresses Columbia River Basin flooding and water resources regulation. While the agreement is due to expire in 2024 and would have to be renegotiated, the U.S. Bureau of Reclamation, the U.S. Army Corps of Engineers, and BPA are integrating climate change data in their review of the treaty (BPA 2011a). A significant amount of the Columbia River Basin storage capacity is located in Canada (USACE and BPA 2013a). As a part of the treaty, Canada is entitled to 50% of power generated downstream in the Columbia River; this power is delivered to British Columbia and either used in Canada or re-sold to the western United States (USACE and BPA 2014). Renegotiation of the Columbia River Treaty that affects the dispensation of water rights in the region could also affect future levels of available hydropower production (Dalton et al. 2013).

For the Columbia River Basin, recommendations from the United States for modernizing the Columbia River Treaty post-2024 will consider competing interests for water in Canada and the Northwestern United States and the possibility of reduced hydropower generation capability and other effects due to climate change and other factors.

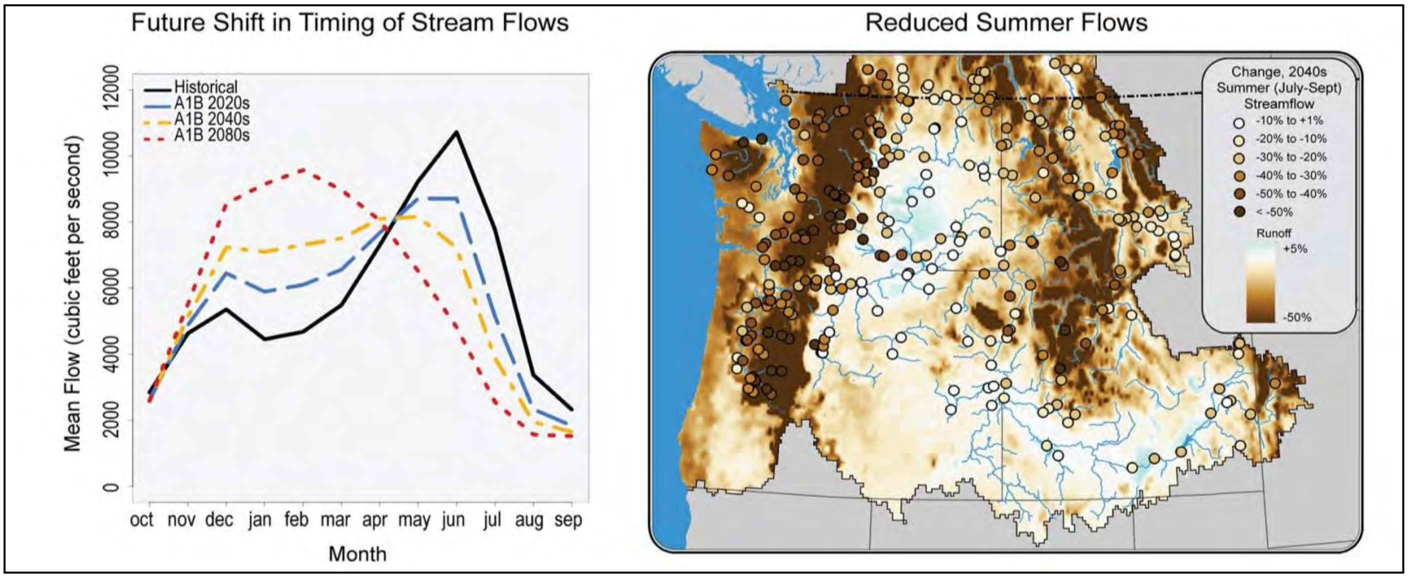

Figure 2-2. (Left) Projected increased winter flows and decreased summer flows by the 2020s, 2040s, and 2080s in the Yakima River Basin under the A1B emissions scenario (compared to 1916–2006). (Right) Projected changes in local runoff (shading) and streamflow (colored circles) for the 2040s summer (compared to 1915–2006) under the A1B Scenario.

Source: USGCRP 2014

Additional hydropower capacity, either through new facilities or through increased turbine efficiency and/or capacity at existing dams, could help address some issues related to reduced water availability. However, recent assessments of capacity expansion at existing federally owned dams found minimal opportunity for economic expansion in the Northwest (DOI et al. 2007, USBR 2011).

Engineering solutions to control water supply for hydroelectric power production must be balanced with potentially competing requirements for flood control and wildlife conservation (USGCRP 2014). Water conservation measures in other sectors may help to reduce conflicting demands on water resources, and improved planning can help to better manage competing demands (DOE 2013, Doppelt 2009). Increased deployment of technologies such as pumped storage can improve short-term response to changes in power demand; however, alternative sources of power generation may be more economically efficient (DOE 2013, MWH 2009, NPCC 2010).

Examples of recent hydropower shortages

2015: Above average temperatures and below average precipitation in the winter led the Northwest River Forecast Center to project lower-than-average runoff in the Columbia River Basin for the summer of 2015. Runoff projections are below historical averages for almost every measurement site, including major dams such as The Dalles (projected to see only 67% of average runoff), John Day (69%), and Grand Coulee (74%) (Hernandez 2015, NWRFC 2015).

2010: BPA experienced basin-wide precipitation and streamflows well below normal during the first half of 2010. By year's end, runoff at The Dalles Dam was 16% below normal (BPA 2011b).

2001: The second-lowest flow of river runoff ever recorded led BPA to declare a power emergency and stop spills along the Columbia and Snake rivers. Power shortages led to industrial plant shutdowns and rate increases (Harrison 2008).

2000: A summer water shortage in the Northwest helped spur a power crisis and soaring market prices on the West Coast. In response, BPA deployed a power trading strategy to keep reservoirs full by restricting hydropower production during the day while importing power from the Southwest and sending power to California utilities at night (Harrison 2008).

The provision of accurate information about future resource availability and demand is critical for avoiding shortfalls. Forecasting snowmelt timing based on snowpack and temperature trends gives system operators critical information in predicting seasonal availability of hydropower generation, which can be used to prepare and execute contingency plans if shortfalls are projected. Forecasts of snowmelt timing are provided by the Northwest River Forecast Center, operated by the U.S. National Oceanographic and Atmospheric Administration (EIA 2014c). Utilities, such as Seattle City Light, have projects underway to assess climate change impacts on hydropower generation and characterize present and future glacier contribution to summer streamflow, update streamflow projections with multiple climate scenarios and glacier runoff, and develop regional climate model projections of changes in windstorm and convective storm frequency and timing (Seattle City Light 2012, Raymond 2014a, Raymond 2014b).

Greater supply diversification may also be an effective strategy to increase system resilience to climate change. Since the western power crisis in 2000, the region has relied on natural gas and wind power to supply additional capacity needs. Those two sources accounted for 96% of new capacity added between 2000 and 2012 (EIA 2013d). If shortages in hydropower lead to increased dispatch from these new sources, electricity prices in the region (currently at a historic low) may also increase. In addition, the recent significant expansion of wind generation capacity will require grid system operators to explore options to appropriately balance supply from variable wind energy production with other energy sources, such as hydropower, to optimize supply and demand and enhance resilience. Frequent cycling of hydropower to compensate for wind's intermittent supply is a sub-optimal generation practice and causes significant wear on hydroelectric turbine gates (BPA 2011c).

Storage systems could allow intermittent renewable generation sources such as wind power to store energy and then deliver it when needed. This ability could prove especially useful in the Northwest, as wind power generators have faced curtailments in the past due to the availability of lower-cost hydropower (McKenna 2011). A recent study of pumped hydropower storage in the Northwest found that wide-scale deployment could allow economic integration of intermittent generation. Over 13,000 MW of pumped storage projects have received preliminary permits in the region (MWH 2009).

Electricity Demand

Subsector Vulnerabilities

The changing demand profile for electric power is critically important to the region's energy sector. Historically, the Northwest's electricity prices have been the lowest in the nation, and a substantial amount of built infrastructure, such as building heating, has come to rely upon low-cost electricity (CIG 2009, EIA 2014a). Climate change is only one of several factors (including population growth and changing technologies, such as electric vehicles) that may drive changes in electricity demand (DOE 2012a). While these factors are likely to increase the region's demand for electricity, existing constraints on water usage and ecological considerations mean that relatively little potential hydropower capacity remains untapped to offset demand increases (CIG 2009, DOE 2012b).

Climate change is projected to have the following impact on electricity demand in the Northwest:

- Higher maximum temperatures, longer and more severe heat waves, and higher overnight lows are expected to increase electricity demand for cooling in the summer (BPA 2011a, DOE 2012a, DOE 2013, USGCRP 2014).

Climate change is projected to increase the annual number of CDDs in the region by up to 400 degree days, depending on the emissions scenario (NOAA 2013).

Several studies indicate that the region's peak load and total electricity demand may increase significantly as a result of rising temperatures. The Northwest Power and Conservation Council (NPCC) estimated that, by 2030, increases in peak load due to temperature alone would exceed 2,800 MW in July and approach 3,200 MW in August under a scenario of a 2°F increase in annual average temperature. The study also found declines in December and January of over 1,000 MW (NPCC 2010). Another study—the 2009 Washington Climate Change Impacts Assessment—found that, by 2080, Washington's demand for cooling energy alone may be 11 to 20 times higher than demand in the 1980s, depending on the emissions scenario, population growth, and air conditioning market penetration rates (CIG 2009). The assessment also found that, while heating energy demand would likely fall significantly under a warming climate, population growth could more than offset this effect, leading to increased energy demand for both heating and cooling (CIG 2009).

Excluding population growth, warmer winter temperatures are expected to decrease demand for heating energy due to less frequent extremely cold nights and a decrease in the number of heating degree days (HDDs) (DOE 2012a, DOE 2013, USGCRP 2014).

Increasing summer demand for power can also affect other regions that rely on power exports from the Northwest. California depends on power imports to supplement its generation during periods of peak demand, much of which comes from hydropower in the Northwest (DOE 2012a, EIA 2014d). In addition, California—where summer electricity demand is greater than in the Northwest—could face CDD increases that are more than double those in the Northwest, as well as declines in water availability that could affect California's in-state generation (EIA 2014d, NOAA 2013, USGCRP 2014).

Electricity Demand

Resilience Solutions

Measures to address increasing electricity demand include adding new electric generating capacity and implementing technologies, policies, or measures to reduce overall demand or reduce consumption at peak hours. New generating capacity can be designed to operate year-round (baseload) or only during periods of greatest demand (peaking). Likewise, overall demand can be reduced by improving the energy efficiency of buildings, appliances, and other significant loads, and peak demand can be reduced by incentivizing large industrial and commercial consumers or groups of residential consumers to turn off equipment or reduce their cooling energy consumption (e.g., by turning up their thermostats) during peak hours. Because the Northwest exports electricity outside the region, demand management measures being implemented in other states, particularly California, may help mitigate potential supply shortages during summer season peaks (FERC 2013).

Decisions to invest in new capacity are typically made in the context of integrated resource planning, a process that may consider a number of factors affecting future demand, including population change, technology change, policy risk, and climate change, as well as existing and future resources. The NPCC considered a number of scenarios in its Sixth Power Plan (in 2010) and proposed a near-term strategy to 2030. The plan involves an additional 4.5 GW of new wind capacity (assumed to produce an average of 1.45 GW), 1.0 GW of combined-cycle natural gas capacity, and expanded energy efficiency measures. The primary factor driving wind development in the strategy is the mandate for new renewables in state renewable portfolio standard (RPS) policies. In scenarios considered by the NPCC that did not consider RPS policies, new wind development is considerably lower (NPCC 2010). NPCC's analysis finds that in scenarios that involve greater retirements of existing capacity, natural gas capacity would be deployed to fill the gap.

Although hydropower provides the large majority of generating capacity in the region, capacity expansion at federally owned dams in the Columbia River basin is not a strategy currently under consideration (BPA 2012). Moreover, the most recent assessment of all federally owned dams in the region found only two dams with potential for economic expansion of capacity. Together, these projects could add 17 MW of capacity (DOI et al. 2007).

Renewable energy development is a means of expanding clean energy capacity and diversifying generating resources to enhance resilience, which are goals supported by the federal government. For example, DOE issued a $1.3 billion partial loan guarantee to finance one of the largest wind farms in the world. The Caithness Shepherds Flat wind project is an 845 MW wind-powered electrical generating facility located in eastern Oregon. To leverage the region's low-temperature geothermal resources, DOE issued a $97 million partial loan guarantee to USG Oregon LLC for the construction of the Neal Hot Springs geothermal power plant (Figure 2-3). This technology more efficiently extracts heat from lower-temperature geothermal wells, allowing energy generation from previously untapped locations (DOE 2011, DOE 2014).

Figure 2-3. Neal Hot Springs 20 MW geothermal power plant in Malheur County, Oregon
Source: DOE 2015

Energy efficiency, load management, and other programs administered by regional power producers have already helped reduce total and peak electricity demand in the Northwest. For example, to delay the construction of new peaking facilities, Idaho Power has implemented a number of energy efficiency and load management programs. The program strategy includes incentives for residential customers who implement home upgrades and install energy efficient appliances and remote-controlled thermostats, and incentives for commercial customers participating in the FlexPeak load-shaving program that allows businesses to customize which load reductions they will make at what times. Together, Idaho Power's demand reduction programs cut summer peak load by 101 MW, with a total demand reduction capacity of 438 MW in 2012 (EIA 2013e, Idaho Power 2013).

In the Northwest, a total of 37,000 residential customers, 3,100 industrial customers, and 170 commercial customers are participating in price-responsive, incentive-based demand-side management programs, while more than 46,000 residential customers, 600 industrial customers, and 680 commercial customers are in time-based rate demand-side management programs (EIA 2013e). By 2012, a total of almost 800 MW in peak load reductions had been achieved from existing demand management programs across residential, commercial, and industrial customers, with approximately 700 MW achieved through energy efficiency programs and 100 MW achieved through load management (EIA 2013e).

The NPCC identified almost 7,000 MW of technically achievable conservation potential by 2029 (NPCC 2010). Although not all technically achievable efficiency measures were identified as cost-effective, almost 6,000 MW were estimated to be achievable at a levelized cost of less than $200/MWh (with more than half of that estimated to be achievable at a price of $30–$40/MWh), including 2,600 MW from residential buildings and appliances, 1,400 MW from commercial buildings (especially from lighting), 800 MW from consumer electronics, and 800 MW from industry. Additionally, while the plan assumed 1,500 MW and 1,700 MW of available demand response by 2030 in the winter and summer respectively, the NPCC found that the region lacks sufficient experience with demand response to provide a detailed estimate of potential resources. Looking forward, the NPCC anticipates that the levelized cost of efficiency developed in its resource strategy is $36/MWh (NPCC 2010).

Grid-scale energy storage systems can also contribute to meeting the region's changing demand profile (see the Hydroelectric Power section for a discussion of the use of pumped hydropower storage). Other potentially feasible grid-scale energy storage technologies include compressed air, flow batteries, and sodium-sulfur batteries (NPCC 2010).

Electric Grid

Subsector Vulnerabilities

The Northwest is part of the Western Interconnection, the wide-area AC power transmission grid that stretches from Western Canada southward to Baja California and eastward to the Great Plains (EIA 2014a). The region is also the northern terminus of the Pacific Intertie, a high-voltage DC (HVDC) power line that connects Columbia River hydropower resources to demand in the Los Angeles-area (EIA 2014a). About three fourths of the region's transmission infrastructure is owned and operated by BPA (BPA 2013a).

Climate change is expected to have the following impacts on energy transmission, storage, and distribution in the Northwest:

- Increased risk of physical damage from wildfires—including associated heat, soot, and fire retardants—causing damage to transmission infrastructure and disruption of power supply (DOE 2013, USGCRP 2014).
- Increased transmission and distribution equipment losses, damage to transformers, and reduced capacity due to higher temperatures (Bérubé 2007, DOE 2013).

Energy transmission, storage, and distribution infrastructure are vulnerable to physical damage from increasing wildfires. Fires can damage wooden transmission line poles, and the associated heat, smoke, and soot can affect transmission line capacity (Figure 2-4) (DOE 2013, SDG&E 2008). For example, following the Soda Fire in 2015, Idaho Power Company had to replace 129 poles and 2.5 miles of power lines (Kahn 2015). Soot can also reduce the electrical resistance of the air, increasing the risk of transmission lines arcing to other lines or to nearby vegetation (DOE 2013). Other lasting effects from wildfires that can impact the energy system can include increased soil erosion and risk of landslides and changes in water quality (through increased amounts of sediment) (Dalton et al. 2013, FS 2014, USGS 2015).

Figure 2-4. Transmission lines following wildfire in Washington
Source: BPA 2014

Since the 1970s, wildfires have increased in number and extent in the Northwest, with the trend expected to continue (USGCRP 2014). Under one scenario, the median area burned each year by wildfires in the Northwest would quadruple (to 2 million acres, with a range of 0.2 million acres to 9.8 million acres for the entire region) by the 2080s, compared to the average for the 20th century (USGCRP 2014).[3]

Higher temperatures can reduce the efficiency and capacity of power lines and other power grid components, such as transformers, and can increase the risk of disruption to transmission lines (DOE 2013). Increased temperatures can also cause conductors to expand, leading to sagging power lines that are more likely to strike trees and automatically close, shutting off the power line (DOE 2013). Tree strikes can cause power outages if sufficient redundancy is not available and can ignite brush fires, which may cause even more damage. Temperature-related risks are exacerbated by the relationship between temperatures and summer peak energy demand; the greatest demand for electricity typically occurs during periods of highest temperature and thus is when temperature effects on grid capacity are greatest. Increased temperatures also shorten the lifetime of transformers. At higher temperatures, transformers age at accelerated rates, typically up to 100 times faster than normal during emergency overloading conditions (Bérubé 2007). On very hot days, grid operators must reduce transformer loading or risk causing additional damage (Hashmi et al. 2013, USBR 2000).

Electric Grid

Resilience Solutions

Strategies to improve the resilience of new and existing transmission infrastructure will rely upon improved technology, designs, and planning, as well as improved vegetation management practices to reduce the build-up of hazardous fuels near key power lines (DOE 2013). Increasing redundancy in the transmission grid can also improve system resilience to climate change impacts (DOE 2013).

Strengthening power lines and towers to resist physical damage—e.g., replacing wood towers with steel towers for the most vulnerable lines—can improve individual lines' resilience to wildfires, limiting damage and expediting restoration (Figure 2-5) (SDG&E 2008). Approximately one third of BPA's transmission line circuit miles are supported by wood poles, many with aging and outdated equipment (BPA 2013a). Other technological measures may include development of new compounds safe for use around active power lines that may improve firefighting crews' ability to protect key lines without causing disruptions.

Figure 2-5. Structural failure of wooden power poles
Source: BPA 2013b

Proactive vegetation management is also an important practice for increasing resilience against transmission and distribution line damage resulting from increased wildfires, as well as for reducing the risk of wildfires caused by transmission line tree strikes. Management practices include tree trimming, forest thinning, and prescribed burning to reduce fuel buildup, as well as reducing potential ignition points (SDG&E 2008, USGCRP 2014). In 2008, an overgrown tree struck one of BPA's 230 kV feeder lines, resulting in $20 million in damages (BPA 2013a). In response, BPA has redeveloped its vegetation management practices, including establishing metrics for the program and reaching agreements with stakeholders, and has since achieved zero "grow-in" outages (outages caused by vegetation growing into the path of a line) (BPA 2013a).

Expansion of regional transmission capacity can address capacity reductions resulting from higher temperatures and

[3] Under the A1B scenario; 20th century baseline includes the period covering 1916–2007

increasing summer demand for cooling energy. To facilitate coordinated grid planning, the region's utilities have formed two regional planning groups: ColumbiaGrid, oriented around BPA and Washington utilities, and Northern Tier Transmission Group, which extends from the Northwest into Montana, Wyoming, and Utah. Recently, ColumbiaGrid implemented a significant number of projects based on BPA's innovative queuing process for analyzing, costing, and financing transmission expansions (NPCC 2010). Load management measures that reduce peak demand on hot days can also improve grid resilience (see Electricity Demand section).

Examples of recent wildfire events

2014: The Carlton Complex Fire, the largest fire in Washington State history, led to several weeks of power outages (Burns 2014, La Ganga and Muskal 2014).

2009: An Oregon wildfire damaged a transmission line and left 25,000 customers without power (Crombie 2009).

2006: Wildfires threatened the Pacific Intertie, which transmits power from the Pacific Northwest to Los Angeles, California (AP 2006).

Operational practices can also help prevent physical damage to overheating power transformers. By monitoring temperatures and managing loading of transformers on hotter days, operators can prevent excessive damage and premature aging. Physical measures to prevent damage to transformers include upgraded insulators capable of handling higher operating temperatures and installation of cooling fans to reduce thermal loading on hot days (Bérubé et al. 2007, USBR 2000).

Thermoelectric Power Generation

Subsector Vulnerabilities

Electricity from thermoelectric power plants represents approximately 18% of the generation mix in the region (Table 2-2). Washington has 21 natural gas-fired power plants, eight biomass-fired power plant, one nuclear power station, and one large coal-fired power plant. The coal-fired plant is scheduled to shut down in 2025, while the nuclear plant is licensed through 2043 (EIA 2014a, NRC 2012). In Oregon, a coal generating station in Boardman is the state's only coal power plant, and it is scheduled to close in 2020 (EIA 2014a). In Idaho, coal is used for two industrial co-generation facilities but not for any commercial power production (EIA 2014a). There are 39 natural gas power plants across the region, many of which are simple-cycle gas turbines (EIA 2014a).

The region also has several geothermal generating stations, including the 20 MW Neal Hot Springs plant, Oregon's only commercial unit (Oregon Dept. of Geology and Mineral Industries 2013). Washington has fewer high-temperature resources, which are located in the volcanic Cascade Range. Idaho has 13 MW of commercial geothermal generation at the Raft River facility in the southeastern portion of the state (EIA 2014a).

Climate change could have the following impacts on thermoelectric power generation in the Northwest:

- Higher average temperatures and extreme temperatures that lower thermoelectric plant efficiency, reducing generating capacity (DOE 2013, Sathaye et al. 2012, USGCRP 2014).
- Increased height of storm surge and tidal action due to sea level rise, resulting in a higher rate of coastal erosion and higher risk of flooding for coastal infrastructure (including the Puget Sound) (USGCRP 2014).

Higher average temperatures are expected to reduce the efficiency of thermoelectric power generation, reducing the total amount of power a plant can produce (DOE 2013). As thermoelectric power plants are increasingly relied upon to provide peaking power during periods of maximum demand on the hottest days, reduced peak capacity may increase the risk of generation shortfalls. One study of natural gas power plants found that most plants are designed to operate optimally at 15°C (59°F) and that a 1°C increase in ambient temperature above the design point could reduce capacity 0.7% for a combined-cycle gas plant and 1% for a simple-cycle plant (Sathaye et al. 2012).

Coastal power plants in the Northwest are also vulnerable to the impacts of rising sea levels. However, along much of the region's coastline, sea levels are expected to rise more slowly than in other regions, as much of the Pacific Northwest coastline is undergoing tectonic uplift, which reduces the rate of relative sea level rise compared to the global average (USGCRP 2014). The rate of local tectonic uplift varies significantly, and some areas (including the Puget Sound) are more vulnerable to sea level rise than others (Verdonck 2006). For example, over the last century, tide gauges in Seattle show sea level rise at a rate of 2.1 mm per year (over the period 1900–2005), while in Astoria, Oregon (on the mouth of the Columbia River), sea levels have been falling at a rate of 0.3 mm per year (1925–2005) (Verdonck 2006).

Although most of the region's thermoelectric power plants are well above sea level, four plants in Washington's Puget Sound are situated on properties in which at least part of the land is at or below four feet above sea level—the upper end of expected increases in global average sea levels by the end of the century (Climate Central 2014, USGCRP 2014). In addition, three more plants, as well as one of the region's oil refineries, are at or below seven feet above sea level (Climate Central 2014). Coastal flooding is typically the product of storm surge and wave action on top of average sea levels, and increasing sea levels in the Puget Sound can make flooding during storms more likely (USGCRP 2014). The record highest tide in Seattle occurred on December 17, 2012, when a storm combined with an especially high tide to produce tide levels of 14.5 feet (Broom 2012).

Thermoelectric Power Generation

Resilience Solutions

Reduced available generation capacity due to higher average or extreme air temperatures can be addressed primarily by building new dispatchable capacity or by ensuring adequate transmission infrastructure exists to import additional power during peak hours. Capacity reductions can also be ameliorated by demand-side efficiency and load-shedding programs (discussed in the Electricity Demand section), and storage systems are another option to accommodate the Northwest's changing demand profile (discussed in the Hydroelectric Power and Electricity Demand sections).

Engineered barriers such as levees can effectively protect vulnerable thermoelectric power plants from flooding. Utilities may also elevate critical equipment to protect against flooding. Planners can protect new capacity by locating new generators at higher elevations that are not at risk of flooding due to sea level rise.

Fuel Transport

Subsector Vulnerabilities

Washington serves as the principal refining center for regional markets and is ranked fifth in the nation for crude oil-refining capacity. The largest refinery is the Cherry Point Refinery operated by British Petroleum, followed by Shell's Anacortes Refinery, Tesoro's Anacortes Refinery, Phillips' Ferndale Refinery, and U.S. Oil's Tacoma Refinery. Refineries receive crude oil primarily from Alaska but are increasingly receiving imports from Canada (EIA 2014a, EIA 2014b). The regional network of petroleum refining and distribution systems is illustrated in Figure 2-6.

Oregon and Idaho do not have any refineries; most petroleum is imported into these states by pipeline and barge. The three main pipelines in the region are the Olympic, Yellowstone, and Chevron Pipelines. The Olympic pipeline is operated by Enbridge and provides Oregon with refined petroleum from refineries in northwest Washington. The Yellowstone pipeline, operated by Phillips 66, runs from Montana into Washington through northern Idaho. The Chevron pipeline transfers petroleum products from Utah to southern Idaho, northeast Oregon, and southeast Washington (EIA 2014a, EIA 2014b, WDOC 2013).

Idaho, Oregon, and Washington rely primarily on natural gas supplied from Canada and receive natural gas by three pipelines (the Mist gas field in Oregon is the only producing natural gas field in the region, but production has declined during the past 30 years) (EIA 2014a). The Northwest pipeline runs from Canada southward into western Washington and Oregon and turns eastward from Oregon into southern Idaho. The Gas Transmission–Northwest pipeline runs southward from Canada through northern Idaho and into eastern Washington and Oregon. The Ruby pipeline runs along the southern border of Oregon (EIA 2014a). Two proposed LNG export terminals in Oregon are seeking federal permits (EIA 2014a).

In recent years, a number of shipping terminals for coal export have been proposed in the region. Current proposals include two ports in Washington (Cherry Point and Longview) and one in Oregon (Boardman) (ODOEQ 2014, WDOE 2013). All of the proposed terminals would export coal transported from the Powder River Basin in Wyoming via new or existing rail lines and barge routes. There are no active coal mines in the Northwest (EIA 2014a), nor are there any estimated coal resources (USGS 2014b). Coal is shipped into the region from Montana, Utah, and Wyoming (EIA 2014a).

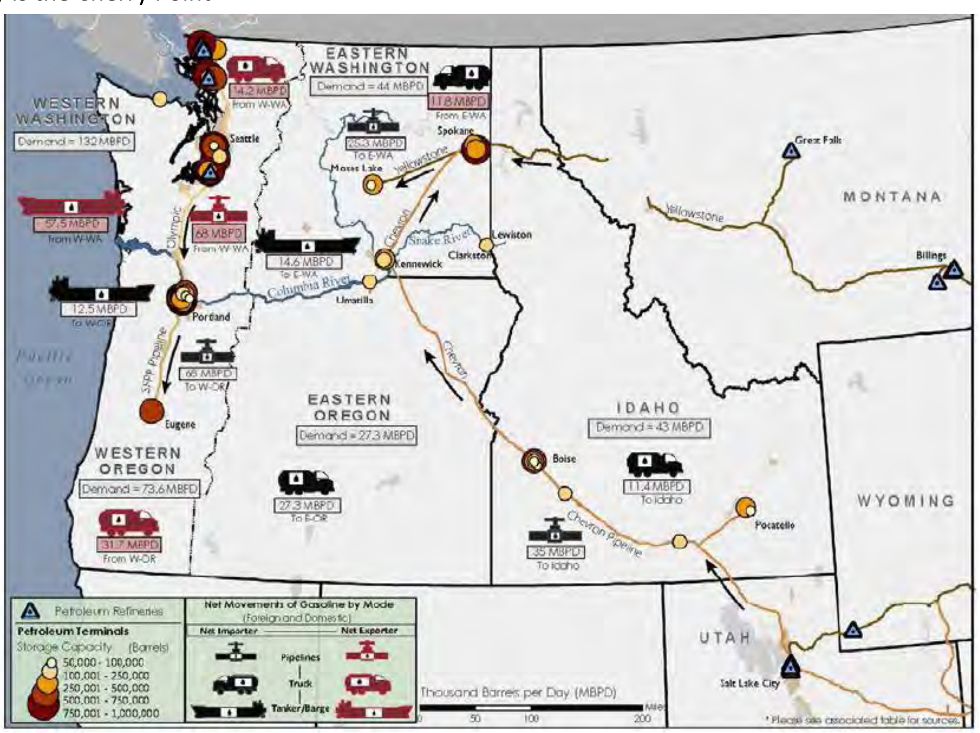

Figure 2-6. Movement of gasoline in the Northwest, 2010

Source: WDOC 2013

Climate change may have the following impacts on petroleum refining and fuel transportation in the Northwest:

- Increased height of storm surge and tidal action due to sea level rise, resulting in more damage, a higher rate of coastal erosion, and higher risk of flooding for coastal infrastructure, including refineries, terminals, pipelines, and railroads (CIG 2013, USGCRP 2014).
- Increasing precipitation increases the risk of inland flooding for riparian infrastructure in rain-fed and mixed-source basins, including railroads and pipelines at river crossings or that follow river courses (CCSP 2008, CIG 2013, USGCRP 2014).

Coastal infrastructure, including petroleum ports and refineries, coal terminals, and pipelines may be threatened by the effects of rising sea levels, including heightened wave action and storm surge during storms. Along much of the region's coastline, sea levels are expected to rise more slowly than in other regions, as the underlying land is rising (USGCRP 2014). However, as noted above in the Thermoelectric Power Generation section, local rates of relative sea level rise vary significantly, and the Puget Sound is expected to experience greater sea level rise than other coastal areas in the region (Verdonck 2006). For example, low-lying rail yards in the Port of Seattle are vulnerable to permanent inundation if sea levels rise more than three feet (CIG 2013).

Most of the region's refinery facilities are well above sea level, with the single exception of U.S. Oil's Tacoma Refinery, which is located in the Port of Tacoma (Figure 2-7). Coastal equipment, petroleum ports, and pipelines located at sea level may be exposed to heightened sea levels and coastal flooding as well as greater rates of erosion (DOE 2013, USGCRP 2014).

Figure 2-7. Aerial image of U.S. Oil's Tacoma Refinery
Source: WDOE 2015

Inland flooding of river valleys and flood plains can affect pipelines, railroads, and other infrastructure at river crossings, or that follows river courses (DOE 2013). Flooding can wash-out rail track beds and cause disruptions, and increased streamflow can erode riverbanks, undercutting railroads and scouring bridge piers (CCSP 2008, DOE 2013). Buried pipelines are less vulnerable to flooding impacts, but may be subject to damage from flood-borne debris if high streamflow erodes the soil and exposes pipelines buried in riverbanks or under a riverbed (CCSP 2008, GAO 2014). Projected increases in precipitation are more likely to increase the risk of flooding in river basins that are primarily rain-fed and mixed rather than those that are primarily snow-fed (USGCRP 2014). However, as winter precipitation shifts from snow to rain, more watersheds in the region are expected to become primarily rain-fed (CIG 2013).

Fuel Transport

Resilience Solutions

As the threats of coastal flooding, heightened storm surge, and increasing erosion mount, coastal hardening measures, including the construction of sea walls or natural barriers such as wetlands to reduce the impacts of storm surge, may be necessary for existing infrastructure, (CCSP 2008, DOE 2013). Planning future infrastructure—including LNG or coal export terminals—for higher sea levels is also critical to build resilience (DOE 2013). For example, the Army Corps of Engineers directs analysts to consider what effect changing relative sea level rates could have on designs, and agency reports are required to contain scenarios that include accelerating future sea level rise (USACE 2011).

Railroads can be protected from wash-out from flooding with engineering solutions and track upgrades such as elevating rails and bridges; however these can be costly (CCSP 2008, DOT 2009). Additional resilience solutions include upgrading drainage systems and ensuring culverts can handle increased runoff from heavy precipitation events (DOT 2009). Policy measures that restrict new rail line development in floodplains or revised standards for drainage capacity or elevating tracks can also improve resilience. The risk of erosion can be reduced through the use of manmade or natural barriers along vulnerable riverbanks. At crossings, bridge piers can be protected with riprap, and vulnerable buried pipelines can be protected by using horizontal drilling techniques to bury the pipe significantly deeper than traditional trenching methods (Brown 2013, DOT 2009, Miller and Bryski 2012). Pipelines at risk from erosion can also be replaced with materials that are less likely to leak or rupture from impacts (e.g., coated steel rather than cast iron or bare steel).

Wind Energy

Subsector Vulnerabilities

Oregon has more than 3,000 MW in operational wind farms, and Washington has an installed capacity of more than 2,500 MW. Idaho has substantial wind energy potential, and wind-generated electricity in the state was almost six times greater in 2013 than in 2010 (EIA 2014a).

There is not yet substantial agreement among sources as to how a changing climate will ultimately affect wind resources in the United States in general, and in the Northwest in particular (DOE 2013). One study of the Northwest region found significant seasonal declines in wind speed in parts of the Northwest, but this result has not been confirmed by additional studies (DOE 2013). It is uncertain how wind power production may be disrupted by climate change-driven changes to wind patterns, or if wind power will see an increase in available capacity.

Despite the uncertainty of potential climate impacts on wind speeds, additional wind capacity has created the need for new transmission lines, often in remote locations (Durbin 2010). Compared to other sources of power, wind generators may be especially vulnerable to wildfires threatening power transmission infrastructure.

Wind Energy

Resilience Solutions

When siting wind farms in the Northwest, the threat of wildfire on power lines connecting the wind farms to the grid should be considered in the risk management of the projects and in long-term asset planning.

Ensuring adequate transmission capacity to optimize the use of available energy sources, including renewable energy, is also important for resilience. For example, states such as Montana may have relatively large wind energy resources that exceed energy demand in the state, and could serve a role as a major exporter of wind energy, helping other western states to meet their energy demand (NREL 2014). However, transmission infrastructure is needed to tap this resource and transfer the electricity out of Montana, while states like California and Nevada have the demand, but may not have the wind capacity.

As noted in the Hydroelectric Power and Electricity Demand sections, energy storage systems could allow wind power, an intermittent renewable generation source, to store energy and then deliver it when needed.

Regional Climate Change Observations and Projections in Detail

Higher Temperatures

Historical observations

- **Average temperatures have increased 1.3°F from 1895 to 2011** (USGCRP 2014).

Future projections

- **Average temperatures are projected to increase at a faster rate:** Increases of 3.3°F–9.7°F[4] are projected by 2070–2099, compared to 1970–1999 levels (USGCRP 2014).
- **Extremely hot days are projected to become slightly more common:** Under a higher emissions scenario (A2), across most of the region, 0–6 more days with a daily maximum >95°F are projected by mid-century (2041–2070) compared to 1980–2000; southern Idaho may see up to 15 more hot days per year (NOAA 2013).
- **Extremely cold nights are projected to become much less common:** Under a higher emissions scenario (A2), across most of the region, 10–30 fewer days with daily minimums <10°F are projected by mid-century (2041–2070), with inland regions seeing the largest decrease; the coasts may see 0–5 fewer cold nights per year (NOAA 2013).
- **CDDs are expected to increase, but less so than in other regions:** Under a higher emissions scenario (A2), an increase of 0–400 CDDs is projected across the region by mid-century (2041–2070) compared to 1980–2000, although this increase is large when compared to relatively low historical averages (NOAA 2013).
- **Heating degree days (HDDs) are projected to fall more severely**: Under a higher emissions scenario (A2), declines of 700–1,100 HDDs along the coasts, and up to 1,600 HDDs in the mountains, are projected by mid-century (2041–2070) compared to 1980–2000 (NOAA 2013).

Drier Summer Seasons and Changing Water Patterns

Historical observations

- **Average annual precipitation has increased, but the trend is small from 1895 to 2011** (USGCRP 2014).
- **Spring snowpack has decreased:** Area-averaged snowpack in the Cascades, as measured on April 1, has fallen 20% since 1950 (USGCRP 2014).
- **Spring snowmelt has been occurring earlier:** Since 1950, spring snowmelt has occurred 0–30 days earlier depending on location, late winter/early spring streamflows have been a 0%–20%+ greater share of annual flow, and summer flows have decreased 0%–15% (USGCRP 2014).

Future projections

- **Future changes to total annual precipitation are uncertain:** Changes of -11% to +12% are projected by 2030–2059 and -10% to +18% by 2070–2099, compared to 1970–1999 (USGCRP 2014).
- **Seasonal changes are expected to be much larger:** Decreases in summer precipitation as great as 30% below 1970–1999 levels are projected by the end of the century under a higher (A2) emissions scenario, while average projected decreases are 10% (USGCRP 2014).
- **Snowmelt is projected to occur much earlier, decreasing summer flow:** By 2050, snowmelt may occur three to four weeks earlier than the 20th century average, even under a lower-emissions scenario (USGCRP 2014).

Extreme Precipitation, Wildfires, and Sea Level Rise

Historical observations

- **Dry spells are projected to increase:** The maximum number of consecutive dry days with <3 mm of precipitation are projected increase up to 9% by mid-century (2041–2070) compared to 1980–2000, with increases of 9%–15% along the coast (NOAA 2013).

Future projections

- **Increasing fire activity is projected to continue in the future:** By the 2080s, the median annual area burned in the region is projected to be four times greater than the 20th century median (1916–2007), increasing to 2 million acres under the A1B scenario (USGCRP 2014).

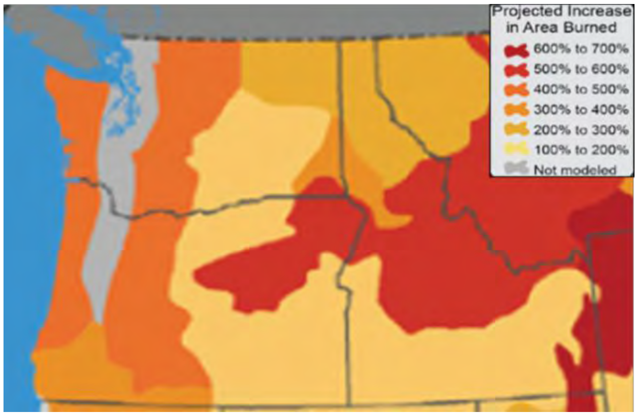

Figure 2-8. Increases in area burned that would result from regional temperature and precipitation changes associated with 1°C warming, relative to 1950–2003
Source: USGCRP 2014

- **Increases in extreme precipitation are projected in some areas:** The number of days with precipitation >1 inch is projected to increase by an average of 13% by mid-century (2041–2070) across the region compared to 1971–2000 (USGCRP 2014).[5]
- **Relative sea level rise is not as severe in the region as elsewhere in the United States:** Tectonic uplift across most of the Northwestern coastline is countering the

[4] Range largely dependent on total global heat-trapping gas emissions

[5] For the high emissions (A2) scenario

effects of sea level rise, meaning local sea levels are rising more slowly than elsewhere in the country, although uplift is varied. However, a major earthquake (as is expected in the region in the next several hundred years) may lead to rapid sea level rise of 40 inches or more (USGCRP 2014, Verdonck 2006).

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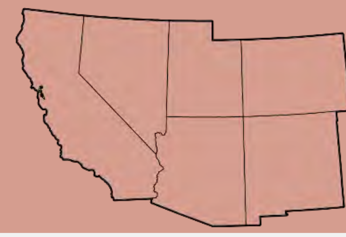
Chapter 2 Endnotes

[a] Source: USGCRP 2014
[b] Source: USGCRP 2014
[c] CDD projections under A2 scenario; mid-century refers to average for period (2041–2070). Sources: BPA 2011a, DOE 2012a, DOE 2013, NOAA 2013, USGCRP 2014
[d] Sources: BPA 2011a, DOE 2012a, DOE 2013, USGCRP 2014
[e] Projection relative to 20th Century (1916–2007) median under A1B scenario. Source: USGCRP 2014.
[f] Source: DOE 2013
[g] Sources: USGCRP 2014, Verdonck 2006
[h] Source: USGCRP 2014
[i] Compared to 20th century hydropower generation levels. On an annual basis, hydropower production could decrease by 3.0%–3.5% (CIG 2009).
[j] Sources: DOE 2013, Doppelt 2009, EIA 2014c
[k] Sources: NOAA 2013, NPCC 2010, USGCRP 2014
[l] Based on 2°F increase in annual average temperature (NPCC 2010).
[m] Sources: Doppelt 2009, DOE 2013
[n] Source: DOE 2013
[o] Source: Crombie 2009
[p] Source: AP 2006
[q] Source: DOE 2013
[r] Source: USGCRP 2014
[s] Climate Central analyzed FEMA-reported facility GPS coordinates and compared the reported position of each facility to average sea levels. For large facilities, the GPS point may not represent the entire facility (Climate Central 2014).

Chapter 3: **Southwest**

Climate Change and the Energy Sector



Overview

The large and geographically diverse Southwest region includes mild coastal climates, an arid interior, and mountain ranges that store critical water supplies as snow. The region is home to a large and growing population. Key energy infrastructure includes oil and gas refineries and large amounts of power plant capacity. Major climate change impacts projected to increasingly threaten the region's energy infrastructure include the following:

- **Average temperatures and cooling degree days (CDDs) are projected to increase across the region, with hotter, more frequent, and longer-lasting heat waves.**[a] Increases in CDDs, extreme temperatures, and heat waves result in expanded air conditioner use. These projections are also expected to increase both average and peak demand for cooling while reducing the efficiency and available capacity of power plants and transmission lines.[b]
- **Average and summer seasonal precipitation is projected to decrease, droughts are projected to intensify, and streamflow in major river basins is projected to decline.**[c] Power plants that rely on surface water for cooling may face shortages and ecological or safety-related curtailments that reduce available generation capacity. Oil producers may also face water shortages.[d]
- **Spring thaws are projected to occur earlier, and a greater fraction of precipitation is projected to fall as rain rather than as snow, reducing mountain snowpack.**[e] Alongside reduced overall precipitation, less snowpack could reduce total potential hydropower production at high-elevation dams. Changing streamflow timing, decreased precipitation, and increased evaporation may impair hydropower production during peak summer electricity demand.[f]
- **The risk of wildfire and the annual average area burned is expected to increase across the region.**[g] Wildfires threaten physical damage to power lines, including fouling of lines and increased risk of arcing.[h]

QUICK FACTS

Southwest States:	Arizona, California, Colorado, Nevada, New Mexico, Utah
Population (2013)	58,000,000 (18% of U.S.)
Area (square miles)	686,000 (19% of U.S.)
Energy expenditures	$208 billion

ENERGY SUPPLY & DEMAND		**Annual Production**	**Annual Consumption**	***% for electric power***
Electric power	*TWh*	474	476	*n/a*
Petroleum	*MMbbls*	362	948	*<1%*
Coal	*million tons*	76	75	*96%*
Natural gas	*Bcf*	3,662	3,920	*38%*

ELECTRIC POWER	**Annual Production (TWh)**	***% of Total Production***	**Capacity (GW)**	**Power plants >1 MW***
Natural gas	202	*44%*	84	398
Coal	136	*30%*	24	42
Nuclear	50	*11%*	9	3
Hydroelectric	38	*8%*	19	347
Wind	19	*4%*	9	147
Geothermal	15	*3%*	3	57
Biomass	7	*1%*	2	119
Solar	3	*<1%*	2	214

CRITICAL INFRASTRUCTURE			
Petroleum		**Electric Power**	
Wells (>1 boe/d):	64,400	Power plants (> 1 MW):	1,346
Refineries:	29	Interstate transmission lines:	32
Liquids pipelines:	21	**Coal**	
Ports (>200 tons/yr):	6	Mines:	26
Natural Gas		**Waterways**	
Wells:	68,500	Coal and petroleum routes:	5
Interstate pipelines:	30	**Railroads**	
Market hubs:	5	Miles of freight track:	14,000

Note: Table presents 2012 data except number of oil wells, which is 2009 data.
*Some plants use multiple fuels, and individual generating units may be <1 MW.
Sources: AAR 2014, EIA 2011a, EIA 2013a, EIA 2013b, EIA 2013d, EIA 2014a, EIA 2014b, EIA 2014c, EIA 2014e, EIA 2014h, EIA 2014i, EIA 2014k, US Census Bureau 2014, USACE 2014

Table 3-1. Examples of important energy sector vulnerabilities and climate resilience solutions in the Southwest

Subsector	Vulnerability	Magnitude	Illustrative Resilience Solutions
Electricity Demand	Increased demand for cooling energy from increasing CDDs and average and peak temperatures[i]	Increases of up to 1,000 CDDs by mid-century, with peak demand increasing 12%–24% owing to higher extreme temperatures[j]	Capacity expansion, increased power imports, efficiency, and demand-side management
Thermoelectric Power Generation	Reduced power plant capacity due to higher temperatures and reduced water availability, and coastal plants vulnerable to sea level rise[k]	Capacity reductions of up to 4.5%, up to 12 coal-fired power plants vulnerable to water shortages, and 25 coastal plants vulnerable to sea level rise[l]	Capacity expansion and diversification, water-efficient technologies, coastal hardening
Hydropower Generation	Reduced capacity in some seasons from earlier peak streamflow, and declining snowpack and precipitation[m]	Snowpack reductions of up to 43% in California by the end of the century[n]	Integrated water planning to optimize water use, upgraded equipment to increase efficiency
Electric Grid	Reduced capacity from higher temperatures, and threat of disruptions from increased wildfires[o]	Transmission line capacity losses of 1.5%–2.5%, substation losses of 1%–3% from rising temperatures[p]	Transmission capacity expansion and redundancy, improved vegetation management

Regional Energy Sector Vulnerabilities and Resilience Solutions

The following sections discuss key energy subsectors and illustrative examples of resilience solutions in the Southwest. System components that are most vulnerable to climate change are described first.

Electricity Demand

Subsector Vulnerabilities

Electric power demand in the Southwest is dominated by end-use in California, accounting for more than half of the region's electricity consumption (EIA 2013c).[1] Interregional electricity flows are oriented towards serving California's load. In the Western Interconnection (shown Figure 3-1), hydropower resources in the Northwest and mixed generation in the interior Southwest supply almost 25% of California's electricity (EIA 2011b). Power imports from the Northwest peak during spring and early summer (DOE 2012, EIA 2011b, EIA 2014d). Arizona, New Mexico, and Utah are net power exporters, producing 48%, 58%, and 33% more power than they consume, respectively (EIA 2013c).

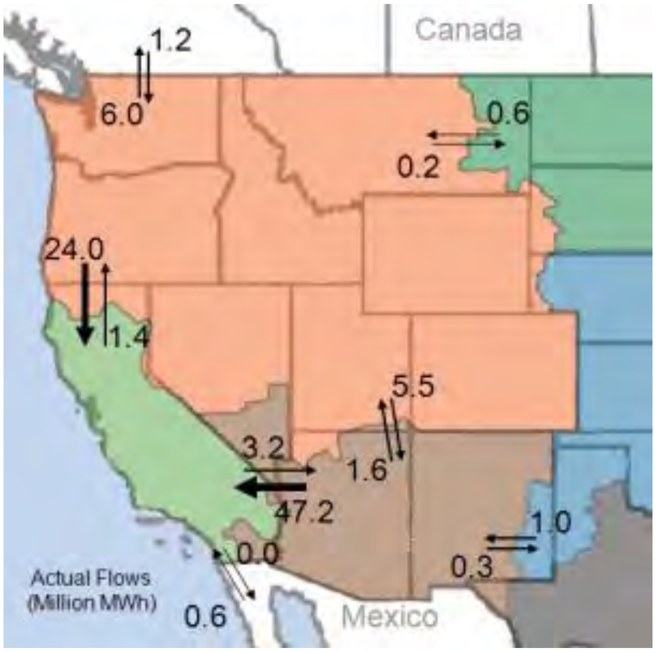


Figure 3-1. Annualized net electricity flows within the Western Interconnection in 2010 (Million MWh)
Source: EIA 2011b

[1] On a per capita basis, California's electricity consumption is about 40% lower than other states in the region (EIA 2013c). This is partly due to the relatively low number of CDDs experienced in California's coastal cities, as well as the lower rate of air conditioning use in California households. In California, 56% of households are air conditioned, while the average rate is 71% for other states in the region and 91% in Arizona, the region's second most populous state (EIA 2013c, EIA 2013g).

Climate change is expected to affect the region's electricity demand in the following ways:

- Higher average temperatures will increase the number of CDDs, increasing demand for cooling energy (NOAA 2013, USGCRP 2014).
- Hotter summer temperatures and an increase in the length, intensity, and frequency of heat waves are expected to increase peak electricity demand, potentially exceeding current generation and transmission capacities in some areas (NOAA 2013, Sathaye et al. 2012, USGCRP 2014).

Changes to temperature and to the total annual number of CDDs are expected to be largest where temperatures are already highest. For example, southeastern California and southwestern Arizona could see an increase of up to 1,000 CDDs per year (Figure 3-2). Important changes in electricity demand may also occur where populations are concentrated and the percentage of homes currently with air conditioners is low, such as coastal California. In these areas, large scale adoption of air conditioners may result in significant increases in electricity demand (EIA 2013g, NOAA 2013).

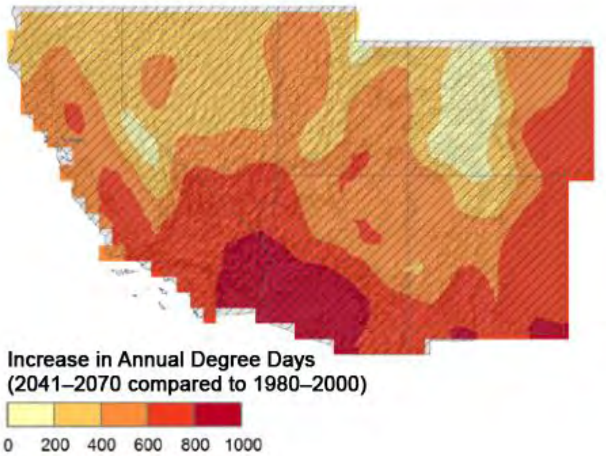


Figure 3-2. Increase in annual CDDs by mid-century under an A2 emissions scenario
Source: NOAA 2013

Under a higher emissions scenario, higher temperatures alone could increase average per capita peak energy demand in California by 12%–24% by the end of the century (compared to 2003–2009), according to an analysis conducted by the California Energy Commission (CEC) (Sathaye et al. 2012). This study supports the findings of an earlier CEC study that estimated end-of-century increases in peak demand due to temperature increases alone could be 4%–19% (compared to 1961–1990), depending on emissions scenario (Miller et al. 2007). When population and economic growth are considered, increases in peak electricity demand could be even larger, as regional population is projected to increase 68% by 2050 (DOE 2015a). Almost half of California households do not currently have air conditioning; cooling energy demand may grow at a faster rate than increases in CDDs if efficiency improvements do not offset additional air conditioning penetration (Auffhammer 2011, EIA 2013c). In states with already-high air conditioning use, such as Arizona and Nevada, increases in demand for cooling energy may increase faster than the rise in average temperatures (Aroonruengsawat and Auffhammer 2009).

The effects of extreme temperatures on electricity demand will be exacerbated by the influence of urban heat islands since air conditioning use is focused in urbanized areas. The three most extreme urban heat islands in the previous decade, as measured by the temperature difference between urban centers and surrounding areas, are located in the region: Albuquerque, Denver, and Las Vegas (Figure 3-3) (Climate Central 2014b).

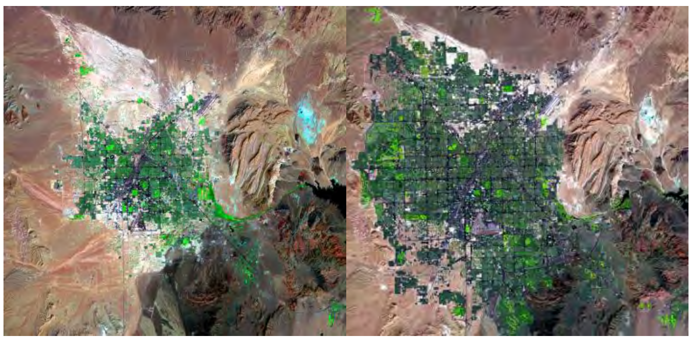


Figure 3-3. Satellite images showing population growth in Las Vegas, Nevada, from 1982 (left) to 2013 (right), which contributes to increasing electricity and water demand
Source: USGS 2015

The seasonal timing of peak energy demand and the potential for reduced availability of power imports from the Northwest may compound the effects of increased energy demand from temperature alone. California relies heavily on power imports from the Northwest during the summer (EIA 2011b). The Northwest, which generates more than 70% of its power from hydroelectric plants, is projected to experience shifts in the timing of snowmelt and peak streamflows away from the summer and towards the early spring, potentially making less power available to export to the Southwest region in the summer (USGCRP 2014).

In the winter, the region is expected to experience a decrease in the number of heating degree days, reducing the demand for heating energy (USGCRP 2014). Heating energy is provided by electricity and other fuels, such as natural gas. Southwest states with cold winters, including Colorado, use primarily natural gas as a space heating fuel; while states with mild winters, including Arizona, use mainly electricity for space heating (EIA 2013g). On average, electric utilities in the region have a summer demand peak about 25% higher than their winter peak, and warmer temperatures in the Southwest are likely to increase the summer electricity peak more than they will decrease the winter electricity peak (ANL 2008, EIA 2013h).

Electricity Demand

Resilience Solutions

Strategies to address increasing electricity demand include capacity expansion, energy efficiency, and implementation of measures that reduce demand at peak hours. New generating capacity can be designed to operate year-round (baseload) or only during periods of greatest demand (peaking). Demand can be reduced through improved end-use energy efficiency and demand management strategies.

Because of economic and population growth trends, new technologies such as electric vehicles, as well as climate change-driven reductions in existing generation capacity, new capacity may be a necessary part of a comprehensive response strategy to increases in peak demand. Evolving emissions regulations and existing water constraints suggest that new baseload thermoelectric plants in the region may employ water-efficient combined-cycle natural gas turbines similar to the Public Service Company of New Mexico's (PNM's) Afton plant, which uses hybrid cooling technology (PNM 2011). A study of demand growth and capacity changes found that gas-fired peaking generators may be required to meet peak electricity demand (Sathaye et al. 2012). New solar power can also contribute to meeting growing peak demand.

Efficiency standards reduce total energy demand, and most states in the region have integrated energy efficiency into statewide electric sector planning and regulations (ACEEE 2014a). In the past decade, Arizona, California, Colorado, and New Mexico state legislatures have all passed new energy efficiency resource standards (EERS) with quantitative targets for investor-owned utilities requiring that they achieve consumption reduction goals. In addition, both California and New Mexico have policies in place that decouple utility profits from the amount of electricity sold to customers (ACEEE 2014a). In 2008, California adopted a strategic plan for energy efficiency that ensures that energy efficiency is the highest priority resource for meeting current and future energy demand (CPUC 2008). CEC also approved new building codes that exceed International Energy Conservation Code (IECC) standards by 25% for residential buildings and 30% for nonresidential construction (CEC 2014a). Many regional utilities offer rebates for energy efficiency measures. For example, Colorado Springs Utilities offers rebates to residential customers of up to $250 each for upgraded windows, appliances, and other improvements (CSU 2014). In response to energy savings goals set by the Public Utilities Commission of the State of Colorado in 2008, the state's largest investor-owned utility, Xcel Energy, has spent almost $320 million on energy efficiency incentives through 2013 (SWEEP 2014). Similarly, Pacific Gas and Electric Company (PG&E) has an energy efficiency program that covers a diverse array of programs and services, some of which helped customers save more than $155 million in 2013 (PG&E 2014a).

Salt Lake City actions for greater climate resilience

Salt Lake City, Utah, which has been recognized as a Climate Action Champion by the White House, is working to improve resilience in part by reducing its energy consumption (White House 2015). As outlined in *Sustainable Salt Lake–Plan 2015*, goals for 2015 include reducing city-wide building energy use by 5%, increasing the number of LEED and EnergyStar buildings, and converting all city facilities to "net-zero" energy use (SLC 2014).

Demand response is another method for reducing peak demand. California's demand response resource represents slightly more than 5% of California's 2012 peak load (FERC 2013). In addition, the California Public Utilities Commission, CEC, and the state's independent system operator (CAISO) have been working to allow residential ratepayers to participate in demand response, potentially expanding the resource (FERC 2013). Arizona Public Service (APS) offers a cooling energy load management program with financial incentives that allows APS to control customer thermostats to reduce air conditioning load during summer peak demand periods (DOE 2014b). Similarly, Las Vegas utility NV Energy offers commercial customers rate incentives for use of remotely controllable thermostats that reduce cooling during peak demand periods. Tucson Electric Power offers its commercial, institutional, and industrial customers a year-round program that compensates participants for reducing electricity usage during peak demand events (DOE 2014b).

Thermoelectric Power Generation

Subsector Vulnerabilities

Power in the Southwest is generated from diverse sources; natural gas, coal, nuclear, biomass, and geothermal power plants produced 87% of the region's net electric generation in 2012 (EIA 2013c). The efficiency of thermoelectric power plants is sensitive to ambient air and water temperatures, and the plants need large amounts of water to generate steam and to cool process components. The Southwest is predominantly arid, and much of the region has traditionally experienced water constraints. For this reason, few thermoelectric plants in the region use freshwater-intensive once-through cooling systems and instead employ recirculating cooling and, increasingly, advanced technologies such as wet–dry hybrid and dry cooling (UCS 2012). Climate change is projected to further reduce water availability in some seasons and parts of the region, and increasing temperatures may exacerbate the impacts of water scarcity by reducing the efficiency of power production and increasing the volume of water required for cooling. Additionally, many thermoelectric plants along the coast that use seawater for cooling are vulnerable to the threats posed by accelerating sea level rise.

Climate change is projected to have the following impacts on thermoelectric power generation in the Southwest:

- Increasing average temperatures and more frequent and severe extreme temperatures are expected to reduce the efficiency and available generating capacity of thermoelectric power plants (DOE 2013, Sathaye et al. 2012, USGCRP 2014).
- Reduced availability of surface water resources and changing seasonal flow patterns of some sources of cooling water may increase the risk of thermoelectric power plant de-ratings (Cayan et al. 2013, DOE 2013, USGCRP 2014).
- Accelerating sea level rise increases the vulnerability of coastal energy infrastructure to inundation (Climate Central 2014a, NRC 2012, USGCRP 2014).

As temperatures increase, efficiency of thermoelectric power plants will decrease and, in turn, reduce available capacity. Plant equipment is typically designed for optimal operation at a set ambient temperature; deviation from those conditions can affect both efficiency and available capacity. The standard design conditions for air-breathing combustion turbines are 59° F (15°C) at pressure at sea level , and a 1°C increase in ambient temperature above the design point could reduce capacity by 0.7% for a combined-cycle gas plant and 1% for a simple cycle plant (Sathaye et al. 2012). Based on these rates, climate change-driven temperature increases could lead to reductions of 1.7%–4.5% of peak capacity across California's natural gas power plants by the end of the century (2070–2099), depending on emissions scenario (Sathaye et al. 2012).

Electric impedance in assets also increases with higher temperature, which leads to higher electric losses, and hotter processes require more cooling water to operate, meaning more power is required to pump greater volumes of water (DOE 2013). Higher air temperature also leads to warmer water temperature, which exacerbates the need for pumping. In some cases, hotter sources of cooling water can lead to mandatory plant shutdowns for environmental reasons (DOE 2013).

Only about half of the installed generating capacity in the region uses water-intensive once-through cooling, and of the plants that do, very few use freshwater sources (Figure 3-4) (UCS 2012). Most thermoelectric plants use recirculating cooling or use ocean water for cooling, and many of those that use freshwater for once-through cooling are set to retire or are inactive. Groundwater is a significant water source, although 74% of groundwater withdrawals for thermoelectric cooling are saline and do not currently compete with fresh groundwater users (UCS 2012, USGS 2005).

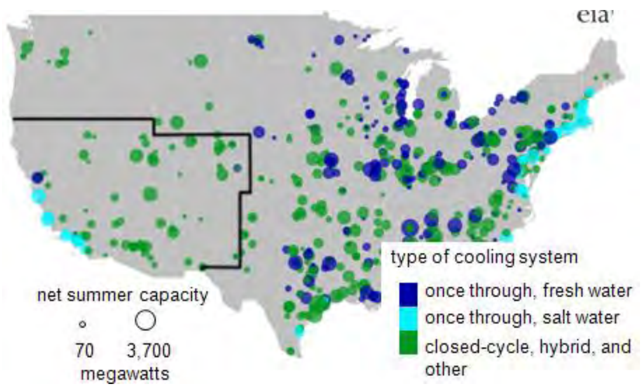


Figure 3-4. Types of cooling systems for U.S. plants (note limited once-through cooling systems that use freshwater sources in the Southwest)
Source: EIA 2012

Coal power plants in the interior may be particularly vulnerable to declining water supplies. One 2010 study found that, without taking future climate change into account, the water sources for 12 coal-fired power plants in the Southwest's Great Basin and Colorado River watersheds are already vulnerable to decreasing supply or increasing demand (Figure 3-5). Several of these plants have since reduced generation or closed (NETL 2010, PNM 2011).

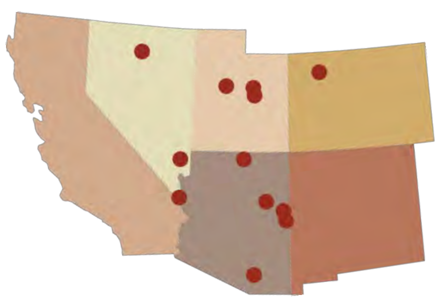


Figure 3-5. Coal power plants identified as vulnerable to water supply and demand concerns
Sources: EIA 2014c, NETL 2010

Coal-fired power plants are facing increasing economic pressure and may be retired before their lifetimes expire because of higher coal prices, lower wholesale electricity prices, increasing deployment of natural gas and renewable capacity, and environmental regulations that require investment in emissions reduction (EIA 2014l) (see side bar: The changing face of Southwest coal). For example, following passage of Colorado's Clean Air, Clean Jobs Act, which requires that utilities reduce emissions by 30% by 2020, Xcel Energy announced that 702 MW of coal-fired generation would be retired and replaced with new natural gas-fired generation (Xcel Energy 2015). Retirements of coal-fired generation may reduce the burden on the water supply. One study that considered aggregate thermoelectric water demand in the region found that in the reference case, freshwater withdrawals are estimated to fall 30% by 2050 (Macknick et al. 2012).[2] These declines are primarily due to the retirement of older thermoelectric units and introduction of natural gas-fired combined-cycle plants, which require significantly less cooling water than existing coal and nuclear plants (DOE 2013, Macknick et al. 2012).

Consumption of freshwater for thermoelectric power generation is projected to decrease in the Lower Colorado Basin, though total region-wide water consumption for power generation is not projected to change significantly (Macknick et al. 2012).

The changing face of Southwest coal

During the last decade, a number of large coal power plants in the region shut down, reduced their output, or secured new sources of water to cope with developing regulations and changes to water supplies (PNM 2011).

2013: PNM announced the decommissioning of two of four coal-fired units at the San Juan Generating Station, replacing the capacity with new natural gas plants and uprated nuclear capacity (EIA 2013d). Also, in response to the U.S. Environmental Protection Agency's (EPA's) Regional Haze Program, three of the five coal-fired units at the APS Four Corners Power Plant closed (Randazzo 2013).

2005: The 1,580 MW Mohave Generating Station closed after Southern California Edison was unable to secure necessary water and coal contracts to fulfill its obligations under a consent decree with the EPA (Edwards 2009).

2002: In response to drought conditions, PNM sought additional water sources for its San Juan Generating Station and entered into shortage sharing agreements with local tribes and other water users in the region (PNM 2011).

Sea level rise poses a threat to low-lying coastal power plants in California. Rising sea levels accelerate erosion and can increase the risk of inundation during high tides and storm surges. Approximately 25 coastal power plants have been classified as at risk of inundation from a 100-year flood with a 1.4-meter sea level rise, although site-specific analyses are required in order to establish actual risk (Sathaye et al. 2012).

[2] Estimate does not account for increased demand due to climate change but does include economic and population growth as well as the retirement and replacement of older plants.

Thermoelectric Power Generation

Resilience Solutions

Strategies to increase power plant resilience include the addition of new capacity (including low-water renewables such as wind or solar photovoltaics [PV]), deployment of water-efficient technologies and non-traditional water sources for cooling, and coastal hardening for plants vulnerable to sea level rise.

Reduced available generation capacity is primarily addressed by building new capacity or by importing additional power. Capacity reductions can also be ameliorated by demand-side efficiency and demand response programs (discussed in the Electricity Demand section).

Declining water availability can be addressed through deployment of technologies that increase water efficiency, use non-traditional water sources, or provide alternative generation sources that inherently require less or no water. Many thermoelectric power plants in the region already use recirculating cooling technology, and almost all plants in the region that use once-through cooling are supplied by ocean water (Table 3-2) (UCS 2012). In 2010, California opted to phase out once-through systems in coastal power plants, which will reduce withdrawals and the impact of discharge on California estuaries (CEC 2014c). Under a previous CEC policy, new power plants in California are essentially prohibited from using freshwater for cooling (CEC 2003).

Table 3-2. Southwest thermoelectric capacity by type of cooling technology, 2005

Once-through cooling	**51.4%**
Ocean water	*50.3%*
Surface	*0.9%*
Municipal	*0.2%*
Recirculating/cooling pond	**42.9%**
Groundwater	*14.5%*
Surface	*13.7%*
Wastewater	*8.3%*
Municipal	*6.2%*
Unknown	*0.2%*
Dry cooling	**4.4%**
Unknown/other	**1.3%**

Source: UCS 2012

Some new plants in the region are being built to use extremely water-efficient hybrid wet–dry cooling technology, which allows the plant to use cooling water when it is available but, in case of a shortage, to operate on dry cooling or with advanced dry cooling technologies that use minimal water. PNM's Afton Generating Station is a natural gas combined-cycle (NGCC) plant that uses hybrid cooling to reduce water intensity by 60% compared to PNM's other NGCC plant (PNM 2011). Three of PG&E's natural gas-fired power plants rely on dry cooling systems that minimize water use and discharge. The Humboldt Bay Generating Station uses minimal amounts of water by implementing a closed-loop liquid coolant cooling system with air radiators (PG&E 2014a). Compared to a plant with a traditional once-through cooling system, PG&E's Gateway Generating Station's air-cooled condenser requires about 97% less water and discharges about 98% less wastewater, and PG&E's Colusa Generating Station has a zero liquid discharge system that recycles wastewater (PG&E 2014a).

However, plants with dry cooling systems are more susceptible to decreasing efficiency due to high temperatures than those with wet cooling systems (GAO 2014, Garfin et al. 2013). Plants with dry cooling systems can lose 0.5% of capacity for every 1°F increase in peak temperature, about twice the capacity lost in plants with wet cooling systems under the same conditions (Garfin et al. 2013, Gordon and Ojima 2015).

Switching to non-traditional water sources, such as saline groundwater, municipal and industrial wastewater, and recycled brown water from landscaping, also present viable options for resilient water supplies (PNM 2011). For example, the Palo Verde Nuclear Generating Station in Arizona has been converted to use municipal wastewater (Figure 3-6) (PNM 2011).

Figure 3-6. The Palo Verde Nuclear Generating Station, which uses municipal wastewater for cooling
Source: USNRC 2015

Expanded deployment of renewable technologies such as wind and solar PV could significantly reduce water demand for energy. In low-carbon scenarios with wider deployment of solar PV and wind technologies, 2050 water withdrawals and consumption could decline up to 90% and 72%, respectively, depending on technology assumptions (Macknick et al. 2012). To support clean renewables in the region, the U.S. Department of Energy (DOE) has granted a number of loan guarantees for solar PV and wind projects. For example, DOE issued a loan guarantee to support the 550 MW Desert Sunlight solar PV project in California, the nation's largest solar project on public lands. Deployment of solar PV projects near thermoelectric power plants can provide additional benefits by shading water supply for these plants, potentially reducing evaporation from the water supply and decreasing the temperature of the intake water.

DOE has also supported expanded deployment of solar thermal technologies that employ low-water strategies in the Southwest. One such project is the 392 MW Ivanpah Solar Generating Station in California (Figure 3-7). The plant employs advanced dry cooling technology for its steam condensers to reduce its burden on freshwater resources, and it uses groundwater to supplement evaporative losses as well as to wash its mirror array, while it also recycles on-site wastewater to further reduce water needs (CEC 2014b).

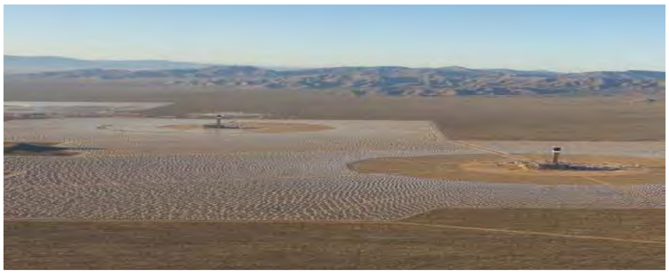


Figure 3-7. Ivanpah Solar Electric Generating System
Photo Credit: BrightSource Energy

Beyond technology changes, operations and planning can also improve resilience to water shortages. For example, the Public Utilities Commission of the State of Colorado requires that generators bidding to serve new power to investor-owned utilities must disclose information about the source and cost of their water supplies (WWA 2011). For coastal impacts from sea level rise and erosion, resilience solutions include hardening shorelines and sub-sea infrastructure (such as water intakes) to resist erosion and scouring, installing engineered barriers such as levees, raising vulnerable equipment, ensuring critical equipment is submersible, upgrading plants with watertight doors, and building coastal defenses like wetland habitats, where relevant.

Hydroelectric Power

Subsector Vulnerabilities

Hydropower is a significant resource in the Southwest, with approximately 19 GW of installed capacity providing 8% of electricity generation (EIA 2013c, EIA 2013d). More than 70% of the region's capacity is located in California, where most dams are powered by highly seasonal melting snowpack from the Sierra Nevada mountains (Figure 3-8). In addition to its own hydropower generation, California also relies on hydropower imports from the Northwest to meet its peak summer power demands.[3] The Colorado River watershed hosts a smaller number of large dams, including the Glen Canyon and Hoover dams (Figure 3-9).

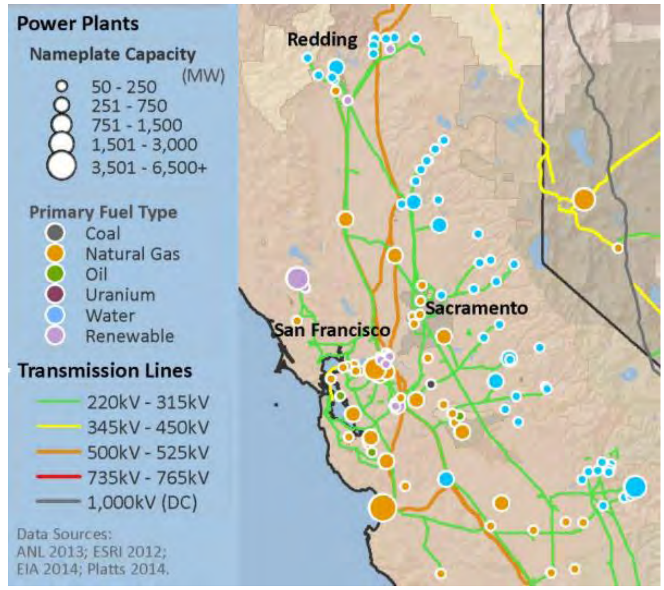


Figure 3-8. Hydroelectric facilities (blue) in the Sierra Nevada
Source: DOE 2015b

Figure 3-9. The 1,312 MW Glen Canyon Dam on the Colorado River watershed in Arizona
Source: USBR 2009

Hydropower production in the region is vulnerable to the following climate impacts:

- Declining April 1 snowpack and earlier spring snowmelt is expected to shift peak streamflow timing in snowmelt-fed rivers, potentially reducing summer water availability and hydropower generation (AEG and Cubed 2005, Cayan et al. 2013, NOAA 2013, USGCRP 2014).
- Winter precipitation is expected to increase, with a greater fraction expected to fall as rain rather than as snow. Overall, annual average precipitation is expected to decline (Barnett et al. 2008, NOAA 2013, USGCRP 2014).

[3] Northwest hydropower production and climate vulnerabilities are discussed in the Northwest regional profile.

Climate impacts affecting hydropower generation are expected to result from changes to both the total amount of water available in the region and to the timing of seasonal snowmelt and water flows. These changes could diminish the availability and capacity of hydropower resources.

From 2012 through 2014, California experienced historic drought conditions and a reduction of approximately 34,000 GWh of hydroelectricity compared to average water years. The cost of reduced hydroelectricity production and the use of additional natural gas to meet energy demand was estimated at $1.4 billion dollars (Pacific Institute 2015). The drought has continued in 2015, and is projected to contribute to a 10.4% decrease in annual hydropower in the United States in 2015 compared to 2014 (EIA 2015b).

Changes in regional precipitation and increasing evapotranspiration are generally expected to reduce water availability across the region. During the last decade, precipitation declines compared to the historical average in both the Sacramento–San Joaquin and Colorado River basins have been correlated to significant declines in streamflow (Garfin et al. 2013).[4] In the Colorado River watershed, reduced precipitation may exacerbate water management issues already being faced by the basin's major dams. One study estimates that without taking climate changes into account, there is already a 50% chance that the lakes could hold insufficient quantities of water to produce power by 2021 (Barnett and Pierce 2008).

Of California's fleet of dams, high-elevation dams are the most important for hydropower generation,[5] but they typically have much smaller reservoirs than low-lying dams and are more reliant on snowpack to supply water in the spring and early summer (AEG and Cubed 2005). For California's hydropower resources, changes to total annual precipitation may be less important than a number of factors affecting the accumulation and timing of winter snowpack, including increases in winter precipitation, shifts from snow to rain, and earlier spring snowpack melting.

Winter precipitation is projected to increase by mid-century (NOAA 2013). But as winters become warmer, more winter precipitation is expected to fall as rain rather than snow, decreasing snowpack (Barnett et al. 2008, USGCRP 2014). The trend toward increased winter rainfall is strongest in California's Sierra Nevada range, where most of California's high-elevation hydropower is located (EIA 2014c, Knowles et al. 2007). Furthermore, the annual pattern of spring snowpack melting is expected to occur earlier across the region as winter and spring temperatures increase (USGCRP 2014). Earlier peak melting presents problems for power planning since greater hydropower production is desirable during the summer when electricity demand is the highest. The total amount of snowpack available on April 1 has fallen at measurement sites across much of the region since 1955.[6] In 2015, April 1 snowpack was 6% of the long-term average, the lowest water content on record, owing to high temperatures and dry conditions that a recent study suggests are more likely to co-occur in the future (CDWR 2015, Diffenbaugh et al. 2015). Climate change is expected to lead to significant continued reductions in snowpack (EPA 2014, USGCRP 2014). Under a higher emissions scenario (A2), California snowpack could fall to 43% of recent levels by the end of this century (2070–2099) compared to 1971–2000 (USGCRP 2014).

It is uncertain how these changes will interact to affect the total accumulation of high-elevation snowpack, and thus the region's ability to produce hydropower, but the effects could be substantial. One study estimates annual streamflow changes could drive changes in generation in California's American River Watershed ranging from a 13% decrease to a 14% increase by 2070–2099, depending on emissions scenario and other modeling uncertainties (Vicuna et al. 2007).[7]

Hydroelectric Power

Resilience Solutions

Operational measures to increase hydropower resilience will require consideration of a larger integrated water management approach, as seasonal and extended water scarcity continues to have an impact on the region. In the face of competing demands, and depending on available alternatives, hydropower may not be seen as the highest-priority user. Reducing spill and better utilizing or storing early-spring runoff can improve hydropower resilience but may conflict with other water management goals, such as flood control. Expanding and diversifying non-hydro capacity would help ensure reliable electricity delivery during dry periods.

[4] During the last decade (2001–2010), streamflow in the Sacramento–San Joaquin basin was 37% lower and precipitation 7% lower than average amounts for the period 1931–2000. On the Colorado River, streamflow was 16% lower and precipitation 4% lower than the average levels for 1901–2000.

[5] The primary purpose of many low-elevation dams in California is flood control and water supply, not power production (AEG and Cubed 2005).

[6] In the southern Sierra Nevadas, the recent historical trend has not followed the regional pattern of earlier melting, as wetter-than-average conditions have acted to increase April 1 snowpack (EPA 2014, Pierce et al. 2008). Long-run warming is expected to reverse this trend and lead to declines in snowpack in the southern range (Cayan et al. 2013, USGCRP 2014).

[7] The study examined the 11 reservoirs and 8 hydroelectric facilities that compose the Sacramento Municipal Utility District's Upper American River Project and modeled system impacts under the A2 and B1 climate change scenarios.

PG&E has actively engaged with state and local stakeholders and developed strategies to adapt to reductions in snowpack in the Sierra Nevada Mountains. These strategies include maintaining higher winter carryover reservoir storage levels, reducing discretionary reservoir releases, and developing new modeling tools for forecasting runoff (GAO 2014, PG&E 2014a).

For dams facing declining water availability, technological options to increase resilience include overhauling and upgrading plant equipment to minimize water leaks and increase turbine efficiency. In 2001, in response to falling water levels in Lake Mead, ongoing work by the Bureau of Reclamation to overhaul the Hoover Dam's 17 turbine-generator pairs shifted focus to increasing efficiency and regaining lost capacity. By reducing water leaks and overhauling the turbines, efficiency is now 3%–4% higher at each overhauled unit, and more water is being conserved for power generation (HydroWorld 2009). On a much smaller scale, the City of Boulder replaced the nearly 50-year-old turbine and generator at its Boulder Canyon Generating Station with a significantly more efficient 5 MW unit, increasing capacity by 30% (City of Boulder 2014).

To reduce the impact of decreasing hydropower production in dry years on customers, Sacramento Municipal Utility District (SMUD) has implemented a rate-stabilization fund, which uses savings from high-production years to buy power during drought years (Kasler 2014).

Electric Grid

Subsector Vulnerabilities

The operational structure of the electric grid varies within the Southwest region. In California, the grid is operated by CAISO, while interior states mainly have vertically integrated utilities that plan and operate generation and transmission capacity internally (DOE 2014a). In some parts of the Southwest, including parts of Arizona and New Mexico, there is less redundancy built into the grid system compared to other parts of the country (BLM 2013).

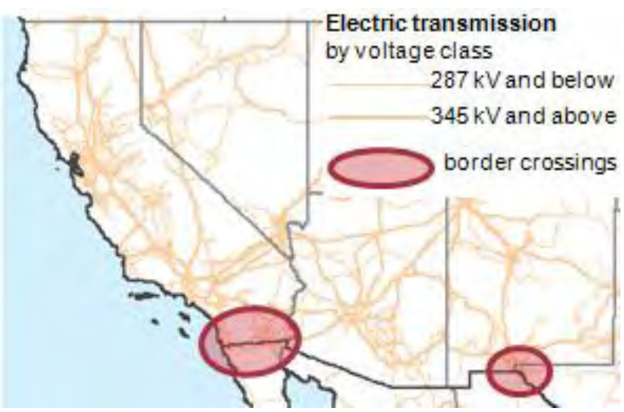


Figure 3-10. Power flows between the Southwest and Mexico, including a synchronous tie between California and Mexico
Source: EIA 2013i

small amount of power flows internationally between Mexico and California (EIA 2013i). The Comisión Federal de Electricidad (CFE) Baja California Control Area is connected by two 230 kV transmission lines to the Western Interconnection (Figure 3-10) (CEC 2008). The CFE Baja Control Area transmits power generated at two plants in Mexico with a combined capacity of 1,120 MW to supply demand in the San Diego area (CEC 2008). The tie in Baja California is the only synchronous cross-border tie between Mexico and the United States (EIA 2013i).

Interstate power flows in the region are generally oriented toward California (discussed in the Electricity Demand section). Several major power corridors, including the Pacific DC Intertie, the California–Oregon Intertie (Path 66), and the Intermountain Power Project DC line, supply significant peaking capacity to California from neighboring states (CAISO 2012). Across the region, construction of new transmission lines has accelerated in recent years, as electricity flows need to keep up with changing demand and distribution of existing generation, including upcoming retirements and new generating capacity (DOE 2014a).

Climate change could have the following impacts on the electric grid:

- Increasing frequency and size of wildfires and associated heat, soot, and application of fire retardants may damage and disrupt power transmission infrastructure (DOE 2013, Sathaye et al. 2012, USGCRP 2014).
- Increasing average and extreme temperatures reduce the capacity of power lines and substations and increase the risk of damage to power transformers (Bérubé et al. 2007, DOE 2013, Sathaye et al. 2012, USGCRP 2014).
- Rising sea levels increase the exposure of low-lying coastal substations to inundation during storm surges (Sathaye et al. 2012, USGCRP 2014).

Projected increases in the frequency and extent of wildfires heighten the risk of grid outages and safety shutdowns. Both tree mortality and wildfires have increased dramatically in the past several decades, with the area burned in western mid-elevation conifer forests increasing almost sevenfold during the late 20th century (USGCRP 2014).[8] Wildfires can burn and destroy wooden power poles that typically hold smaller transmission lines, and the associated smoke, soot, fire retardants, and heat from fires can damage and disrupt larger grid assets by fouling lines and insulators, increasing risk of arcing and reducing transmission capacity (DOE 2013, Sathaye et al. 2012, SDG&E 2008). For example, in early September 2015, the Valley, Butte, and Rough Fires damaged grid infrastructure

[8] The measurement period is 1970–2003.

Wildfire disrupts electricity in San Diego

In 2007, wildfire knocked out the Southwest Power Link, a transmission line connecting San Diego to distant generation, requiring 500 MW of load shedding in San Diego by San Diego Gas & Electric and Southern California Edison. Over the next week, fires took out two dozen additional transmission lines, destroying 35 miles of wire and 1,500 poles. Nearly 80,000 customers in San Diego lost power, some for more than two weeks (PPIC 2008, SDG&E 2007).

Figure 3-11. The Witch Creek/Guejito wildland urban interface fire of October 2007
Source: U.S. Department of Commerce 2013

and knocked out power to more than 15,000 PG&E customers in Northern and Central California (DOE 2015d).

Wildfire models have estimated the impact that climate change, in concert with other changes such as future development, may have on the extent of wildfires in the Southwest. In the southern Rockies, the average area burned each year may double by mid-century (Litschert et al. 2012, USGCRP 2014).[9] In California, projections indicate that under a higher emissions scenario, wildfires could increase in all forested areas by the end of the century (Sathaye et al. 2012). In the Sierra Nevada, fires are projected to increase by almost 75% by the end of the century (compared to 1960–1990) (USGCRP 2014).

Models estimating the probability of wildfire impacts on transmission lines in California have shown that lines in two regions—the state's northern border and the region north of Los Angeles—are particularly vulnerable to wildfire under higher emissions scenarios (Sathaye et al. 2012). Compounding the vulnerability of northern California is the lack of alternate or redundant routes to the Northwest power market and the projection that Path 66—the artery that connects northern California loads to low-cost Northwest hydropower and the Diablo Canyon nuclear plant—will become significantly more vulnerable to wildfire (Sathaye et al. 2012). Southern California relies on even greater amounts of power imports to meet peak demand in the summer, although with a larger number of transmission corridors; about one-third of peak capacity is provided via transmission lines connecting to interior states (Sathaye et al. 2012).

Higher temperatures may result in decreases in the available current-carrying capacity of power lines and substations and exacerbate vulnerabilities of the broader energy system in the region, particularly during peak demand periods (Figure 3-12) (DOE 2013). High temperatures cause thermal expansion of power line materials, and greater sag in transmission lines increases the risk of widespread power outages when lines arc to trees, the ground, or other power lines (DOE 2013). Furthermore, when transmission lines arc, they may ignite overgrown vegetation. To prevent damage to lines, operators may reduce the capacity on transmission lines. By the end of the century the combined effects of higher demand and temperature could increase total loss factors for the transmission and distribution grids by 1.5%–2.5%,

Impacts of higher electricity demand are compounded by efficiency reductions in power sector

A CEC study found that increasing energy demand and capacity losses across power sector infrastructure could, under a higher emissions scenario, require a 38.5% increase in the nameplate capacity of gas-fired peaking generators by the end of the century (Sathaye et al. 2012). Figure 3-12 shows how efficiency penalties along generation, transmission, and substations serve to compound the impacts of increasing energy demand on system resource requirements.

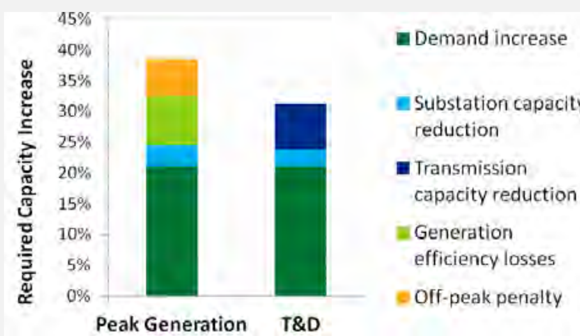


Figure 3-12. Required increase in capacity in California due to higher temperatures, in order to provide 1961–1990 levels of per-capita peak power by the end of this century. Assumes A2 scenario, and a 90th-percentile temperature.
Source: Based on Sathaye et al. 2012

[9] Increases are for the period 2041–2070, compared to 1970–2006.

while reducing capacity by 7%–8% (for a 9°F increase in air temperature) (Sathaye et al. 2012). Higher temperatures may also reduce substation capacity 1%–3% compared to current capacity (Sathaye et al. 2012).

Increased temperatures also shorten the lifetimes of power transformers. At higher temperatures, the insulation in transformers breaks down at an accelerated rate (Bérubé 2007). At extreme temperatures, such as those encountered during grid emergencies when some transformers may be overloaded, significant overheating can rapidly shorten transformer lifetime. On very hot days, grid operators must reduce transformer loading or risk causing additional damage (Hashmi et al. 2013, USBR 2000). Increasing nighttime temperatures will prevent equipment from cooling off, which may exacerbate the effects of high temperatures on power lines and transformers (DOE 2013).

As climate change leads to higher relative sea levels, coastal flooding may pose a risk to some low-lying electric substations, especially when combined with storm surge. In a scenario with a 4.6-foot rise in sea level, one study determined that 3% of California's electric substations would be vulnerable to a 100-year coastal flood (Sathaye et al. 2012).[10] Increases in winter precipitation may also affect inland flooding via rain-on-snow events, which produce large amounts of runoff in mountain drainages. However, recent trends in the Western United States have shown these events occurring less frequently (McCabe et al. 2007, USGCRP 2014).

Electric Grid

Resilience Solutions

Measures to improve the resilience of new and existing electric transmission infrastructure include engineering structures to better withstand sea-level rise and hotter conditions, increased fire management practices to reduce short-term threats such as overloaded equipment, long-term planning to increase network redundancy where wildfires are likely to occur, and transmission capacity expansion when necessary (DOE 2013).

To reduce wildfire risk, utilities engage in vegetation management, including tree trimming, as well as thinning and prescribed burning to reduce fuel buildup (USGCRP 2014). Adequate vegetation management can also reduce the risk of wildfires caused by tree strikes, and California regulators have cleared the way for utilities to take more proactive measures by requiring management on lower-voltage power lines and by allowing utilities to cut off service to properties that will not allow tree trimming (EEI 2014). Three California utilities—San Diego Gas & Electric (SDG&E), PG&E, and Southern California Edison—are also jointly funding the development of a statewide fire-threat map that will indicate physical and environmental conditions that are associated with higher risk of power line fires (EEI 2014). PG&E has also partnered with local fire safe councils to help fund fuel reduction and emergency response access projects, such as installing remote fire detection cameras on lookout towers in critical fire risk areas (PG&E 2014b). To help ensure that power outages are identified and restored quickly, advanced communications and control technologies, such as state-of-the-art automated switch technologies, can "self-heal" the grid (PG&E 2015).

Technologies to improve transformer resilience include installing or upgrading cooling fans or replacing transformers with more expensive, higher-temperature-rated units (Bérubé et al. 2007, USBR 2000). Management practices for protecting grid equipment, such as reducing loading on transformers during heat waves, can help prevent short-term damage (Hashmi et al. 2013). In 2014, Colorado Springs Utilities partnered with Landis+Gyr to install an advanced load management program to protect distribution system assets during peak power consumption by dynamically reducing loads. The utility is planning to deploy 1,900 smart thermostats and software applications to enable load shedding on specific feeder circuits to protect transformers and other distribution equipment, while maintaining reliable electric service (Landis+Gyr 2014).

Illustrative electric grid resilience solutions

Following the damaging wildfires of 2007, SDG&E implemented greater minimum clearances for vegetation and has explored using LiDAR to identify clearance issues (Fotland 2012). The utility has also hardened critical portions of its lines, including replacing wood poles with steel, replacing power conductors with stronger steel-core lines, increasing transmission line spacing, and installing advanced line closers to protect lines in case of emergency. In June 2012, SDG&E activated the Sunrise Powerlink transmission line connecting San Diego to the Imperial Valley to improve reliability during summer heat waves (SDG&E 2012). SDG&E also partnered with the U.S. Forest Service and University of California, Los Angeles, to develop the Santa Ana Wildfire Threat Index, a web-based tool available to the public that assesses the risk of wildfires during Santa Ana wind events (Rolinski et al. 2014).

[10] Out of 2,690 substations, 86 are at risk (Sathaye et al. 2012).

Oil and Gas Exploration and Production

Subsector Vulnerabilities

The Southwest's oil and gas infrastructure includes oil and gas wells, oil refineries, and natural gas processing facilities. About 13% of domestic oil production is in the region, mostly in California, but also in New Mexico, Colorado, and Utah (EIA 2014a). The region's refinery capacity is also concentrated in California, mostly along the coast, and locally produced oil is primarily refined and consumed in the region (EIA 2014f, EIA 2014g). About 14% of the nation's natural gas is produced in the region, with Colorado and New Mexico as the largest producers (EIA 2013f).

Climate change may have the following impacts on oil and gas exploration and production:

- Rising sea levels, when combined with land subsidence and storm surge, could accelerate erosion and inundate low-lying and coastal oil and gas infrastructure (DOE 2013, USGCRP 2014).
- Declining water availability, including increased risk of drought, may affect production and refining operations that require freshwater resources (DOE 2013, Tiedeman et al. 2014, USGCRP 2014).

Flooding and inundation risks associated with rising sea levels may affect facilities along the entire California coastline, although land subsidence and concentrations of energy assets localize the impact to a few areas. Over the last century, sea levels in California have increased 6.7–7.9 inches. South of Cape Mendocino, where tectonic shifts are causing land subsidence, sea levels are expected to increase another 1.4–5.5 feet by 2100, depending on emissions scenario and other uncertainties (NRC 2012).

The vulnerability of specific energy assets is sensitive to their elevation and proximity to coastlines. An analysis of flooding impacts on utilities in Los Angeles (including electric power, water, and fuel systems) found that assuming 1.4 meter (4.6 feet) of sea level rise, combined with a once-in-100-year flood, caused moderate damage to three of the city's oil refineries but affected none of the city's power plants or natural gas facilities (Grifman et al. 2013).

Energy production can also be affected by prolonged drought. California's oil production is mostly composed of older wells undergoing water-intensive secondary and tertiary enhanced recovery processes. For the period 1999–2012, the water intensity of the median California oil well increased more than 20%, and many wells are located in areas that may experience moderate to severe water stress by 2025 (Tiedeman et al. 2014). In the midst of a recent drought, California has passed new legislation mandating that oil drillers report the amount and source of water used in oil recovery (California Department of Conservation 2015, Carroll 2014). Throughout the region, hydraulically fractured wells, which require about 3–6 million gallons of water per well for drilling and fracturing (Mantell 2011), are located in areas with water stress challenges that could be exacerbated by declining precipitation. One study found that over 95% of hydraulic fractured wells in Colorado and California are in locations considered "high" or "extremely high" water stress (Ceres 2014).

Like thermoelectric power plants, oil refineries require a substantial amount of cooling water and may face escalating costs as droughts and critical water shortages become more frequent (DOE 2013).

Oil and Gas Exploration and Production

Resilience Solutions

Resilience strategies to protect the Southwest's coastal oil and gas infrastructure from inundation include both hardening and management solutions.

Oil and gas companies facing periodic water constraints on drilling and refining operations can use degraded water or wastewater to reduce demand for municipal or freshwater. For example, a BP oil refinery in Los Angeles recently switched to recycled municipal wastewater to meet some of its process water needs (Troeh 2012). Oil production operations using water-intensive enhanced oil recovery could expand use of brackish groundwater or reuse produced water (DOE 2013). Alternative fracturing techniques that are typically used to promote enhanced product recovery in select shale formations may also reduce water use; these includeLiquid Petroleum Gas (LPG) fracturing, which uses propane and chemical additives in lieu of water; foam-based fracturing, which uses water, a foaming agent, and nitrogen or carbon dioxide; and channel fracturing, which uses proppant-laden fluid and gelled fluid to create channels (GAO 2015). In addition, enhanced oil recovery using carbon dioxide injection from carbon capture, storage, and use activities could contribute to reduced greenhouse gas emissions (climate mitigation) as well as enhanced resilience to climate change. Because water management is already a high-priority issue for most Southwestern states, solutions to problems of increased energy infrastructure vulnerability will continue to require comprehensive resilience strategies that address stakeholders in multiple sectors.

Fuel Transport

Subsector Vulnerabilities

Much of the Southwest region is dependent on the extensive fuel transport infrastructure located along the California coast (Figure 3-13) (EIA 2014c). In particular, refineries in California rely on coastal infrastructure, such as ports in Los Angeles, Long Beach, and the Bay area, for imports of crude oil (EIA 2014c, CEC 2015). Once refined, gasoline and other petroleum products are transported primarily by pipelines to customers in California, Nevada, and Arizona (CDPC 2010). In addition, the region has become increasingly dependent on domestic shipments of crude oil by rail.

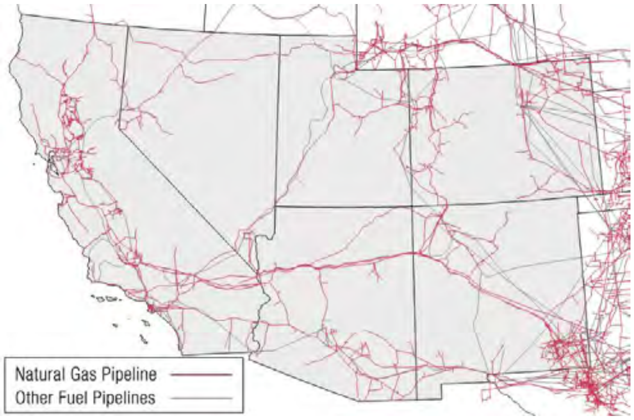


Figure 3-13. Natural gas and other fuel pipelines in the Southwest
Source: Adapted from EIA 2014c

New Mexico and Colorado are major producers of natural gas, which is consumed in-state and transported via pipeline to other western states. Markets in California are served by natural gas from Arizona, Nevada, and the Northwest (EIA 2014c). California exports and imports a limited amount of natural gas by pipeline to and from Mexico (EIA 2014m, EIA 2015a).

Climate change may have the following impacts on fuel transport:

- Rising sea levels could result in a higher rate of coastal erosion and a greater likelihood of flooding coastal infrastructure, including ports, terminals, pipelines, and railroads (CEC 2012, Sathaye et al. 2012, USGCRP 2014).

Coastal ports and facilities are vulnerable to increased flood regimes along the coast due to higher sea levels, and may be at greater risk of being forced to stop or delay operations during floods. According to one study, 80% of the Port of San Francisco, 60% of the Port of Oakland, and approximately 50% of the Port of Richmond in the Bay Area could be inundated during a 100-year flood event with 1.4 meters (4.6 feet) of sea level rise (CEC 2012). A 100-year flood event combined with sea level rise could also flood almost 1,700 miles of roadway in the Bay area, including almost 170 miles of major highways, stalling port operations by hindering the transport of personnel and goods (CEC 2012). Much of northern California's Sacramento–San Joaquin River Delta region has subsided below sea level and is already highly vulnerable to flooding. The delta contains significant natural gas infrastructure, including the McDonald Island natural gas storage facility and multiple pipelines, that supplies the Bay Area and Sacramento/Stockton (Sathaye et al. 2012).

Pipelines along the coast and in low-lying areas may be vulnerable to corrosion as coastal flooding associated with rising sea levels may increase saltwater intrusion of groundwater. As sea levels rise, pipelines may also be increasingly at risk from flooding that can expose buried pipe, making it susceptible to impact from flood-borne debris (DOE 2013). Pumping stations, terminals, low-lying railroad equipment and other fuel transport infrastructure near the coast are also at increased risk of damage from flooding and erosion as sea level rise accelerates.

Fuel Transport

Resilience Solutions

Fuel transport assets, including port facilities, can be hardened to mitigate the risks from sea level rise, reducing the likelihood of damaging coastal erosion and flooding events. For instance, sea walls and natural barriers such as wetlands can dampen the impacts of sea level rise and prevent coastal erosion in some instances. Pipelines may be upgraded to more robust materials such as coated steel or plastics to prevent corrosion and damage from flood-borne debris. Another resilience measure is elevating or relocating critical equipment such as pumping stations, port assets, and railroad structures out of coastal floodplains. For example, the McDonald Island natural gas storage facility is designed so that the compressor and wellhead controls can still operate under a 20 foot head of water (Sathaye et al. 2012). Some equipment can also be sealed in waterproof enclosures to prevent damage during flood events (DOE 2010). Planning for future sea level rise when siting and designing coastal transport infrastructure will improve long term resilience.

Regional Climate Change Observations and Projections in Detail

Higher Temperatures

Historical observations

- **Since 1895, temperatures have increased an average of 0.17°F per decade, or almost 2°F** (NOAA 2013).
- **Heat waves are occurring more often and cold waves less often:** For 1895–2011, there is a statistically significant increase in the number of heat waves across the region (NOAA 2013).

Future projections

- **Average temperatures are expected to increase at a faster rate, with summer and autumn increases most severe:** Under a higher emissions scenario (A2), temperatures are projected to increase 5.5°F–8.5°F by the end of the century (2070–2099, compared to the climate of 1971–1999), with the lowest increases along the coast. Under a lower emissions scenario (B1), increases may be 3.5°F–5.5°F (NOAA 2013).
- **Extremely hot days are projected to become more common, and consecutive number of days of extreme heat are expected to grow longer:** In the southern part of the region, especially in deserts, arid regions, and high plains, 25–40 more days with a daily maximum temperature >95°F are expected by mid-century (2041–2070, compared to 1980–2000), and the maximum number of consecutive hot days is projected to increase by 16–32; through most of the rest of the region, 10–25 more extremely hot days per year are projected, with annual maximum consecutive hot days growing by 4–16 (NOAA 2013).
- **Cooling degree days (CDDs) are expected to increase:** In much of the region, an increase of 400–1,000 CDDs is expected by mid-century (2041–2070, compared to 1980–2000); increases of 200–400 CDDs are expected in northern parts, and fewer in the Rockies (NOAA 2013).
- **Heating degree days (HDDs) are expected to decrease, cold nights to occur less frequently, and freeze-free season to grow:** The northern and mountainous parts of the region are expected to experience a decline in HDDs of 1,100–1,700 by mid-century (2041–2070, compared to 1980–2000); in the south and along the coast, declines of 500–1,100 HDDs are projected. The freeze-free season is expected to be 20–45 days longer by mid-century, and days with daily minimums less than 10°F are no longer expected to occur, except in high-elevation areas (NOAA 2013).

Changing Water Patterns and Wildfires

Historical observations

- **More winter precipitation has been falling as rain rather than as snow:** Across western mountain regions, October-to-March snow water equivalent (SWE), normalized by total precipitation, has fallen over the period 1950–1999, with a strong indication that up to 60% of the changes are due to climate change (Barnett et al. 2008).

Future projections

- **Annual mean precipitation is expected to decrease:** Under a higher emissions scenario (A2), end-of-century (2070–2099) precipitation is projected to be 3%–12% lower in the southern portion of the region than the period 1971–1999. Under a lower emissions scenario (B1), models are less certain (NOAA 2013).
- **Spring and summer are projected to be drier and winter wetter:** Spring and summer average precipitation may decline by more than 15% in parts of the region by mid-century (2041–2070, compared to 1971–2000); summer coastal precipitation is projected to increase more than 15%; winter precipitation is generally expected to increase, with regions seeing greater than 15% increases (NOAA 2013).
- **Periods with little or no precipitation are likely to become longer:** Across most of the region, the annual maximum number of consecutive days with less than three millimeters of precipitation is projected to increase 5–25 days per year by mid-century (2041–2070, compared to 1980–2000). Projected increases are smallest in eastern Colorado (NOAA 2013).
- **Snowpack may decline across the region:** By mid-century (2041–2070), April 1 SWE is projected to fall by more than 40% compared to 1971–2000 (Cayan et al. 2013).
- **Streamflow in many major basins is expected to decline:** By the 2070s, annual streamflow in the Klamath, Sacramento–San Joaquin, Colorado, and Rio Grande rivers is projected to decline relative to the 1990s (USGCRP 2014). For all but the Colorado River, declines are projected to be greatest between April and July (USGCRP 2014).
- **Droughts are expected to intensify across the region:** Future droughts in the region, and especially in the Colorado River watershed, are projected to become more frequent, intense, and longer-lasting than in the historical record (USGCRP 2014).
- **Risk of wildfire is expected to increase:** The area of land burned in wildfires is projected to increase, including a doubling of area in the southern Rockies by mid-century (2041–2070, compared to 1970–2006) and an almost 75% increase in northern California by end-of-century (compared to 1960–1990) (USGCRP 2014).

Sea Level Rise

Future projections

- **Sea level rise is expected to accelerate:** Along most of the California coastline (south of Mendocino), relative sea levels are projected to increase by 17–66 inches by 2100 compared to 2000, depending on emissions scenario and other uncertainties (NRC 2012).

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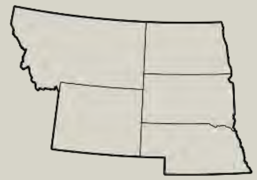
Chapter 3 Endnotes

[a] Source: NOAA 2013
[b] Sources: DOE 2013, NOAA 2013, USGCRP 2014
[c] Sources: NOAA 2013, USGCRP 2014
[d] Sources: DOE 2013, Tiedeman et al. 2014, USGCRP 2014
[e] Sources: Cayan et al. 2013, NOAA 2013, USGCRP 2014
[f] Sources: AEG and Cubed 2005, Garfin et al. 2013, Vicuna et al. 2007, USGCRP 2014
[g] Source: USGCRP 2014
[h] Sources: Sathaye et al. 2012, USGCRP 2014
[i] Sources: NOAA 2013, USGCRP 2014
[j] Changes in CDDs are regional (see Figure 2), compared to 1980–2000 (NOAA 2013). Increases in *per capita* average peak demand by end of the century compared to 2003–2009 under A2 scenario (Sathaye et al. 2012).
[k] Sources: NOAA 2013, NRC 2012, USGCRP 2014
[l] Capacity reductions represent effects of increased ambient temperature on California's natural gas-fired generators and include projections of incremental increased temperature in 2070–2099 (Sathaye et al. 2012). Coal plants identified by NETL 2010. There are 25 plants located in 100-year floodplain assuming 1.4 meter relative SLR (Climate Central 2014a).
[m] Sources: Cayan et al. 2013, NOAA 2013, USGCRP 2014
[n] 1971–2000 compared to 2070–2099 (USGCRP 2014)
[o] Sources: NOAA 2013, Sathaye et al. 2012, USGCRP 2014
[p] Increases in transmission line and substation capacity losses are for California, by the end of the century, depending on region, and compared to current levels (Sathaye et al. 2012).

Chapter 4: Northern Great Plains

Climate Change and the Energy Sector



Overview

The Northern Great Plains is home to less than 2% of the U.S. population but is a major supplier of critical energy resources used throughout the nation. These resources include coal from the Powder River Basin, electricity exported via interstate transmission lines, and rapidly growing oil production from the Bakken formation. Extensive rail and pipeline networks transport energy resources across the region. Major climate change impacts projected to increasingly threaten the region's energy infrastructure include the following:

- **Climate change is projected to increase both the frequency and severity of heavy precipitation events in northern states, increasing heavy runoff and the risk of flooding.**[a] Floods threaten low-lying assets such as power plants, oil and gas facilities, and rail lines located in flood plains, and they can disrupt delivery of fuels and damage infrastructure.[b]
- **Average temperatures are projected to increase, and extremely hot days are projected to occur more frequently. Heat waves are likely to become more frequent, more severe, and longer-lasting.**[c] Extreme heat can delay or disrupt rail service, affecting fuel shipments. As air and water temperatures rise, thermoelectric power plants operate less efficiently, and electricity demand for cooling increases. Higher temperatures also cause sag and increase resistance in transmission lines. Together, these effects may reduce available power supply during the hottest months when demand is highest.[d]
- **Decreasing water availability is projected in the summer for parts of the region as a result of seasonal changes in precipitation patterns from climate change and competing uses for water.**[e] Limited water availability may reduce the availability of thermoelectric power generation and affect biofuel production and oil and gas operations. Power plants, biorefineries, and agriculture are all major water users and require more water as temperatures increase. Competing uses for water, such as crop irrigation, may also contribute to limited availability.[f]

QUICK FACTS

Northern Great Plains States:	Montana, Nebraska, North Dakota, South Dakota, Wyoming	
Population (2013)	5,036,423	(1.6% of U.S.)
Area (square miles)	464,000	(13% of U.S.)
Energy expenditures	$33 billion	

ENERGY SUPPLY & DEMAND		**Annual Production**	**Annual Consumption**	***% for electric power***
Electric power	*TWh*	160	88	*n/a*
Petroleum	*MMbbls*	333	166	*1%*
Coal	*million tons*	466	85	*88%*
Natural gas	*Bcf*	2,280	528	*3%*

ELECTRIC POWER	**Annual Production (TWh)**	***% of Total Production***	**Capacity (GW)**	**Power plants >1 MW***
Natural gas	2	*1%*	4	55
Coal	114	*71%*	18	42
Nuclear	6	*4%*	1	2
Hydroelectric	22	*14%*	5	55
Wind	15	*9%*	5	72
Biomass	<1	*<1%*	<1	4
Solar	0	*0%*	0	0

CRITICAL INFRASTRUCTURE

Petroleum		**Electric Power**	
Wells (>1 boe/d):	15,900	Power plants (> 1 MW):	277
Refineries:	11	Interstate transmission lines:	18
Liquids pipelines:	29	**Coal**	
Ports (>200 tons/yr):	0	Mines:	28
Natural Gas		**Waterways**	
Wells:	29,000	Coal and petroleum routes:	1
Interstate pipelines:	26	**Railroads**	
Market hubs:	1	Miles of freight track:	13,500

Note: Table presents 2012 data except number of oil wells, which is 2009 data.
*Some plants use multiple fuels, and individual generating units may be <1 MW.
Sources: AAR 2014, EIA 2011, EIA 2013a, EIA 2013c, EIA 2014b, EIA 2014e, EIA 2014m, EIA 2014n, EIA 2014o, EIA 2014p, EIA 2014q, USACE 2014, US Census Bureau 2014

Table 4-1. Examples of important energy sector vulnerabilities and climate resilience solutions in the Northern Great Plains

Subsector	Vulnerability	Magnitude	Illustrative Resilience Solutions
Fuel Transport	Increased disruption from roadbed washouts and erosion from heavy precipitation and flooding[g]	From the Bakken fields, rail accounts for more than 70% of total oil shipments and 100% of deliveries to the West Coast[i]	Preventive maintenance, track inspection, and reliability standards[k]
	Increased disruption of coal and oil by rail from extreme heat and rail buckling[h]	Almost 50% of the coal produced in the United States travels along a small number of central rail lines in the region[j]	Improved detection of track defects including buckling and weak points[l]
Thermoelectric Power Generation	Reduced efficiency from increasing air and water temperatures and decreasing water availability	The region exported over 70 TWh of electricity in 2012, so reductions in available generation may also affect neighboring regions[m]	Alternative water sources, recirculating, dry, or wet-dry hybrid cooling systems
Electricity Demand	Increased electricity demand in the summer from higher temperatures[n]	An additional 200–800 CDDs per year is projected by mid-century for most of the region[o]	Capacity expansion, energy efficiency, and demand-side management programs

Regional Energy Infrastructure Vulnerabilities and Resilience Solutions

Key energy subsectors and illustrative examples of resilience solutions in the Northern Great Plains are discussed below. System components that are most vulnerable to climate change are described first.

Fuel Transport

Subsector Vulnerabilities

The Northern Great Plains is a major supplier of both coal and crude oil to U.S. energy markets (see sidebar). The Powder River Basin in Wyoming alone produces almost half of the nation's coal (EIA 2012a), and the rapid development of the Bakken shale in North Dakota has made it one of the top-producing oil fields (EIA 2014a). Railways are an integral part of the transportation infrastructure for both of these resources. Rail is also the primary mode of transport for ethanol.

The Northern Great Plains is also traversed by a substantial network of high-capacity natural gas and oil pipelines. The region is the proposed location of several major new crude oil pipeline routes, with 12 crude oil pipeline projects (ranging from 10,000 barrels per day to 800,000 barrels per day) proposed in the region as of 2012 (KLJ 2012). Gas pipelines are also undergoing expansion, largely as a result of the development of coal bed methane and tight sands natural gas in the Powder River Basin and shale gas production in the Bakken formation (EIA 2014g, EIA 2014i). Since 2005, over $17 billion has been invested in natural gas pipelines connecting to states in the Northern Great Plains (EIA 2014h).

Climate change is expected to have the following impacts on fuel transport in the Northern Great Plains:

- Projected increases in the frequency of heavy precipitation, as well as total annual precipitation, may increase the frequency of damage and disruption to railways and pipelines from flooding (CCSP 2008, USGCRP 2014).
- Rising temperatures, including increases in the frequency, severity, and duration of heat waves, may increase the risk of delays and disruptions to rail shipments, as well as cause damage to—and higher maintenance costs for—rail infrastructure (USGCRP 2014).

Annual precipitation (Figure 4-3) and the frequency and severity of heavy precipitation events are projected to increase in the northern and eastern portions of the area (NOAA 2013a), increasing the risk of flooding impacts on fuel transport.

Powder River Basin coal

The nine largest U.S. coal mines are located in the Powder River Basin (EIA 2014o). Coal from Wyoming supplies power plants in more than 30 states (EIA 2014b). In the western United States, a small number of routes handle very large amounts of coal. Much of this coal is transported in trains of 120 coal cars going from a single mine to a single power plant over distances that can exceed 1,000 miles (EIA 2012b, EIA 2014c).

The Joint Line, a 100-mile rail line, links Powder River Basin coal to the nation's rail network. The Joint Line is the busiest freight railroad in the world as measured by gross ton-miles. Approximately 130 trains, weighing as much as 19,000 tons, move on the Joint Line on a normal day (DOE 2007).

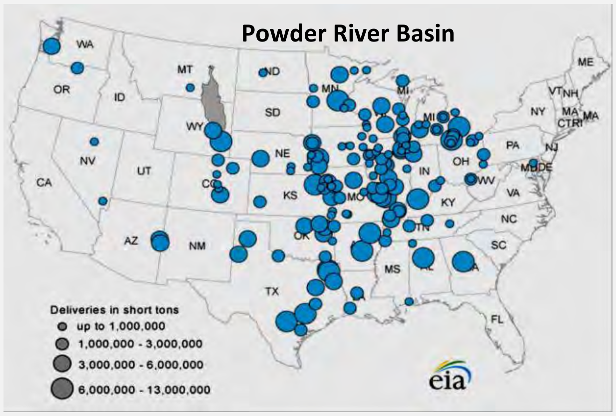


Figure 4-1. Coal deliveries by rail from the Powder River Basin
Source: EIA 2012b

Bakken oil

Crude oil production in the Bakken shale formation of North Dakota has increased more than 750% since 2007 (EIA 2014d). North Dakota currently produces over one million barrels per day, representing over 10% of domestic oil production (EIA 2014e). As the region's crude oil resources become more important to the national energy economy and pipeline capacity remains limited (EIA 2014f), railroads are playing a more important role in transporting crude oil (CRS 2014, EIA 2012c, EIA 2012d).

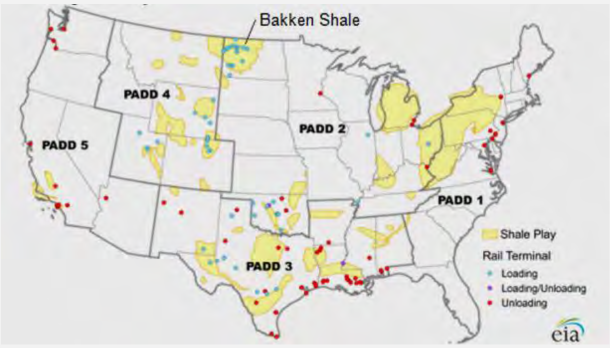


Figure 4-2. Crude-by-rail loading (blue) and unloading (red) terminals
Source: EIA 2014f

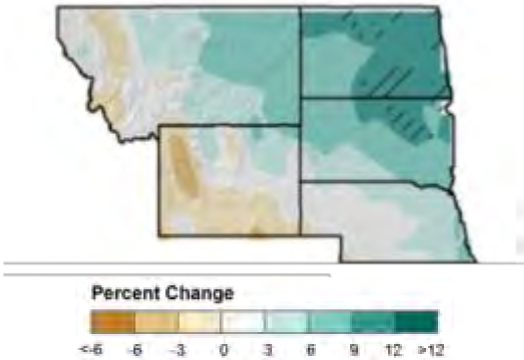


Figure 4-3. Mean change in annual precipitation by mid-century[1]
Source: NOAA 2013c

Both heavy precipitation events and extended periods of rainfall can lead to regional flooding events (NOAA 2013a). Heavy precipitation events can cause high runoff and flooding that can disrupt train traffic and damage submerged track and roadbed (Union Pacific 2011). High streamflows can cause erosion of track beds, especially where railroads run in low-lying areas adjacent to rivers and streambeds (DOE 2013a, USGCRP 2014). In the Red River Valley of North Dakota, one of the most flood-prone rivers in the country, peak streamflows have been steadily increasing from rapid spring snowmelt combined with rainfall (Hirsch and Ryberg 2012, NOAA 2013a).

Intense precipitation events and flooding can also affect buried pipelines by eroding soil cover and exposing the pipeline to damage from flowing water and collisions with flood debris or even vehicles or boats (DOE 2013a, DOT 2014, NRC 2008). Pipelines that are near creeks, rivers, or where water is funneled away are more vulnerable to erosion (DOT 2014). Intense precipitation can also cause ground subsidence, where the soil underneath the pipeline sinks, causing stress on the pipeline structure (NRC 2008). A flooding event in Montana was a key contributing factor in the rupture of the ExxonMobil Silvertip Pipeline that resulted in damages of more than $100 million (DOE 2013a). Historically, however, pipeline damage from natural events is responsible for only a small fraction of damages to pipelines; corrosion and equipment failure are the biggest causes of accidental crude oil pipeline releases (DOT 2012).

Any damage or disruption to major interstate and international pipelines crossing the Northern Great Plains could have a significant impact on energy markets outside the region. Several of the largest interstate natural gas pipelines that operate in the region deliver to customers outside of the region (EIA 2014i).

Temperature increases due to climate change and increased rail traffic may cause the rails to exceed temperature design limits, which can cause track buckling under heat stress (also known as "sun kinks," pictured in Figure 4-4) (CCSP 2008, NRC 2008). Tracks buckle when excessive compressive stress along the track leads to deformation or misalignment (Volpe 2003). Compressive stress can come from both increased track temperature (as the rail material expands) and loading from train traffic (FRA 2011). Since 2003, there have been 49 derailments in the Northern Great Plains directly attributable to buckled or sun-kinked track, and the average temperature at the time of derailment was about 89°F (FRA 2014).

Figure 4-4. Examples of track buckling
Source: Volpe 2003

Railroad operators respond to high ambient temperatures by slowing traffic along rail lines (called slow orders) and reducing loads to prevent buckling and related derailments (CCSP 2008, FRA 2011). Slow orders are costly, as they consume rail capacity, lead to higher operating costs and delays in deliveries, and increase equipment cycle time, requiring railroads to maintain larger fleets (CCSP 2008).

Fuel Transport

Resilience Solutions

Risks to railroads from increased flooding can be mitigated through system and track upgrades, but they can be costly. Resilience solutions include upgrading drainage systems, ensuring culverts can handle increased runoff from heavy precipitation events, and increasing pumping capacity in tunnels (DOT 2009). Policy measures that restrict new rail line development in floodplains, revise standards for drainage capacity or elevating tracks, or require more frequent track inspection can also improve resilience. Track integrity inspections are shifting from visual methods to sophisticated sensing techniques operated from vehicles such as hi-railers (trucks that ride on rails).

Resilience of natural gas and liquid fuels transmission pipelines could be improved by upgrading to pipes made from more robust materials such as coated steel or modern plastics. Pipeline operators may also install barriers (such as berms) or plant grass above pipelines to reduce the risk of erosion and subsequent exposure of buried pipelines, and horizontal directional drilling can be used to bury pipelines deeper to reduce the risk of pipeline exposure (Brown 2013, DOT 2014, Miller & Bryski 2012). After the Silvertip pipeline ruptured in Montana, ExxonMobil was ordered to replace

[1] Projected changes for mid-century (2041–2070) relative to the end of the last century (1971–2000) under an A2 emissions scenario

the existing Yellowstone River, Clarks Fork, and Rock Creek river crossings with horizontal directionally drilled pipelines (Katchmar 2012).

Examples of rail damage and disruption

2011: Exceptional spring rains, combined with rapid snowmelt, produced flooding in the Missouri River basin, threatening Union Pacific's Central Corridor line near North Platte, Nebraska. When the Platte River began to carve a new channel near the rail line, the Nebraska National Guard and Nebraska Highway Department contributed to an effort to build an emergency levee. During the same floods, levee breaks on additional Union Pacific lines near Omaha, Nebraska, led to closures for portions of June and July. To reopen the line, rail workers raised the track bed before the floodwaters had receded (Union Pacific 2011).

2007: Severe flooding in March and April resulting from a blizzard significantly disrupted service on the Powder River Basin's Joint Line. Rail facilities were shut in, and 170 rail loadings were cancelled (DOE 2007).

2005: Greater-than-normal rainfall and accumulating coal dust caused a series of three major derailments and significant damage to Powder River Basin's Joint Line. The derailments caused significant delays in coal deliveries and led to a restriction on new customers that lasted almost two years. Many power plant customers were forced to draw down stockpiles because of delayed or cancelled deliveries, and some had limited coal supplies for the summer when high temperatures led to greater-than-normal energy demand. Following the derailments, production at Powder River Basin mines was curtailed for several months, and problems with deliveries to generators persisted through the spring of 2006 (DOE 2007).

Temperature impacts affecting railroads can be reduced by incorporating climate projections into design considerations when replacing tracks. Rails are designed to withstand temperature gradients based on expected ambient temperatures and heat generated from railcar traffic (FRA 2011, Volpe 2003). Railroad companies that are incorporating higher baseline temperatures into their planning would most likely upgrade tracks when they are replaced for other reasons, including normal wear and tear, upgrades for traffic reasons, or damage from other extreme events, including flooding (CCSP 2008).

Management practices, such as ensuring rails are regularly inspected for signs of damage, can also increase resilience to climate impacts. Manual inspection remains the preferred method to detect erosion damage, buckles, and sun kinks, although rail breakage can be inspected via the application of an electrical current to detect faults remotely (CCSP 2008, Volpe 2003).

Thermoelectric Power Generation

Subsector Vulnerabilities

Electricity from coal-fired thermoelectric power plants dominates the generation mix in Northern Great Plains states (Table 4-2).

Table 4-2. Electricity generation by type for states in the Northern Great Plains

Generator Type	MT	ND	NE	SD	WY	Total
Coal	50%	78%	73%	24%	88%	**71%**
Hydroelectric	41%	7%	4%	50%	2%	**14%**
Wind	5%	15%	4%	24%	9%	**9%**
Nuclear	0%	0%	17%	0%	0%	**4%**
Natural Gas	2%	0%	2%	2%	1%	**1%**
Other	3%	0%	0%	0%	1%	**1%**

Source: EIA 2013c

Climate change is projected to have the following impacts on thermoelectric power generation in the Northern Great Plains:

- Higher average and extreme temperatures are expected to reduce electricity generation and transmission capacity (DOE 2013a, USGCRP 2014).
- Reduced precipitation in the southern and western portions of the region, as well as higher evaporative loss from reservoirs, may affect water availability for thermoelectric power generation (DOE 2013a, NOAA 2013a, USGCRP 2014).
- Increased average and extreme precipitation may heighten the risk of damage or disruption caused by flooding (NOAA 2013a).

Projected changes in precipitation and temperature—both independently and in combination—may restrict the available capacity of thermoelectric power generation in the region. The efficiency of thermoelectric power generation decreases with increasing air and water temperatures (DOE 2013a). Because of projected increases in average and extreme temperatures in the Northern Great Plains, climate change may reduce regional power generation capacity during times of high demand for cooling (USCGRP 2014). Furthermore, high air temperatures reduce transmission capacity (DOE 2013a), which can compound problems of reduced power supply. As shown in Table 4-3, all states in the region except South Dakota export electricity to other states, and capacity restrictions may affect neighboring regions.

Table 4-3. Net interstate trade of electricity for states in the Northern Great Plains, Terawatt-hours (2012)

MT	ND	NE	SD	WY
12.8	21.5	0.8	-0.5	30.1

Source: EIA 2014u

As shown in Figure 4-5, precipitation is projected to increase throughout the region during the winter, but precipitation is projected to decrease in the southern and western portions of the region during warmer seasons, when demand for power is highest. Affected regions include Montana, Nebraska, and Wyoming (NOAA 2013a).

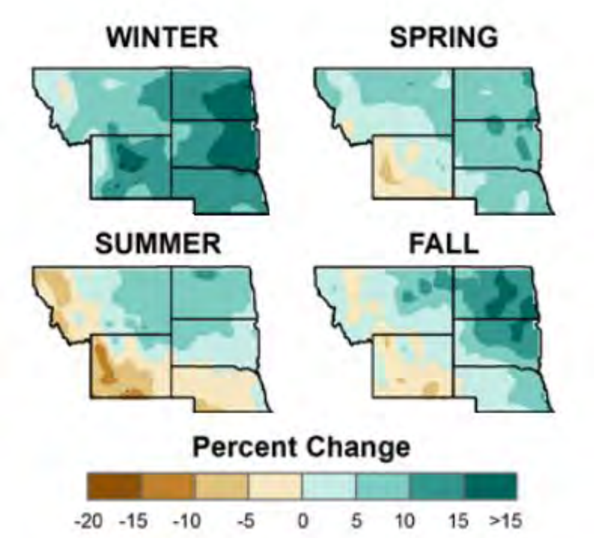


Figure 4-5. Change in seasonal precipitation by mid-century[2]
Source: NOAA 2013c

Decreased availability of water could pose an operational risk to thermoelectric facilities using freshwater for cooling (DOE 2013a). For example, the Platte River, which flows through Wyoming and Nebraska, is a heavily managed and over-appropriated river system (NOAA 2013a). The coal-fired power plants using the Platte River and its tributaries for cooling water are vulnerable to water stress (DOE 2013a). When water shortages occur, power plants in the region are likely to draw from groundwater and compete with irrigated agriculture for scarce water resources (NETL 2009, UCS 2011).

Projected increases in extreme heat could accelerate the loss of surface water reservoirs through evaporation and may compound local water scarcity issues. Across most of the region, 5–20 more days with a daily maximum temperature >95°F are projected by mid-century (NOAA 2013a). Nebraska is likely to be the most affected, including increases of as many as 25 more extremely hot days per year projected (NOAA 2013a). Moreover, because high temperatures decrease thermal efficiency of power generation (DOE 2013a), more extreme high-temperature days could compound the risks to these facilities, particularly during periods of low water availability.

[2] Projected changes for mid-century (2041–2070) relative to the end of the last century (1971–2000) under an A2 emissions scenario

Thermoelectric power plants are also vulnerable to flooding. They are typically located near rivers or other sources of water and are susceptible to physical damage and disruption from flooding. The eastern portion of the Northern Great Plains has experienced an increasing frequency and magnitude of flooding events (Hirsch and Ryberg 2012) and is projected to see higher levels of total precipitation and heavy precipitation events as a result of climate change (NOAA 2013a).

Examples of impacts to power plants from flooding and limited water availability

2011: Missouri River floodwaters surrounded Fort Calhoun Nuclear Power plant in Nebraska. The nuclear reactor remained closed during the summer because of persistent flood waters (DOE 2013a).

2008: Owners of the 1,710 MW Laramie River Station in Wyoming installed a 90,000-foot-long pipeline to deliver groundwater to supplement water from the Grayrocks Reservoir, but a drought lowered the reservoir to 10% of its capacity and forced the utility to purchase water from the Wheatland Irrigation District (NETL 2009, UCS 2011).

2004: The Nebraska Public Power District spent $12 million and installed 40 wells at its 1,300 MW coal-fired Gerald Gentleman Station to ensure there would be enough water in the event that its reservoir goes dry (NETL 2009).

Thermoelectric Power Generation

Resilience Solutions

New generation capacity can help address falling capacity due to decreased plant efficiency during periods of higher air and water temperatures. New generation capacity with sources and supply chains less affected by increasing temperatures and decreased water availability (e.g., wind and solar photovoltaics [PV]) may help make the region's power sector more resilient to climate change. Programs that reduce total and peak electricity demand can also reduce the water needs of thermoelectric generators.

Water scarcity has already threatened major power plants in the region, and several generation facilities have undertaken major infrastructure projects to ensure access to alternative sources of water (NETL 2009). Many facilities have installed recirculating water cooling systems, which withdraw significantly less water than once-through plants (DOE 2013a). Power plant owners in the Northern Great Plains have turned to groundwater to supply cooling water needs when surface water reservoirs have reached critically low levels. Future competition for limited surface and groundwater resources may lead power plants to consider adoption of more water-efficient cooling technologies (e.g., dry cooling, wet–dry hybrid cooling, etc.), use of nontraditional water (e.g., saline and brackish groundwater, municipal waste water, etc.), and additional water conservation measures.

Diversification of power generation sources to fuels requiring little or no water input, such as wind power and solar photovoltaic systems, may help to make the region's power sector more resilient to water scarcity events. For example, in response to Minnesota's Renewable Portfolio Standard (RPS) and North and South Dakota renewable energy objectives, the Otter Tail Power Company has expanded its wind generation resources, which require no cooling water. Through the TailWinds program, customers can choose to purchase 100% of their electricity from wind generation (Otter Tail Power Company 2014).

Programs that reduce total and peak electricity demand can also reduce the water needs of thermoelectric generators, as discussed in the Electricity Demand section.

Engineered barriers such as levees can be effective in protecting vulnerable thermoelectric power plants from flooding during heavy precipitation events. Utilities may also elevate critical equipment to protect against flooding or upgrade low-lying components with submersible equipment or watertight doors. Planners can protect new capacity by locating new equipment at higher elevations or outside of flood plains.

Electricity Demand

Subsector Vulnerabilities

The Northern Great Plains exports more than 50% of the electricity generated in the region and on the whole has sufficient generating capacity to meet increased demand within the region (EIA 2014b). However, neighboring states that receive electricity exports from the Northern Great Plains states, including states in the Midwest, Southwest, and Southern Great Plains, may be affected if local demand grows or generating capacity falls.

The region is situated far from the moderating effects of the oceans and has a distinctly continental climate, with average low temperatures in January about 0–15°F and average high temperatures in July about 80–88°F (NOAA 2015). Like other regions with cold winters, the Northern Great Plains uses primarily natural gas for space heating, with electricity a distant second (EIA 2014l, EIA 2014r). The region's power consumption is typically summer-peaking, with utilities in the region experiencing peak demand about 16% higher in summer than in winter (EIA 2013b). Much of the electricity demand is driven by non-residential uses, including irrigation, food processing, fertilizer and pesticide production, and manufacture of farm and construction equipment (EIA 2014b).

Climate change is projected to have the following impacts on electricity demand in the Northern Great Plains:

- Higher maximum temperatures, longer and more severe heat waves, and higher overnight lows are expected to increase electricity demand for cooling in the summer (DOE 2013a, NOAA 2013a).

Hotter summers will increase electricity demand for air conditioning and refrigeration, while warmer winters may lead to reduced heating demand, with the summer increase in electricity demand outweighing the winter decrease (USCGRP 2014). As shown in Figure 4-6, an increase of 200–800 cooling degree days (CDDs) per year is projected by mid-century for most of the region, with the exception of the higher elevations of Montana and Wyoming (USGCRP 2014). Although the annual CDDs in the region are lower than most other regions, an increase in CDDs may lead to an increased proportion of households and businesses installing air conditioning units (USGCRP 2014). For example, Williston, North Dakota, is projected to experience 200–400 additional CDDs, which is an increase of 43%–86% compared to its historical average (NOAA 2013b). In addition, buildings already with air conditioning are expected to increase electricity demand for cooling (USGCRP 2014).

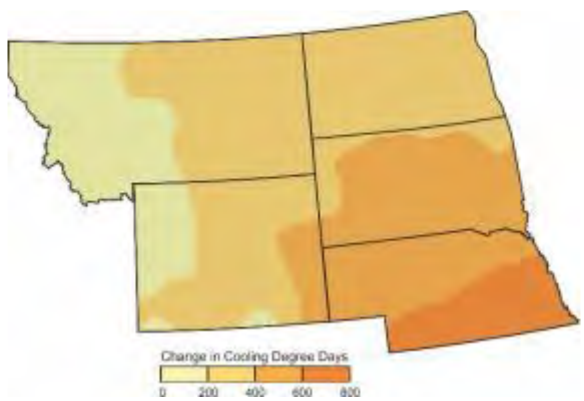


Figure 4-6. Change in annual CDDs by mid-century[3]
Source: NOAA 2013c

Climate change is only one of several factors projected to drive changes in demand for electricity. Population shifts from rural to urban areas and electricity use associated with growing oil production in the Bakken region are also altering the demand profile, as well as other unrelated changes to demand resulting from new devices and technologies. One study projects electricity demand (electrical load) in the Bakken region will increase more than 200% in 20 years, from 1,209 MW in 2012 to 3,721 MW in 2032, excluding demand shifts expected due to climate change (KLJ 2012).

[3] Projected changes for mid-century (2041–2070) relative to the reference period (1980–2000) under an A2 emissions scenario

With the region being a net exporter of electricity, there is likely adequate electricity supply to meet additional demand. However, shifting demand loads within the region may also require additional investments in transmission capacity to reach the expanding areas (Basin 2014), which is further discussed in the Electric Grid section.

Electricity Demand

Resilience Solutions

Capacity expansion, energy efficiency, load management, and other programs administered by regional power producers can help reduce total electric power demand and peak loads. Power producers in the Northern Great Plains states have already implemented a number of demand-side management practices to reduce the load and improve energy efficiency. These efforts have so far reduced the region's peak load by 2,100 MW, and over 4,000 industrial customers are enrolled in price-responsive programs to reduce consumption during peak demand (EIA 2013b). Because the Northern Great Plains exports electricity outside of the region, measures being implemented in other states can also help mitigate critical summer season peaks.

Demand response resources program

Montana–Dakota Utilities Co. has contracted with Constellation Energy to offer a demand response resources program for commercial and industrial customers. Participants in Montana, North Dakota, and South Dakota agree to curtail non-critical load during demand response events initiated by the utility and will receive financial compensation (both capacity and energy payments) in return (Constellation Energy 2011).

Many agricultural-heavy electric utilities use demand response programs to manage a large number of small users connected to the grid. For example, Nebraska's Dawson Public Power partners with agricultural customers who allow the utility to control the electric usage of these systems when demand for electricity is high (EIA 2014j).

Energy storage systems provide one potential solution to addressing the region's changing demand profile. The region has seen expanding wind power assets, with net generation from wind power increasing by over 300% from 2002 to 2012, and storage systems could allow these intermittent sources to store generated energy and then deliver it when needed (EIA 2013c).

Capacity expansions may also help alleviate growing demand for electricity, especially in remote areas where the cost of installing new transmission capacity is high. Owing to the region's extensive wind resources, new generation is likely to include expanded wind capacity (NREL 2014). For example, Montana–Dakota Utilities Co. announced in 2013 that, to meet growing customer demand, the company was purchasing a 107 MW wind farm (Capital Journal 2014).

Electric Grid

Subsector Vulnerabilities

As Northern Great Plains states are net exporters of electricity, neighboring regions are dependent on a reliable flow of power from those states. The region straddles the divide between the western and eastern electricity grids, with Montana and Wyoming largely part of the Western Interconnection, and most of Nebraska, North Dakota, and South Dakota connected to the Eastern Interconnection. The Northern Great Plains is home to four of the six DC ties between the western and eastern grids (WAPA 2015).

Climate change is expected to have following impacts on the electric grid in the Great Plains North region:

- Higher average and extreme air temperatures are expected to reduce the efficiency and capacity of transmission lines and substations, and may damage power transformers (Bérubé 2007, DOE 2013a).
- Increased wildfire activity in the western, forested part of the region is expected to increase the risk of physical damage to transmission lines and distribution systems (DOE 2013a, USGCRP 2014).

Higher temperatures decrease the current-carrying capacity of transmission lines and reduce the efficiency of substation equipment (DOE 2013a). High temperatures also cause thermal expansion of transmission line materials, and sagging lines increase the risk of power outages when they make contact with other lines, trees, or the ground (DOE 2013a). When energized transmission lines come into contact with vegetation, they can also spark wildfires, potentially leading to much greater damage. Additionally, elevated ambient air temperatures may also put transformers at a greater risk of damage and force operators to reduce the loading of transformers on the hottest days (Hashmi et al. 2013, USBR 2000). Incremental changes in transformer operating temperature lead to exponentially larger rates of irreversible transformer insulation breakdown, so even small increases in ambient air temperatures can lead to extensive damage if protective measures are not taken (Bérubé 2007, Hashmi et al. 2013).

Electricity transmission and distribution infrastructure is also vulnerable to physical damage from increasing wildfires, which can destroy wood poles and steel towers, damage extensive miles of conductor, and foul lines with soot and fire retardant (DOE 2013a). Wildfires can also cause operators to shut down or derate lines to protect them from wildfire-associated heat and smoke (CPUC and DOI 2008, DOE 2013a). Soot and smoke can reduce the electrical resistance of air, increasing the likelihood of tree strikes or arcing between lines. In addition, wildfires remove vegetation and can increase exposure of electricity poles to erosion resulting from subsequent heavy precipitation events.

The risk of wildfires is projected to increase in the mountainous forest and shrubland areas of Montana and Wyoming, as warmer temperatures, increased evapotranspiration, and a longer growing season can dry soils and contribute to a buildup of combustible biomass (USDA 2013). Some ecosystems may experience a four-fold increase or more in the average area burned per year for each 1°C global temperature rise (NRC 2011). Increased wildfire risk areas coincide with the location of several large transmission lines (>345 kV) in the region (Figure 4-7). In 2005, the Tarkio fire burned under two of the Bonneville Power Administration's (BPA's) 500 kV transmission lines in western Montana, causing BPA to preemptively shut the lines down (Montana Standard 2005). In another recent example, the 2012 Ash Creek Complex Fire in southeast Montana caused significant damage to the area's grid as it burned through a major transmission line (KTVQ 2012).

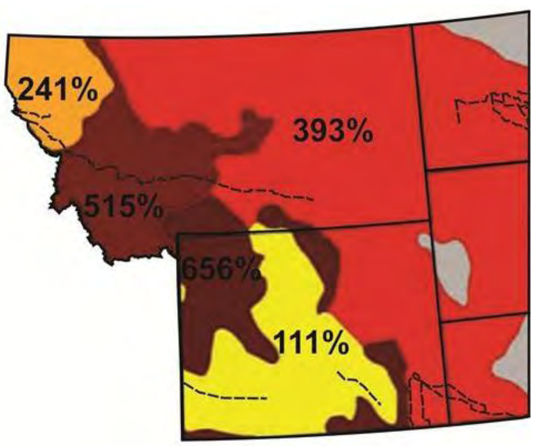


Figure 4-7. Electric transmissions lines (>345 kV), shown by dashed lines on the map, and projected percentage increase in burned areas for a 1°C increase in global average temperature[4]
Sources: NRC 2011, EIA 2014k

Electric Grid

Resilience Solutions

Both operational and hardening measures can be taken to improve the resilience of new and existing transmission infrastructure. The detrimental effects of increased temperatures on grid capacity may require expanding capacity or reducing demand, while assets can be protected from increased fire activity with both system upgrades and improved management practices.

Adding grid capacity and redundancy can increase resilience to falling capacity on extremely hot days, especially as the hottest days will likely see the highest demand for electricity (DOE 2013a). Utility measures to reduce demand, including energy efficiency and load management programs, can also reduce the need for new transmission capacity (DOE 2013a). As the region is a significant electricity exporter, local demand management programs may have limited efficacy when addressing falling transmission capacity on long-distance interstate transmission lines. However, such measures may be effective for reducing burdens on transmission lines connecting small communities to the grid. Such programs are discussed in the Electricity Demand section.

To prevent damage to transformers, operators can reduce transformer loads when air temperatures are high (Hashmi et al. 2013). Operators can also install or upgrade cooling systems for large transformers and invest in newer thermally upgraded transformers (USBR 2000, Bérubé 2007).

Proactive vegetation management is an important practice for increasing resilience to both increasing temperatures and wildfire. Managers can reduce the risk of tree strikes resulting from sagging lines by trimming trees along transmission rights-of-way. Vegetation management is a key practice for reducing transmission line vulnerabilities to wildfire. Active forest management includes measures to reduce build-up of hazardous fuels near key power lines—such as forest thinning and prescribed burning—and reduce the likelihood of human-caused ignition (e.g., campfires, short circuits from faulty equipment on power lines) (CPUC and DOI 2008, DOE 2013a, USGCRP 2014). PacifiCorp, a power company that operates Rocky Mountain Power in the Northern Great Plains and Southwest region, has developed an app to monitor wildfires that could damage lines and disrupt service to customers. The app allows the utility to monitor and protect transmission lines and prevent power outages even when lines are damaged (ESRI 2014).

Strengthening of power lines and towers to resist physical damage, including the installation of steel towers for the most vulnerable lines, can improve the resilience of individual lines to wildfires, limiting damage and expediting restoration (DOE 2013a). Resilience could also be improved through increased redundancy in the transmission networks (DOE 2013a).

Hydroelectric Power

Subsector Vulnerabilities

Hydroelectric generation produces 14% of the region's electric power (see Table 4-2 on page 4-4) (EIA 2013c). Hydroelectric facilities in Montana and South Dakota make up the majority of the region's total output of hydropower,

[4] Wildfire projections are based on temperature and precipitation patterns associated with a 1°C increase in global average temperature and are relative to the median area burned during 1950–2003.

generating about 11 million MWh per year and 6 million MWh per year, respectively (Figure 4-8) (EIA 2013c).

Figure 4-8. Canyon Ferry Dam and Reservoir near Helena, Montana
Source: USBR 2013

Climate change in the Northern Great Plains may affect hydropower in the following ways:

- In the Columbia River Basin, decreasing summer streamflows may reduce downstream hydropower production, and increasing winter and early spring streamflows may increase production (BPA 2011, DOE 2013a, USGCRP 2014).
- In the Missouri River basin, projected seasonal declines in precipitation in the southern and western portion of the region may reduce the water available to generate hydropower (USGCRP 2014).

The Northern Great Plains largely lies to the east of the Continental Divide; however, four dams in Montana are located in the Columbia River Basin on the Flathead, Kootenai, and Clark Fork Rivers (EIA 2014t). Spring snowpack and summer precipitation in far western Montana are expected to decline in a warming climate, contributing to decreased summer streamflows for power plants in the Columbia River Basin (BPA 2011, DOE 2012).

The Missouri River basin stretches across most of the region, and its drainage provides water to many of the hydroelectric generators in both Montana and South Dakota. For example, the Platte River basin in Wyoming and Nebraska, which is part of the Missouri River system, is the source of numerous hydropower facilities (EIA 2014b). The Missouri River basin draws from a large area where climate models project both increasing and decreasing precipitation, depending on the season, location, and emissions scenario. The gradient towards reduced precipitation in the southwestern portion of the region suggests that facilities drawing on water flows from those areas could face reductions in available generating capacity, although there is uncertainty about these projections.

Hydroelectric Power

Resilience Solutions

Most of the Northern Great Plains is projected to see higher precipitation during the winter (Figure 4-5). If excess river flow remains within the reservoir capacities of dams, then hydropower facilities may be able to store the water for generation (DOE 2013a). Otherwise, potentially reduced summer flows may have an impact on generation.

In the western, mountainous parts of the region, forecasting snowmelt timing based on snowpack and temperature trends will facilitate the prediction of seasonal availability of hydropower generation. Leveraging these data resources can improve the resilience of regional power production—not only by supporting the preparation and execution of contingency plans for hydropower production but also by improving the effectiveness of overall regional water management strategies that affect thermoelectric generation and other water users.

Bioenergy

Subsector Vulnerabilities

As a major producer of biofuels, the Northern Great Plains is vulnerable to climate impacts that affect the cultivation, transportation, and conversion of crops to fuel. Bioenergy production and consumption in the region is dominated by ethanol production from corn and also includes a small amount of biodiesel from canola oil and electricity generation from captured landfill and wastewater gases.

The region is home to almost a quarter of the nation's ethanol refining capacity, with operational facilities capable of producing 3.2 billion gallons of ethanol per year (Figure 4-9) (NEO 2014). Of the 48 ethanol biorefineries in the region, all but one use corn as a feedstock (RFA 2014). The region harvested 22% of the nation's corn acres in 2013 (USDA 2014).

Figure 4-9. Industrial biorefinery in York County, Nebraska
Source: ORNL 2006

Climate change in the Northern Great Plains may affect bioenergy production in the following ways:

- Increasing temperatures may benefit certain crops, but extreme temperatures may harm them; warmer temperatures may also benefit weeds, disease, and pests (USGCRP 2014).
- Lower numbers of freezing days and a lengthening of the frost-free growing season may extend the range where biofuel crops can be grown (Bjerga 2012, NOAA 2013a, Roberts and Schlenker 2011).
- Changes to precipitation and evapotranspiration, including an increasing risk of periodic drought or floods, may either benefit or harm agricultural production (NOAA 2013a, USGCRP 2014).

Climate change impacts on corn growth are complex, with a mix of outcomes depending on the region, and are evolving over time. Changes in the length of the frost-free season in the plains are projected to be favorable, with increases of 15–24 days per year by mid-century, depending on the location (NOAA 2013a). A longer growing season will improve northern farmers' ability to grow a more diverse set of crops, expanding from wheat in the northern parts of the region to include both corn and soy (Bjerga 2012, Roberts and Schlenker 2011). Plant growth is generally aided by increased average temperatures and CO_2 levels; however, beneficial effects to crops may be outpaced by adverse impacts such as increased growth of weeds and survival of diseases and pests farther north as winters warm (USGCRP 2014). Projected increases in winter and spring precipitation may also benefit agricultural productivity as soil moisture reserves are recharged, although increased heavy precipitation events can erode soils, flood fields, and damage or destroy crops (USGCRP 2014).

Higher temperatures increase evapotranspiration, and declining summer precipitation may increase instances of drought (USGCRP 2014). In 2012, drought coincided with a 16% decline in Nebraska corn production compared to 2011 levels, and surface water irrigation withdrawals were halted in some areas to maintain sufficient streamflow (Plume 2012, USDA 2012a, USDA 2014). The corn shortage resulted in Nebraska's ethanol plants operating at 70% of capacity, and eight ethanol plants in Nebraska and Minnesota stopped production (Nebraska Ethanol Board 2012, Salter 2013).

Biorefineries are also vulnerable to decreasing water availability during drier summers and periods of drought (DOE 2013a, USGCRP 2014). Biorefineries use about 2.7 gallons of water per gallon of ethanol produced (Wu et al. 2011). A typical 100 million gallon-per-year ethanol plant requires approximately one million gallons of water per day (DOE 2013a).

Bioenergy

Resilience Solutions

Resilience strategies for agriculture include diversification of crops, increased and efficient application of pesticides, and additional practices associated with sustainable agriculture, such as no-till farming to better retain soil moisture and reduce erosion (USGCRP 2014).

Although water efficiency in biorefineries has significantly improved over the past decade, there are additional opportunities for process improvements (Wu et al. 2011). Freshwater demand could be substantially reduced by recycling water or using alternative water resources (DOE 2013a). For example, Tharaldson Ethanol LLC in Casselton, North Dakota, uses wastewater from Fargo, North Dakota, as its main source of water (Schuh 2010).

Water use efficiency in cellulosic ethanol plants

The Dakota Spirit AgEnergy cellulosic ethanol plant is expected to function as a prototype for a high level of water-use efficiency when it is constructed. The plant in Jamestown, North Dakota, will use steam from the Spiritwood Energy Station, an electricity generating station that uses wastewater from the City of Jamestown as its main water source (Schuch 2010).

Oil and Gas Exploration and Production

Subsector Vulnerabilities

The region's oil and gas industry is driven by increasing crude oil production from the Williston Basin's Bakken and Three Forks formations in North Dakota and eastern Montana. Advances in drilling methods and technology, high oil prices for the past decade, and a better understanding of the geology of the Bakken have contributed to the growth of the region's oil industry (EIA 2014s).

Climate change is projected to affect oil and gas exploration and production in the Northern Great Plains as follows:

- Declining water availability in the summer may increase costs for oil production operations, which require freshwater resources (DOE 2013a, USGCRP 2014).
- More frequent and intense heavy precipitation events increase the likelihood of associated flooding, which could damage facilities and disrupt operations (DOE 2013a, USGCRP 2014).

Under a high emissions scenario, some models project summer precipitation to decline in the Missouri River basin (USGCRP 2014). Decreasing precipitation in the summer and warmer temperatures accelerating evaporation of surface water could limit local water available in the Bakken region for oil and gas operations, which mainly uses surface water sources such as Lake Sakakawea in North Dakota

(Figure 4-10). Other surface water systems in the Bakken region do not provide a reliable source of water because of seasonal flow variations (NDIC 2010). Lake Sakakawea is a main water supply source for competing uses, such as the large agriculture sector, and decreasing water availability can increase costs and amplify current challenges for the oil industry in obtaining water. Water used in North Dakota's Bakken for hydraulic fracturing can be as high as 60,000 barrels (bbl) (3 million gallons) per shale well, depending on the number of stages in the fracture. Companies must truck water to many well site locations in 7,500–8,000 gallon tanker trucks, and resulting transport costs can lead to purchased water costs ranging from $0.88/bbl to $6.05/bbl (NDIC 2010).

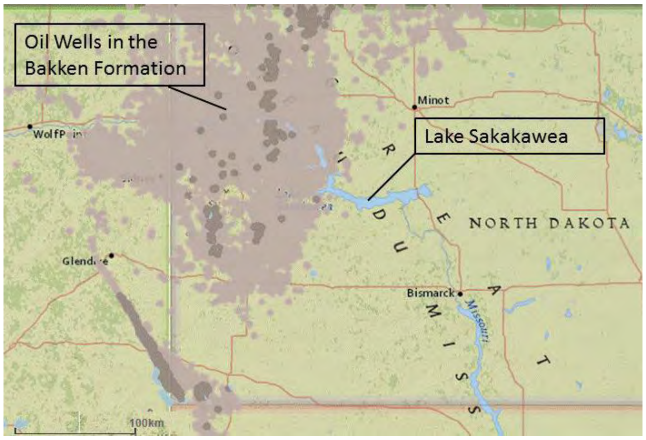


Figure 4-10. Proximity of Lake Sakakawea to Bakken oil and gas operations
Source: EIA 2014k

While seasonal water availability could decline, annual average precipitation and heavy rainfall events are expected to increase (NOAA 2013a). Extreme precipitation events cause large volumes of runoff to flow quickly over farmland and rangeland into streams and rivers, increasing the chance of overland and river flooding. Oil and gas equipment and operations in low-lying areas are susceptible to physical damage and disruption from floods. In June 2015, North Dakota oil regulators ordered an oil producer to shut-in 15 oil wells near the confluence of the Missouri River and Yellowstone River after more than 1.5 inches of rainfall sparked flooding concerns (DOE 2015).

In the winter, warmer temperatures could benefit oil production. Cold and icy weather can strand wells, cause producers to scale back on drilling and completions, and reduce output (DOE 2014b). Cold waves are projected to be less intense in the future (USGCRP 2014).

Oil and Gas Exploration and Production

Resilience Solutions

As competition for limited water resources increases, oil and gas companies can take measures to reduce their vulnerability to freshwater scarcity. Resilience solutions include water reuse/recycling and switching to lower-quality water, such as produced water, degraded water, wastewater, or brackish groundwater sources, which do not compete with irrigation and municipal water needs. Companies may also be able to utilize alternative fracturing techniques such as foam-based fracturing, Liquid Petroleum Gas (LPG) fracturing, or channel fracturing. These methods use alternate fluids for fracturing and may reduce water requirements while promoting enhanced recovery, but only work in formations with specific characteristics (GAO 2015).

Planners can protect oil and gas operations from flooding by locating new equipment at higher elevations or outside of flood plains, where practical. Levees or other engineered barriers can also be an effective option to prevent damage to valuable equipment from floods.

Wind Energy

Subsector Vulnerabilities

The Northern Great Plains region has over 5,100 MW of operational wind generating capacity, or almost 15% of total electricity generation capacity in the region, and some of the best onshore wind resources in the country (EIA 2013a, NREL 2014). In the region, there are 38 utilities operating 72 wind generation stations (EIA 2013a).

There is not yet substantial agreement among sources as to how a changing climate will ultimately affect wind resources in the United States in general and in the Northern Great Plains in particular (DOE 2013a). It is uncertain whether wind power production will be disrupted by climate-driven changes to wind patterns or whether it will see an increase in available capacity.

Wind Energy

Resilience Solutions

Sophisticated wind forecasting systems allow operators to better predict available wind generation and determine when wind power needs to be supplemented with other generation sources to meet customer demand. Xcel Energy, a utility operating throughout the midwestern and western United States, has deployed the WindWX system, which uses real-time, turbine-level operating data to forecast wind generation (Edison Foundation 2013).

Wyoming's Foote Creek Rim project has 183 wind turbines with a generating capacity of 135 MW. These turbines are designed to withstand 125-mph gusts and are also adapted to operate reliably in extremely cold conditions (

Figure 4-11). The project also has electronic control systems that point each turbine into the wind and adjust the pitch of the blades to make the best use of wind in variable operating conditions (BLM 2011).

Figure 4-11. Foote Creek Rim wind project in southeastern Wyoming, which is equipped with technology to maximize generating output under a range of conditions
Source: BLM 2011

Regional Climate Change Observations and Projections in Detail

Higher Temperatures

Historical observations

- **Since 1895, average temperatures have increased 0.2°F per decade, or almost 2.2°F** (NOAA 2013a).
- **Winters have warmed faster than other seasons:** Since 1895, average temperatures have increased 0.33°F per decade in the winter, compared to 0.20°F per decade in the spring, 0.14°F per decade in the summer, and 0.13°F per decade in the fall (NOAA 2013a).
- **Freeze-free season has been growing:** Across all of the Great Plains, the length of the freeze-free season has grown since 1895. The average freeze-free season was about six days longer during 1991–2010 than during 1961–1990 (NOAA 2013a).

Future projections

- **Average temperatures are projected to increase at a faster rate:** Increases of 3.5°F–9.5°F are projected by 2070–2099 compared to 1971–1999 levels, depending on the region and greenhouse gas emissions (NOAA 2013c).
- **Extremely hot days are projected to become more common:** Across most of the region, 5–20 more days with a daily maximum >95°F are projected by mid-century (2041–2070, compared to 1980–2000); Nebraska is likely to be most affected, including increases of as many as 25 more extremely hot days per year projected (NOAA 2013c).
- **Consecutive number of days of extreme heat are expected to become longer:** The annual maximum number of consecutive days with a daily high >95°F is projected to increase by 0–12 days by mid-century (2041–2070, compared to 1980–2000) across most of the region, with larger increases in the southern part (NOAA 2013c).
- **Extremely cold nights are projected to become much less common:** Across the region, 10–30 fewer days with daily minimums <10°F are projected by mid-century (2041–2070, compared to 1980–2000), with mountainous regions seeing the largest decrease and Nebraska and South Dakota seeing the smallest change (NOAA 2013c).
- **Freeze-free season is projected to lengthen:** Across most of the region, the freeze-free season is projected to be 18–24 days longer by mid-century (2041–2070, compared to 1980–2000), with larger increases in the mountains (NOAA 2013c).
- **Cooling degree days (CDDs) are projected to increase:** In Nebraska and South Dakota, an increase of 400–800 CDDs is projected by mid-century (2041–2070, compared to 1980–2000), while increases are projected to be lower elsewhere in the region, especially in the mountains (NOAA 2013c).
- **Heating degree days (HDDs) are projected to decrease:** Across the region, declines of 850–1,650 HDDs are projected by mid-century (2041–2070, compared to 1980–2000), with the lowest declines in Nebraska and the highest declines in the western and northern portions of the region (NOAA 2013c).

Changing Precipitation Patterns and Wildfire

Historical observations

- **Historical trends in precipitation are not statistically significant, neither annually nor seasonally** (NOAA 2013a).
- **Across the Great Plains, extreme precipitation events have occurred more frequently:** An index of one-day precipitation events projected to occur once every five years shows a statistically significant upward trend since 1895 (NOAA 2013c).
- **April snowpack in Montana and Wyoming has declined:** From 1955 through 2013, annual total snowpack in April has declined at most observation sites in the region's mountains (EPA 2014).
- **Snowmelt in Wyoming has occurred earlier over the last half-century:** From 1961–2002, snowmelt in Wyoming has occurred earlier (USGCRP 2014).

Future projections

- **Across most of the region, annual precipitation is projected to increase:** By the end of the century (2070–2099, compared to 1971–1999), precipitation is projected to increase 0%–9% across the entire region excluding Nebraska and depending on both latitude and emissions scenario. Generally, the projected increase increases with latitude (NOAA 2013c).
- **Winter and spring precipitation is projected to increase:** In general, northern state winters and springs are projected to see increased precipitation relative to the 1970–1999 period average under a higher emissions (A2) scenario, while changes to summer and fall precipitation are small (USGCRP 2014).
- **Drier summers are projected:** In the central Great Plains, a trend toward drier summers is projected (USGCRP 2014).
- **Extreme precipitation is projected to occur more frequently in the northern states:** Very heavy precipitation events are projected to increase in northern states, leading to increased runoff and flooding (USGCRP 2014).
- **Risk of wildfire is projected to increase:** For every 1°C rise in global temperature, the area burned by wildfire in the western Northern Great Plains region is projected to increase by 73% to over 600% (compared to the median annual burned from 1950–2003), depending on the ecosystem (NRC 2011).

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Chapter 4 Endnotes

[a] Source: USGCRP 2014
[b] Sources: CCSP 2008, USGCRP 2014, NOAA 2013a
[c] Sources: NOAA 2013c, USGCRP 2014
[d] Sources: CCSP 2008, DOE 2013a, NRC 2008
[e] Source: USGCRP 2014
[f] Sources: DOE 2013a, USDA 2012b, USGCRP 2014
[g] Sources: USGCRP 2014, Union Pacific 2011
[h] Sources: CCSP 2008, USGCRP 2014
[i] Source: DOE 2014a
[j] Sources: DOE 2007, EIA 2012a
[k] Source: CRS 2014
[l] Source: CCSP 2008
[m] Sources: EIA 2013a, EIA 2013b, EIA 2013c
[n] Source: DOE 2013a
[o] Source: NOAA 2013c

Chapter 5: Southern Great Plains

Climate Change and the Energy Sector

Overview

The Southern Great Plains region, comprising Kansas, Oklahoma, and Texas, contains oil and gas infrastructure critical to the nation's energy supply, including numerous offshore platforms, onshore oil and gas wells, oil refineries, natural gas processing plants, pipelines, and shipping terminals. Many of these assets are located near the Texas Gulf Coast. Key climate change impacts projected for the region include the following:

- **The intensity of Atlantic hurricanes is projected to increase, and the most intense hurricanes (Category 4 and 5) are projected to occur more frequently. Associated storm surge impacts may be enhanced by higher sea levels. Sea level rise is expected to be greater in some areas because of local land subsidence.**[a] Critical oil and gas infrastructure, power plants, and transport infrastructure such as bridges and pipelines located along the Texas Gulf Coast may be at risk of damage from more powerful hurricanes and storm surges amplified by sea level rise. High winds from more intense hurricanes may increase risk of damage to power lines.[b]
- **Average temperatures are projected to increase, and extremely hot days are likely to occur more often. Heat waves are projected to become more severe and last longer. By mid-century, the average number of cooling degree days (CDDs) may increase by 600–1,000 per year.**[c] Increasing air and water temperatures in the Southern Great Plains will reduce the efficiency and available capacity of power plants and transmission lines while also increasing average and peak electricity demand for electricity for cooling in the summer.[d]
- **Precipitation is projected to decrease across most of the region, with the largest declines occurring in the summer. Dry spells may become longer. These changes may lead to more frequent droughts.**[e] Combined with increasing demand and competition for water from other sectors, climate change may further limit the availability of water for energy. This includes withdrawals for critical operations such as power generation, oil refining, and the region's growing unconventional oil and gas production.[f]

QUICK FACTS

Southern Great Plains States:	Kansas, Oklahoma, Texas
Population (2013)	33,000,000 (11% of U.S.)
Area (square miles)	412,000 (12% of U.S.)
Energy expenditures	$190 billion

ENERGY SUPPLY & DEMAND		**Annual Production**	**Annual Consumption**	***% for electric power***
Electric power	*TWh*	552	465	*n/a*
Petroleum	*MMbbls*	861	1,460	*<1%*
Coal	*million tons*	45	135	*99%*
Natural gas	*Bcf*	9,800	4,800	*39%*

ELECTRIC POWER	**Annual Production (TWh)**	***% of Total Production***	**Capacity (GW)**	**Power plants >1 MW***
Natural gas	256	*46%*	95	257
Coal	195	*35%*	36	35
Nuclear	47	*8%*	6	3
Hydroelectric	2	*<1%*	2	36
Wind	46	*8%*	18	146
Biomass	2	*<1%*	<1	30
Solar	<1	*<1%*	<1	6

CRITICAL INFRASTRUCTURE

Petroleum		**Electric Power**	
Wells (>1 boe/d):	133,000	Power plants (> 1 MW):	555
Refineries:	36	Interstate transmission lines:	24
Liquids pipelines:	32	**Coal**	
Ports (>200 tons/yr):	13	Mines:	20
Natural Gas		**Waterways**	
Wells:	161,000	Coal and petroleum routes:	11
Interstate pipelines:	41	**Railroads**	
Market hubs:	8	Miles of freight track:	18,600

Note: Table presents 2012 data except number of oil wells, which is 2009 data.
*Some plants use multiple fuels, and individual generating units may be <1 MW.
Sources: AAR 2014, EIA 2011a, EIA 2013b, EIA 2013d, EIA 2013e, EIA 2014a, EIA 2014d, EIA 2014f, EIA 2014g, EIA 2014h, EIA 2014i, EIA 2014j, U.S. Census Bureau 2014a

Table 5-1. Examples of important energy sector vulnerabilities and climate resilience solutions in the Southern Great Plains

Subsector	Vulnerability	Magnitude	Illustrative Resilience Solutions
Oil and Gas Exploration and Production	Heightened exposure to damage and disruption from an increasing intensity and frequency of the most intense hurricanes[g]	Increasing numbers of Category 4 and 5 hurricanes by the end of the century[h]	Infrastructure hardening and elevation, improved operations protocols, restoration of coastal habitats
Electricity Demand	Increased demand for cooling energy in the summer, coinciding with reduced available capacity of power generation and transmission[i]	Increasing CDDs by as much as 1,000 degree days by mid-century compared to historical averages[j]	Energy efficiency, demand-side management programs and policies, new peak load capacity
Thermoelectric Power Generation; Electric Grid	Reduced available generation capacity from higher temperatures and decreased water availability, and reduced capacity of electric lines from higher temperatures[k]	Increasing air temperatures by 3.5°F–8.5°F and decreasing summer rainfall by 10%–30% by the end of the century[l]	Alternative water sources and water-efficient power generation technologies, new generation and transmission capacity[m]

Regional Energy Sector Vulnerabilities and Resilience Solutions

Key energy subsectors and illustrative examples of resilience solutions in the Southern Great Plains are discussed below. System components that are most vulnerable to climate change are described first.

Oil and Gas Exploration and Production

Subsector Vulnerabilities

The Southern Great Plains is a principal element of the U.S. oil and gas supply network. The region includes extensive upstream exploration and production infrastructure, as well as downstream refining and product delivery systems. The region accounts for 40% of total domestic crude oil production, with Texas the leading crude oil-producing state in the nation (EIA 2014a). Oil refineries in the region account for one third of the nation's capacity (Table 5-2).

Table 5-2. Southern Great Plains crude oil production and refinery capacity, 2013

	KS	OK	TX	Total
Crude Oil Production (million bbl)	47	114	924	1,084
Share of U.S. Total	*2%*	*4%*	*34%*	*40%*
Refinery Capacity (million bbl/d)	0.3	0.5	5.1	6.0
Share of U.S. Total	*2%*	*3%*	*29%*	*34%*

Sources: EIA 2014a, EIA 2014b

Climate change is projected to have the following impacts on the subsector:

- Increasing frequency of intense hurricanes increases the risk of damage or disruption to coastal and offshore oil and gas facilities (DOE 2013, USGCRP 2014).
- Rising sea levels, combined with projected increases in hurricane intensity and associated heavy rainfall, leads to intensified flood regimes along coasts (USGCRP 2014).
- Decreasing water availability and drought could affect unconventional oil and gas production and oil refining operations (DOE 2013).

More intense hurricanes and rising sea levels will expose the region's extensive oil and gas exploration, production, and refining infrastructure to increased risk of damage and disruption (DOE 2013). The intensity, frequency, and duration of North Atlantic hurricanes, as well as the frequency of the strongest storms (Category 4 and 5), have all increased since the early 1980s. As the climate continues to warm, hurricane-associated storm intensity and rainfall rates are projected to increase (USGCRP 2014).

Examples of Gulf Coast infrastructure damage from hurricanes*

Hurricanes Gustav and Ike (2008)

- At peak of disruptions, more than 20% of U.S. refinery capacity was offline (API 2014a).
- Significant destruction to electric power infrastructure delayed the restart of pipeline and refinery operations (API 2014a).
- 60 offshore platforms (approximately 1% of total offshore oil production) were destroyed (API 2014a).
- Three of the four Strategic Petroleum Reserve sites sustained extensive damage (DOE 2010a).

Hurricanes Rita and Katrina (2005)

- The storms destroyed 115 platforms and damaged 52 others, and 19 drilling rigs were set adrift (API 2014a).
- Hundreds of platforms were shut down, and over 400 offshore pipelines were damaged (DOE 2009).
- An estimated 29% of U.S. refinery capacity was taken offline (API 2014a).

Hurricane Ivan (2004)

- Seven platforms were destroyed and 24 damaged (API 2014a).
- At the time, Hurricane Ivan was considered the costliest hurricane season ever to the oil and gas industry (Cruz and Krausmann 2008).

* Includes all Gulf Coast states

Offshore oil and gas platforms are vulnerable to high winds and damaging surf caused by hurricanes. One study found that approximately 3%–6% of offshore platforms exposed to hurricane force winds[1] typically experience damage that can take less than a month to over six months to repair, and 2%–4% are typically destroyed (Kaiser and Yu 2009). As the frequency of Category 4 and 5 hurricanes increases, damage from these intense storms will increase as well.

Offshore platforms typically follow the design specifications of the American Petroleum Institute (API), which sets performance standards for withstanding stresses such as wind speeds and wave heights for a 100-year storm. However, some of these threshold limits have been significantly surpassed in recent years (Cruz and Krausmann 2008). Furthermore, as oil exploration and production operations move farther offshore into deeper waters, the potential for damage increases (DOE 2013).

[1] Hurricane force winds typically extend 25–50 miles from the eye of the storm (Kaiser and Yu 2009).

Dependence of refineries on electricity

Many refineries rely on offsite power generation and transmission systems to operate at full capacity. This interdependence with the electric grid means that interrupted electricity supply, transmission, and distribution may result in broad disruptions to petroleum production and distribution systems.

Hurricane force winds can also cause severe damage to refineries, including refining cooling towers. For example, during Hurricane Rita, 50% of the cooling towers at facilities in Port Arthur, Texas, were damaged (NIST 2006).

Hurricanes also destroy wetlands and other features that help protect coastal infrastructure, increasing the vulnerability of coastal and inland infrastructure to future storms. Moreover, the exposure of coastal energy facilities to damage and disruption from hurricanes is magnified by sea level rise, which amplifies the height of storm surges (Figure 5-1) (DOE 2013). In Texas, 17 major energy facilities are located less than four feet above sea level (Climate Central 2014).[2]

Figure 5-1. Flooded Texas refinery in 2008 following Hurricane Ike
Source: PBS 2008

Depending on location, relative mean sea level in Texas has already increased by approximately one to three inches per decade because of a combination of global sea level rise and land subsidence in the region (NOAA 2009). Future sea level rise is projected to climb between one and five inches per decade in the first half of the 21st century and to accelerate over time (USGCRP 2014).

Decreasing water availability may negatively affect the oil and gas sector. Under a high emissions scenario, spring and summer precipitation is projected to decrease by 10%–30% by the end of the century for most of the region (USGCRP 2014). A recent study found that under a high emissions scenario, droughts are likely to be longer, with 80% likelihood that the region will experience a decadal or multi-decadal drought between 2050 and 2099 (Cook et al. 2015). Effects from climate change, including decreasing rainfall, higher temperatures, and increasing evaporation rates, in combination with increasing competing demands for water from increasing population and other factors, are expected to increase water stress on both surface water and groundwater resources.

One of the sectors that may face increasing water stress is the region's rapidly growing unconventional oil and gas industry (Figure 5-2). Ninety percent of hydraulic fracturing operations in Texas currently use groundwater reservoirs (Arnett et al. 2014). In the Eagle Ford shale formation, where hydraulic fracturing is the third-largest consumer of groundwater (after irrigation and municipal districts), aquifers are being depleted 2.5 times faster than the rate of recharge (Arnett et al. 2014).

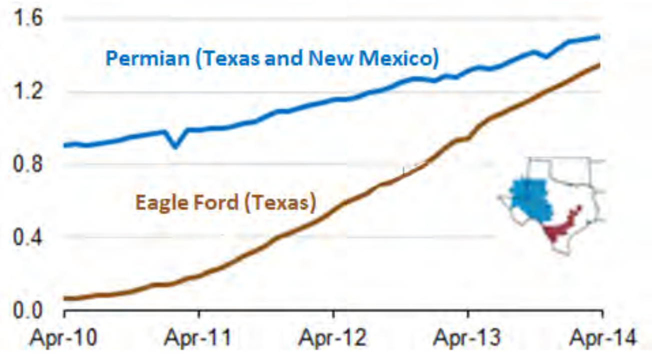

Figure 5-2. Growth of crude oil production (in millions of barrels per day) at two major shale formations in the Southern Great Plains
Source: EIA 2014c

Oil refineries may also be affected by decreasing water availability. Conventional oil refining typically consumes between 0.5 and 2.5 gallons of water per gallon of gasoline equivalent, and securing access to diminishing water supplies may increase costs (DOE 2013).

Example impact from water shortages

2011: During the worst drought ever recorded in Texas, the river that provided water for the ConocoPhillips refinery near the town of Sweeny, Texas, ran dry, forcing the company to construct an emergency pipeline to tap into groundwater (Galbraith 2012).

[2] Climate Central data uses the FEMA HAZUS dataset to define major energy facilities. These include electricity generating stations and substations, natural gas control stations and compressor stations, oil refineries, control stations, and tank farms, among others (Climate Central 2014, FEMA 2014).

Oil and Gas Exploration and Production

Resilience Solutions

The oil and gas industry is experienced with managing hurricane risk and actively pursues measures to mitigate these risks. For example, the API has developed guidance and recommendations for improving the resilience of offshore platforms to hurricane-related damage and operations disruption. In response to heavy damage inflicted by recent storms, new engineering and operations guidance has been developed that provides:

- Modified design specifications for new platforms
- Operations protocols for hurricane season, such as positioning platform decks higher above the sea surface, methods for securing platform equipment to rigs, and locating "jack-up" rigs on more stable areas of the sea floor
- Improved data for wind, wave, current, and surge conditions at higher spatial resolution
- Protocols for post-hurricane structural assessment (API 2014a)

Better coordination between government and industry will also improve the preparation for and response to future hurricanes. The Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE), formerly the Minerals Management Service, has adopted measures to improve pre-season planning and communications among federal agencies and help industry develop new standards and guidelines (Cruz and Krausmann 2008).

Refineries can reduce wind damage to cooling towers through multiple actions, including special braces to stop fan blades from dislodging, and installation of wind girders to deflect wind and reinforce the structural integrity of the tanks to prevent collapse (DOE 2010b).

Engineered barriers such as levees can be effective in protecting vulnerable coastal areas. In addition, wetland restoration and development of other natural barriers ("green infrastructure") may be a cost-effective resilience technique (TNC-DOW 2012). These types of structures—natural and manmade—help protect coastal infrastructure from storm surges and wave impacts (DOE 2013). Historically, the economic value of natural landscape features has not been incorporated into the risk management decisions involved in the planning and construction of coastal infrastructure. Recently, however, projects undertaken between private industry and natural resource conservation stakeholders have shown that collaboration and data sharing can be a successful strategy for integrating the value of environmental features into coastal facilities planning (TNC-DOW 2012).

As competition for declining water resources increases, oil and gas producers using hydraulic fracturing can take measures to reduce vulnerability to water scarcity. In the short term, many producers are resorting to hauling water over long distances by truck (Dittrick 2012). Another option is to switch to brackish groundwater sources, which do not compete with irrigation and municipal water needs but which require additional treatment steps and costs (Nicot and Scanlon 2012). Additional options for some operations include recycling and reuse of produced fracking water or dry fracking. Dry fracking uses highly pressurized gas instead of water to crack rock formations, and at least two companies in Texas are using dry fracking technology (Processing Magazine 2013). Along with technological solutions, market-based approaches to water conservation may be an effective strategy to improve the sector's resilience to climate change (Arnett et al. 2014).

Fuel Transport and Storage

Subsector Vulnerabilities

The Southern Great Plains is a critical node in the nationwide natural gas and liquid fuels transport and distribution network (Figure 5-3). The Cushing oil hub in Oklahoma is the world's largest crude oil storage hub, which transfers approximately 1.7 million barrels per day (Zawadski 2013). The port of Houston is the second largest petrochemical complex in the world and is the location of ExxonMobil's Baytown Refinery, the nation's second largest petrochemical refinery behind Valero's Port Arthur facility (EIA 2014d, Port of Houston 2014).

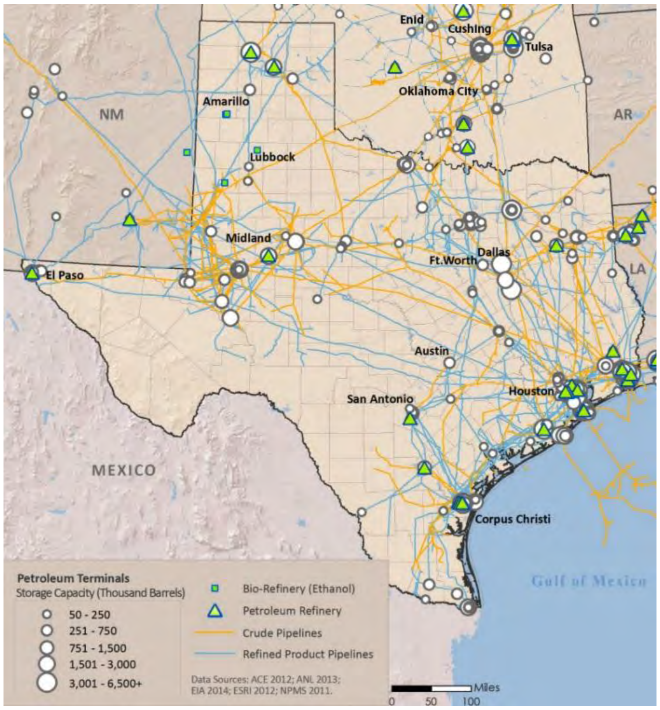

Figure 5-3. Extensive petroleum transport infrastructure in Texas and Oklahoma

Source: DOE 2015b

The Gulf Intracoastal Waterway is a key asset in the distribution of petroleum products (Figure 5-4) (CCSP 2008). In 2010, the Texas portion of the Gulf Intracoastal Waterway transported 67 million short tons of petroleum and chemical products—comprising 91% of the waterway's traffic by weight—and the total value of all shipments was over $25 billion (TxDOT 2013).

Figure 5-4. Gulf Intracoastal Waterway
Source: TxDOT 2013

Offshore, a network of more than 25,000 miles of seafloor pipeline carries the daily production of oil and gas platforms in the Gulf to facilities along the Texas coast and other Gulf states (NOAA 2014). The Texas coast is also the location of two of the nation's four storage sites of the Strategic Petroleum Reserve (SPR) (EIA 2014d). The SPR provides a government-owned emergency stockpile of crude oil, should disruption in commercial oil supplies threaten the U.S. economy.

Climate change is projected to have the following impacts on fuel transport and storage:

- Increasing hurricane intensity, and increasing frequency of the most intense hurricanes (Category 4 and 5) along with associated storm surges and rising sea levels, increases the risk of damage or disruption to coastal and offshore oil and gas transportation and storage facilities from wind, coastal flooding, and storm surge (DOE 2013, USGCRP 2014).

Coastal ports and facilities are vulnerable to high wind speeds and storm surge associated with intense hurricanes. Storm surge has the capacity to knock down terminal buildings, dislodge cargo containers, damage terminal equipment, and damage wharf and pier structures (CCSP 2008). Hurricane- and sea level rise-related impacts may also increase the risk of damage to waterway assets and disruption of operations (CCSP 2008). Storm debris can block navigation channels, and markers and barrier islands can be affected (CCSP 2008). Rail terminals, docks, and ships located along the coast are also vulnerable. Aboveground storage facilities can be damaged by high winds associated with intense hurricanes, and storage tanks can be lifted by floodwaters, which may cause spills of hazardous materials (API 2014a, DOE 2010b, DOE 2015a, Santella et al. 2010). SPR facilities may also be exposed to hurricane damage, including inundation caused by storm surge (DOE 2015a).

Large surface waves and strong near-bottom currents from hurricanes can scour the seafloor and create underwater mudslides that damage subsea pipes and other equipment that rests on the bottom (Burkett 2011). In fact, during the 2005 hurricane season, pipelines were identified by industry experts as the weakest link and were a major cause of delays in bringing production back online (Cruz and Kraussman 2008). The majority of damage to offshore pipelines during previous hurricanes has occurred at or near platform interfaces (DOE 2015a).

Onshore pipelines are vulnerable to damage from coastal and inland flooding events, which can alter the water table or soil stability and damage buried pipes (DOT 2014, GAO 2014). Buried onshore pipes may be further damaged by storm surge and flooding by corrosion due to saltwater intrusion of groundwater (DOT 2014). During hurricanes, debris from high winds and flooding can damage aboveground pipeline infrastructure such as compressor and pumping stations and metering stations, and aboveground infrastructure is vulnerable to flood damage and subsequent scour (DOT 2014).

Dependence of pipelines on electricity

The vulnerability of oil and gas pipelines is closely connected to the operability of the electric grid. Pipeline operations rely on electricity to deliver products to consumers. Electricity is needed for operations of pumps and valves that control the flow of fuel through pipelines. Power disruptions can shut down oil and gas operations, even when there is no direct structural damage (DOE 2013).

The projected increase in intense hurricanes may lead to increased natural gas and oil supply disruptions due to damage and disruption of pipeline and refinery infrastructure, which could in turn affect short-term fuel prices. Supply disruptions during hurricanes may cause natural gas and petroleum product prices to spike while crude oil prices fall (API 2014b).

Fuel Transport and Storage

Resilience Solutions

Options for improving resilience of onshore pipelines include installing manmade or natural barriers to reduce risk of erosion, which could expose buried pipes. Another risk reduction measure is upgrading pipes with more robust materials that are less likely to leak or rupture from seawater-induced corrosion—such as coated steel pipes instead of cast iron or bare steel.

Similar to other low-lying and coastal infrastructure, some fuel storage and transport assets can be hardened to better withstand more intense hurricanes and storm surges. Example measures include installing water-tight doors, elevating critical equipment (substations, control rooms, pump stations), relocating vulnerable facilities, and building or strengthening berms, levees, and floodwalls. Shorelines of critical waterways can be hardened to prevent and offset erosion, and dredging can be employed to maintain shipping access (CCSP 2008, DOE 2010b).

Resilience efforts for wind protection may include installing wind girders on storage tanks (DOE 2010b).

Thermoelectric Power Production

Subsector Vulnerabilities

Fossil fuel-fired power plants dominate the electricity source mix in the region, with natural gas and coal representing over 80% of the total generation (Table 5-3). Thermoelectric power from nuclear plants provides another 8% of generation. Projected changes in temperature and water availability—both independently and in combination—may restrict the available capacity of thermoelectric power generation in the region.

Table 5-3. Net electric power generation by fuel type, 2012

	Kansas	Oklahoma	Texas	Total Region
Natural Gas	6%	50%	50%	**46%**
Coal	63%	38%	32%	**35%**
Nuclear	19%	0%	9%	**8%**
Wind	12%	10%	7%	**8%**
Other	0%	2%	2%	**2%**

Source: EIA 2013b

Climate change is projected to have the following impacts on thermoelectric power generation in the region:

- Reduced surface water availability for cooling in most locations and seasons and higher evaporative loss from surface water sources could reduce generation capacity.
- Higher air and water temperatures reduce plant efficiencies and increase the risk of exceeding thermal water discharge limits (DOE 2013).
- Increased intensity of hurricanes and sea level rise-enhanced storm surge increase risk of damage and disruption to coastal power plants (DOE 2013, USGCRP 2014).

The vast majority of thermoelectric power water withdrawals in the region are from fresh surface water sources[3] (UCS 2012, USGS 2005), making the region's thermoelectric power production infrastructure vulnerable to increasing droughts, including a possible multi-decadal drought by the end of the century projected as a result of climate change (Cook et al. 2015, USGCRP 2014).

A number of power plants have been stressed by limited water availability in recent years. For example, water shortages forced one power plant to curtail operations and threatened more than 3,000 MW of generating capacity in Texas during a historic drought in 2011, and the grid operator put an emergency action alert system in effect to deal with coincident increases in electricity demand (CRS 2013, ERCOT 2011, USGCRP 2014). The impact of drought on electricity supply was exacerbated in Texas by the fact that the state is nearly isolated from the rest of national electricity grid; marginal electricity prices reached the market ceiling of $3,000 per MWh, and daily day-ahead prices reached over $600 per MWh (CRS 2013, EIA 2011b, USGCRP 2014).

Thermoelectric power infrastructure may also face increased stress from higher temperatures. Average annual temperatures in the region are projected to increase by 3.5°F–8.5°F by the end of the century, depending on the emissions scenario, with extremely hot days (>95°F) occurring more frequently and for longer stretches of time (NOAA 2013). Increasing air and water temperatures reduce the efficiency and available generation capacity of thermoelectric power plants (DOE 2013). Higher surface water temperatures will also heighten the likelihood that power plants will exceed thermal water discharge limits mandated to protect aquatic ecosystems, which could further reduce available power capacity. One study found that under a high emissions scenario, curtailments of power plants in Texas could remove up to 5,500 MW of peak load capacity from the ERCOT grid in 2030 (Cook 2013).

Similar to the risk posed to coastal oil and gas infrastructure, increased frequency of intense (Category 4 and 5) hurricanes and sea level rise-enhanced storm surge threatens power plants located near the Texas Gulf coast. Plants farther inland, which are often located along rivers and in low-lying areas, may also be at increased risk from flooding caused by heavy precipitation associated with intense hurricanes. Specific vulnerabilities to hurricanes and sea level rise vary significantly from site to site and are largely dependent on facility elevation, distance from coast, and mitigating measures the facility may have taken to improve its resilience.

Thermoelectric Power Production

Resilience Solutions

Installing water-saving technologies at power plants could significantly reduce water withdrawals. Cooling towers with condensing technology, recirculating cooling, or dry cooling systems are examples. Other solutions include retrofitting

[3] Two different sources provide different estimates: the U.S. Geological Survey provides an estimate that 84% of thermoelectric withdrawals are from fresh surface water, while the Union of Concerned Scientists' EW3 model calculated 94% in 2008.

or replacing plant equipment to accommodate use of nontraditional water (e.g., brackish groundwater or municipal wastewater). For example, the 1,080 MW coal-fired Harrington Station in Amarillo, Texas, uses treated wastewater rather than freshwater to meet cooling needs (UCS 2011). One analysis suggests that most plants vulnerable to drought could be retrofitted for less than \$4/MWh, or for less than a 10% increase in the levelized cost of electricity (Tidwell et al. 2013).

Water availability issues could be partly addressed through policy measures employed at the state and local levels and informed by technical assistance at the federal level. Some areas have established market-driven solutions to address the vulnerability of critical shortages in supply. For example, nineteen water districts using the Edwards Aquifer in San Antonio, Texas, have formed an alliance that creates a streamlined market for trading water rights for sustainable water development through 2060 (USGCRP 2014).

Examples of state policy measures addressing storm damage

In Texas, utilities are required to submit annual reports that describe their efforts to identify areas within their service territories that are particularly susceptible to severe weather damage and harden facilities in those areas (EEI 2014).

New generation capacity with sources and supply chains less affected by increasing temperatures and decreased water availability, such as wind power and solar PV, will also help make the region's power sector more resilient to climate change. Fuel sources that are less dependent on water availability can help supply peak power generation during critical summer days. Indeed, new wind turbines represent about 38% of the new capacity additions in the region since 2000 (Figure 5-5), and in most cases, ERCOT anticipates that new generation resources will primarily be renewables that do not require cooling water (ERCOT 2012).

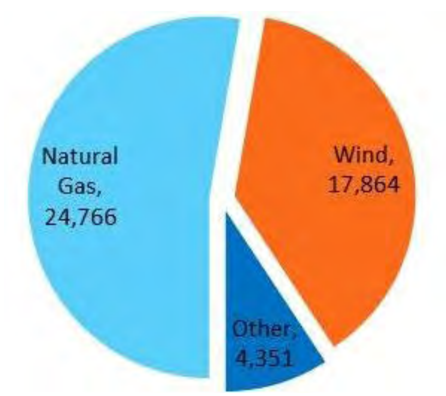

Figure 5-5. Recent additions in Southern Great Plains electric generation nameplate capacity (MW) by fuel type, 2000–2012
Source: EIA 2013d

Shifting from coal-fired power plants to natural gas combined cycle plants (NGCCs) can also reduce annual freshwater consumption. Estimates of the potential effects of coal-to-natural-gas fuel switching in Texas' power sector projected savings of 53 billion gallons of freshwater per year, or 60% of Texas coal power's water footprint, largely due to the higher efficiency of NGCCs (Grubert et al. 2012)

Retrofitting facilities to harden them against more intense hurricanes and storm surges can also reduce vulnerabilities. Improved engineered barriers such as levees can be effective in protecting vulnerable thermoelectric power plants from flooding. Utilities may also elevate critical equipment to protect against flooding or upgrade plants with submersible equipment or watertight doors. Planners can protect new capacity by locating new generators at higher elevations that are not at risk of flooding due to hurricanes or storm surges.

Electricity Demand

Subsector Vulnerabilities

Compared to other areas of the United States, the warmer weather in Texas and its neighboring states means that air conditioning accounts for a greater portion of home energy use (18% compared to 6% nationally), while space heating accounts for a much smaller portion (22% compared to 41% nationally) (EIA 2014d). Almost all residents in the region use air conditioning equipment, with over 80% using central air conditioners. Along with the Southeast region, the Southern Great Plains has among the highest per capita electricity use in the nation (EIA 2014d).

Hotter temperatures and more frequent extreme high temperatures are projected for the Southern Great Plains; these increases are expected to contribute to higher energy demand from increased use of air conditioning (USGCRP 2014).

Climate change is expected to affect electricity demand in the Southern Great Plains as follows:

- Higher maximum temperatures, longer and more severe heat waves, and higher overnight lows are expected to increase electricity demand for cooling in the summer (NOAA 2013, USGCRP 2014).

Example impact from heat waves

2011: During a summer of intense heat, the electricity demand in Texas surpassed a previous record for three consecutive days (Tweed 2012).

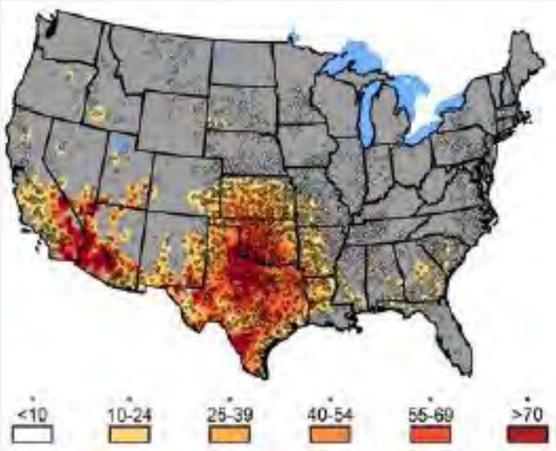

Figure 5-6. Days above 100°F in summer 2011
Source: NOAA 2013

NOAA climate models project that, by mid-century, there will be more than 15 additional days with temperatures reaching 100°F and upwards of 30 more warm nights (>80°F) per year. These warmer temperatures will increase cooling energy demand. Over the same period, the region is expected to have 600 to 1,000 more CDDs per year compared to the end of last century (Figure 5-7) (NOAA 2013).

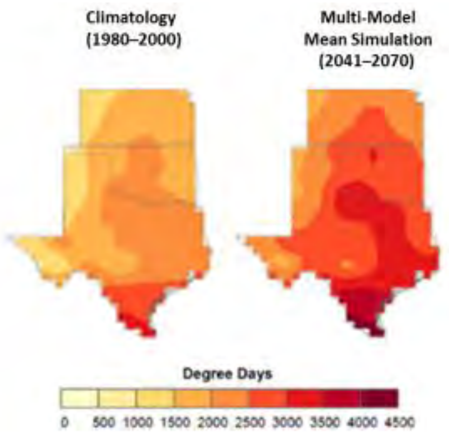

Figure 5-7. Increase in annual CDDs by mid-century[4]
Source: NOAA 2013

Other factors, such as population growth and changing technologies such as electric vehicles, are also important to consider in long-range electricity demand projections, especially in Texas, which contains three of the five fastest-growing cities in the nation and which has faced declining reserve margins in recent years (EIA 2012, U.S. Census Bureau 2014b). These trends will have significant implications for the power sector in the region, as predicted increases in air conditioning demand will require a system that can handle more extreme peak loads. Current forecasts from the Electricity Reliability Council of Texas (ERCOT) anticipate that summer peak reserve margins could fall to 7.3% by 2024 without capacity expansion (ERCOT 2014). ERCOT's forecast did not take future warming into account and instead relied on recent weather averages.

In the winter, warmer temperatures and fewer days below freezing are expected to reduce demand for heating energy (DOE 2013, USGCRP 2014). Almost all homes in the region are heated, and about half of residents use electricity for heating, a greater proportion than the U.S. average (EIA 2013g). However, peak electricity demand in the winter is about 25% less than in the summer,[5] and this difference may increase with warmer temperatures (EIA 2013a, USGCRP 2014).

Compounding power sector vulnerabilities from higher temperatures and reduced water availability

High temperatures stress multiple components of the electric power system. At the same time that higher temperatures increase demand for air conditioning, they also decrease the efficiency of thermoelectric power plants and transmission lines. Meanwhile, power plants require more water for cooling in hot temperatures, when water availability and thermal discharge restrictions are already more likely to be risk factors (DOE 2013).

Electricity Demand

Resilience Solutions

Alongside measures to reduce demand, such as energy efficiency measures and demand-side management programs, capacity expansion can help mitigate falling summer reserve margins.

Capacity expansion in the region is likely to be a necessary component of any adaptive response. In Texas, ERCOT has identified a need to replace 13 GW of retiring natural gas generation, in addition to addressing growing summer peak demand (ERCOT 2012). In its latest Integrated Resource Plan, ERCOT found that demand for new capacity will be met over a 20-year planning horizon by new natural gas combined-cycle units, by wind and solar generation, or by a combination of the three. For example, in one scenario (BAU [business as usual] with Updated Wind Shapes), capacity requirements are met by 17 GW of new wind, 3.6 GW of natural gas combined-cycle units, and 10 GW of solar PV (ERCOT 2012). Wind power currently generates 8% of

[4] Projected changes for mid-century (2041–2070) relative to the end of the last century (1980–2000) under an A2 emissions scenario

[5] On average across all utilities located in the region, peak winter electricity generation is about 25% less than peak summer generation.

the region’s electricity, with 18 GW of wind turbines installed (EIA 2013d). The market penetration of solar PV is also increasing in the region. Since wind and solar PV do not require cooling water, they are inherently more resilient to water stress than many other power generation technologies. Wind and natural gas plants represent most of the new capacity planned to come online in the region (Figure 5-8).

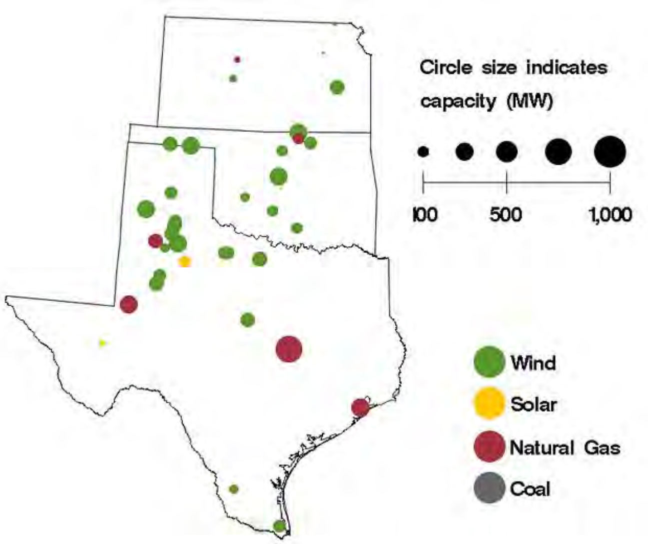

Figure 5-8. Utility-scale generating plants planned to come online from December 2014 to November 2015
Source: EIA 2015

Approximately 3,000 MW of peak load have been avoided through demand-side management programs in the Southern Great Plains (EIA 2013a). Approximately 180,000 residential, commercial, and industrial customers are enrolled in price-responsive programs. The city of San Antonio by itself accounts for almost half of these customers. Time-sensitive programs such as demand response are also established in the region, with almost 120,000 customers enrolled (EIA 2013a). However, on the whole, demand response is mostly an untapped mechanism in the region. As of 2012, demand response potential within ERCOT represented only 2.6% of the total system peak load (FERC 2013).

Grid-scale energy storage systems and other developing technologies can also contribute to meeting the region's changing demand profile. Storage systems could allow intermittent renewable generation sources, such as the region’s burgeoning wind power capacity, to store generated energy and then deliver it when needed.

Electric Grid

Subsector Vulnerabilities

The Southern Great Plains encompasses two regional electricity grids: ERCOT, which covers most of Texas, and the Southwest Power Pool (SPP) market in Kansas, Oklahoma, and the Texas panhandle, which is part of the Eastern Interconnection power grid. Small portions of Texas’ grid are also part of the grid operated by the Midcontinent Independent System Operator (MISO). ERCOT is unique in that, unlike SPP and MISO, it operates as an independent interconnection—i.e., it is not synchronously connected to the Eastern and Western Interconnections that cover the other lower 48 states (FERC 2014). ERCOT is also connected to the Mexican states of Tamaulipas and Chihuahua, although trade between ERCOT and Mexico represents a small portion of electricity supply and typically occurs during periods of constrained supply (EIA 2013h). Six of the seven connections between Mexico and ERCOT are for emergency use only (Center for Energy Economics 2006).

Climate change is projected to have the following impacts on the region’s electric grid:

- Increases in average and extreme temperatures reduce the efficiency and available capacity of transmission lines and substations and could damage power transformers (DOE 2013, USGCRP 2014).
- Hurricane intensity and the frequency of the most intense hurricanes (Category 4 and 5) are projected to increase, and sea level is expected to rise at an accelerating rate, increasing the risk of physical damage to grid infrastructure from wind and coastal flooding (DOE 2013, USGCRP 2014).

Higher temperatures can force transmission operators to decrease the current-carrying capacity of transmission lines, which can exacerbate supply constraint issues during extreme heat events when demand for power is the highest. For example, one California study estimated that a 9°F increase in air temperature could decrease transmission line capacity by 7%–8% (Sathaye et al. 2013). Higher temperatures cause thermal expansion of transmission line materials, and sagging lines increase the risk of power outages when the lines make contact with other lines, trees, or the ground (DOE 2013). More than 825,000 customers in Texas have been affected by electric transmission outages caused by heat waves between 1992 and 2009 (DOE 2015b).

The risk of damage to transformers from higher ambient temperatures can also impel operators to constrain transmission capacity (USBR 2000). As transformers are forced to operate above their rated ambient temperature, their insulation begins to break down at an exponentially increasing rate, eventually destroying the transformer (Bérubé et al. 2007, Hashmi et al. 2013). Transformers are critical to system operations and may be overloaded during system emergencies (such as when transmission capacity is insufficient), pushing temperatures to critical limits.

The infrastructure associated with electric power transmission is also likely to be increasingly threatened by more frequent intense hurricanes. The damage to the electric grid during the 2008 hurricane season, for example, left 2.5 million Texas customers without power (API 2014a). The combined effects of rising sea levels, increasing storm surges, and increases in hurricane rainfall may expose low-lying substations near the Gulf Coast to flooding and inundation, threatening lengthy shutdowns during and after hurricanes (DOE 2013, USGCRP 2014). Furthermore, higher wind speeds associated with higher-intensity hurricanes will increase the threat of damage and disruption to power lines (Figure 5-9). Finally, because of the relative isolation of ERCOT, it is more difficult to import power from other regions when the grid is stressed by capacity limitations, and the risk of cost increases or supply disruptions to power customers in Texas may be higher than in surrounding states and regions.

Figure 5-9. Linemen repairing downed distribution poles following Hurricane Ike near Galveston, Texas
Source: FEMA 2008

Electric Grid
Resilience Solutions
Resilience could be improved through increased transmission redundancy and capacity (DOE 2013). For infrastructure located near the Gulf Coast, hardening measures include activities such as replacing wood power poles with steel, concrete, or composite structures, along with installing guys and other structure supports; burying power lines in areas of high wind exposure; elevating critical equipment and relocating substations to areas less susceptible to flooding; and investing in spare/backup equipment (CCSP 2008, DOE 2010b, EOP 2013).

Utilities also use mobile transformers and substations to temporarily replace damaged energy infrastructure. These temporary units can include a trailer, switchgear, breakers, emergency power supply, and transformers with enhanced cooling capability that allows restoration of grid service while circumventing damaged substation equipment, allowing time to repair grid components (DOE 2010b).

In some instances, energy storage systems can be a viable option for improving resilience to vulnerable areas. For example, AEP, the serving utility in Presidio, Texas, has procured a large-scale energy storage system to provide islanding for the entire town. Presidio is particularly vulnerable to extended outages because the town is supplied by a single transmission line that is difficult to access (NEMA 2013).

Wind Energy
Subsector Vulnerabilities
The Southern Great Plains contains some of the best onshore wind resources in the country (Figure 5-10) and represents almost a third of total installed wind power in the United States. Texas, with over 12,000 MW installed, is the national leader, while Kansas and Oklahoma together contribute about 6,000 MW (EIA 2013d).

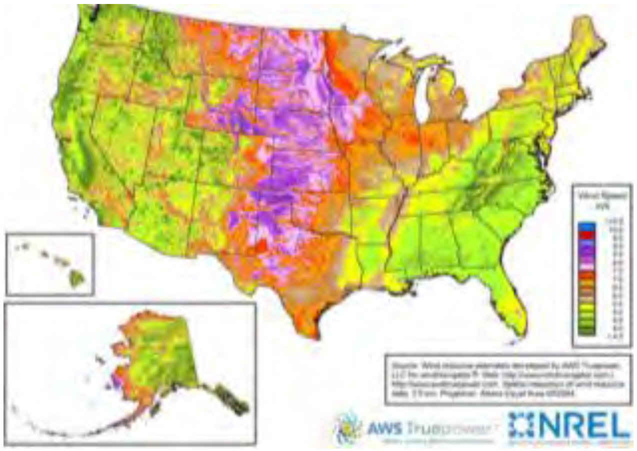

Figure 5-10. Annual average wind speed at 80 meters
Source: NREL 2014

Wind turbines in close proximity to the Gulf Coast may be vulnerable to wind damage from more intense hurricanes. Most wind turbines are designed to withstand sustained wind speeds of 112 mph (Rose et al. 2012), and many hurricanes have winds that significantly exceed this speed. Some climate models have suggested that climate change may lead to changes in average wind speeds, although there is not yet substantial agreement among sources as to how a changing climate will ultimately affect wind resources (DOE 2013).

Wind Energy
Resilience Solutions
There is limited research examining hurricane force wind speeds as pertains to resilience of wind turbine design and construction (Pryor and Barthelmie 2010). While the industry standard design criteria call for turbines to withstand sustained 112 mph wind speeds, more research may be necessary regarding updates to these standard practices and other potential strategies for improving wind turbine resilience.

Regional Climate Change Observations and Projections in Detail

Higher Temperatures

Historical observations

- **Since 1895, average temperatures have increased 0.09°F per decade, or almost 0.99°F** (NOAA 2013).
- **Frost-free season has been lengthening:** The average duration of the frost-free season across the entire Great Plains region increased by about ten days (1991–2012, compared to 1901–1960) (USGCRP 2014).

Future projections

- **Average temperatures are expected to increase at a faster rate:** Depending on the region and greenhouse gas emissions, increases of 3.5°F–8.5°F are expected by 2070–2099 compared to 1971–1999 levels (NOAA 2013).
- **Extremely hot days are projected to become more common:** Across most of the region, 15–30 more days with a daily maximum temperature >95°F are expected by mid-century (2041–2070, compared to 1980–2000); Texas is likely to be the most affected and may see over 30 more extremely hot days per year (NOAA 2013).
- **Consecutive number of days of extreme heat are expected to become longer:** The annual maximum number of consecutive days with a daily high >95°F is projected to increase by 8–20 days by mid-century (2041–2070, compared to 1980–2000) across most of the region; West Texas is likely to be the most affected and may see the number of consecutive days with a daily high >95°F increase by up to 24 days (NOAA 2013).
- **Extremely cold nights are expected to become less common:** Across the region, 0–10 fewer days with daily minimums <10°F are expected by mid-century (2041–2070, compared to 1980–2000) (NOAA 2013).
- **Freeze-free season is expected to lengthen:** Across the region, the freeze-free season is expected to be 21–30 days longer by mid-century (2041–2070, compared to 1980–2000) (NOAA 2013).
- **Cooling degree days (CDDs) are expected to increase:** Across the region, an increase of 600–1,000 CDDs is expected by mid-century (2041–2070, compared to 1980–2000), with Texas and Oklahoma seeing the largest change (NOAA 2013).
- **Heating degree days (HDDs) are expected to decrease:** Across most of the region, declines of 450–850 HDDs are expected by mid-century (2041–2070, compared to 1980–2000); Kansas is likely to be the most affected, with declines of up to 1,050 HDDs possible by mid-century (NOAA 2013).

Changing Precipitation Patterns

Historical observations

- **Historical trends in precipitation are not statistically significant, neither annually nor seasonally** (NOAA 2013).
- **Across the Great Plains, extreme precipitation events have occurred more frequently:** An index of one-day precipitation events expected to occur once every five years shows a statistically significant upward trend since 1895. In 2011, a linear trend of the series showed a 30% increase over the period (NOAA 2013).

Future projections

- **Across most of the region, annual precipitation is expected to decrease:** By the end of the century (2070–2099), precipitation across the region is expected to decrease 0%–12% compared to the period 1971–1999, depending on both latitude and emissions scenario. The decrease in precipitation is expected to be greatest in Texas and southwestern Oklahoma (NOAA 2013).
- **Spring precipitation is projected to decrease in Texas:** Texas is expected to see a 10%–30% decrease in precipitation by the end of the century (2071–2099, compared to 1971–1999) under a higher-emissions scenario (USGCRP 2014).
- **Drier summers are expected across most of the region:** Summer precipitation is expected to decrease by 10%–30% by the end of the century (2071–2099, compared to 1971–1999) under a higher emissions scenario across the entire region, excluding southwestern Texas (USGCRP 2014).
- **Consecutive number of days with little or no precipitation are likely to become longer:** The annual maximum number of consecutive days with less than 3 mm of precipitation is projected to increase 3–15 days by mid-century (2041–2070, compared to 1980–2000) across most of the region, excluding Kansas (NOAA 2013).

Hurricanes and Sea Level Rise

Historical observations

- **Relative mean sea level in Texas has risen because of a combination of global sea level rise and land subsidence in the region:** Relative mean sea level on the Texas coast rose 0.08–0.27 inches/year, depending on the location, between the middle of the 20th century and 2006 (NOAA 2009).

Future projections

- **Sea level rise is expected to accelerate:** Between 1992 and 2050, sea level on the Texas coast is projected to rise at an average rate of 0.14–0.35 inches/year (no ice sheet melt) or 0.27–0.48 inches /year (ice sheet melt), depending on the location (USGCRP 2014).
- **Frequency of intense hurricanes (Category 4 and 5) is projected to increase** (USGCRP 2014).
- **Hurricane-associated storm intensity and rainfall are projected to increase:** Rainfall rates within 100 km of tropical storm centers are projected to increase by 20% by 2100 (USGCRP 2014).

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Chapter 5 Endnotes

[a] Source: USGCRP 2014
[b] Sources: DOE 2013, DOT 2014, USGCRP 2014
[c] CDD projections under A2 scenario; mid-century refers to average for period (2041–2070). Sources: NOAA 2013, USGCRP 2014
[d] Sources: DOE 2013, USGCRP 2014
[e] Sources: NOAA 2013, USGCRP 2014
[f] Sources: DOE 2013, USGCRP 2014
[g] Sources: DOE 2013, USGCRP 2014
[h] Source: USGCRP 2014
[i] Sources: DOE 2013, NOAA 2013
[j] Source: NOAA 2013
[k] Sources: DOE 2013, USGCRP 2014
[l] Under a higher emissions scenario in 2071-2099 compared to 1971-1999 (USGCRP 2014, NOAA 2013)
[m] Source: DOE 2013

Chapter 6: **Midwest**

Climate Change and the Energy Sector

Overview

The Midwest is home to expansive agricultural lands, forests in the north, the Great Lakes, substantial industrial activity, and major urban centers. The region has an energy-intensive economy, and its electricity mix is heavily dependent on thermoelectric plants, with coal- and natural gas-fired power plants accounting for about 70% of annual generation and nuclear power representing more than 20%. More than one quarter of national installed wind energy capacity, one third of biodiesel capacity, and more than two thirds of ethanol production are located in the Midwest. Major climate change impacts projected to increasingly threaten the region's energy infrastructure include the following:

- **Average temperatures are projected to increase, extremely hot days are projected to occur more frequently, and heat waves are projected to become longer and more severe. The average number of cooling degree days (CDDs) is projected to increase by 150–900 by mid-century.**[a] Higher air and water temperatures cause power plants to operate less efficiently and in some cases may force plants to curtail production or temporarily shut down. Transmission line capacity also declines with higher temperatures, reducing the available power supply in the Midwest and in other regions that depend on its electricity exports. At the same time, higher temperatures increase demand for cooling energy, increasing the potential for shortfalls.[b]
- **Heavy precipitation events are projected to occur more frequently, and average winter and spring precipitation levels are projected to increase, increasing the risk of high streamflows and flooding.**[c] Floods can disrupt energy service and damage assets located in flood plains, such as power plants and rail lines. Varying water levels on important shipping routes, including the upper Mississippi River, Illinois River, Missouri River, and Ohio River, as well as the Great Lakes, could disrupt fuel transport along these waterways.[d]

QUICK FACTS

Midwest States:	Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, Ohio, Wisconsin
Population (2013)	61,000,000 (19% of U.S.)
Area (square miles)	447,000 (13% of U.S.)
Energy expenditures	$260 billion

ENERGY SUPPLY & DEMAND		**Annual Production**	**Annual Consumption**	***% for electric power***
Electric power	*TWh*	815	771	*n/a*
Petroleum	*MMbbls*	24	1,150	*<1%*
Coal	*million tons*	112	285	*90%*
Natural gas	*Bcf*	225	4,600	*17%*

ELECTRIC POWER	**Annual Production (TWh)**	***% of Total Production***	**Capacity (GW)**	**Power plants >1 MW***
Natural gas	97	*12%*	69	347
Coal	476	*58%*	105	208
Nuclear	183	*22%*	25	17
Hydroelectric	6	*1%*	2	174
Wind	38	*5%*	15	261
Biomass	8	*1%*	2	140
Solar	<1	*<1%*	<1	10

CRITICAL INFRASTRUCTURE

Petroleum		**Electric Power**	
Wells (>1 boe/d):	5,230	Power plants (>1 MW):	1,421
Refineries:	14	Interstate transmission lines:	48
Liquids pipelines:	27	**Coal**	
Ports (>200 tons/yr):	6	Mines:	94
Natural Gas		**Waterways**	
Wells:	47,000	Coal and petroleum routes:	17
Interstate pipelines:	33	**Railroads**	
Market hubs:	2	Miles of freight track:	35,600

Note: Table presents 2012 data except for the number of oil wells, which is 2009 data.
*Some plants use multiple fuels, and individual generating units may be <1 MW.
Sources: AAR 2014, EIA 2013a, EIA 2013b, EIA 2013c, EIA 2013d, EIA 2014a, EIA 2014b, EIA 2014c, EIA 2014d, EIA 2014e, EIA 2014g, EIA 2014m, NEO 2014, US Census Bureau 2014, USACE 2014

Table 6-1. Examples of important energy sector vulnerabilities and climate resilience solutions in the Midwest

Subsector	Vulnerability	Magnitude	Illustrative Resilience Solutions
Thermoelectric Power Generation; Electric Grid	Reduced power plant generation capacity and reduced electric grid capacity due to higher temperatures[e]	More than 90% of power generation is from thermoelectric plants. The region exports significant quantities of electricity, so reductions in generation also affect neighboring regions[f]	Improved operations protocols, expanded capacity, alternative water sources, recirculating, dry, or wet-dry hybrid cooling systems
Fuel Transport	Increased risk of disruption to rail and barge transport of coal and petroleum due to flooding, drought, and changing waterway levels[g]	The Midwest produces 11% of U.S. coal, and 58% of the region's power plant capacity is coal-fired. Disruptions in rail and barge transport also affect other regions[h]	Elevating infrastructure, upgrading drainage systems, ensuring culverts can handle increased runoff, waterway dredging and maintenance[i]
Electricity Demand	Increased demand for electricity for cooling in the summer due to higher temperatures, severe heat waves, and higher humidity[j]	The region is projected to experience 150–900 CDDs per year by mid-century, as well as increased humidity[k]	Energy efficiency, load management, capacity additions

Regional Energy Sector Vulnerabilities and Resilience Solutions

Key energy subsectors and illustrative examples of resilience solutions in the Midwest are discussed below. System components that are most vulnerable to climate change are described first.

Thermoelectric Power Generation

Subsector Vulnerabilities

Electricity generation in Midwestern states is dominated by thermoelectric power plants, accounting for about 92% of total electricity production, with over half generated from coal-fired plants (EIA 2013d). Projected changes in precipitation and temperature—both independently and in combination—may restrict the available capacity of thermoelectric power generation in the region.

Climate change is projected to have the following impacts on thermoelectric power generation in the Midwest:

- Increasing air and water temperatures are expected to reduce the generation capacity and efficiency of thermoelectric units (DOE 2013).
- Expected increases in heavy precipitation events will increase the likelihood of associated flooding, which could damage facilities and disrupt operations (USGCRP 2014).
- Decreasing summer precipitation and longer periods between rainfall events may limit water availability, affecting power plant operations (DOE 2013, USGCRP 2014).

Projected climate change-induced increases in average and extreme temperatures in the Midwest may reduce regional power generation capacity. Increases in ambient air and water temperatures reduce the thermal efficiencies of thermoelectric power plants, which can result in reduced power output and additional fuel consumption. Approximately 95% of electrical generating infrastructure in the region is susceptible to decreased efficiency due to higher temperatures (USGCRP 2014). In addition, the Midwest is a net exporter of electricity; decreases in power output or increases in fuel consumption could hinder system flexibility or increase costs across the eastern United States (USGCRP 2014).

Increasing water temperatures put power plants at risk of exceeding thermal discharge limits established to protect aquatic ecosystems, and nuclear power plants face safety limits on the intake temperature of water used for cooling (DOE 2013). Plants facing elevated water temperatures may be forced to temporarily shut down or curtail generation. The sidebar presents examples of nuclear and coal plants that, over the last few years, have had to take action because of incoming or outgoing water being inadequate or too warm. These plants have reduced generation, shut down, or sought special exemptions from state regulators to continue to operate.

Examples of high temperatures affecting thermoelectric power generation in the Midwest

2012: Four coal-fired power plants and four nuclear power plants in Illinois requested permission to exceed the permitted water temperature discharge levels, established to prevent adverse ecological impacts. The Illinois Environmental Protection Agency granted special exceptions to the eight power plants, allowing them to discharge water that was hotter than allowed by federal Clean Water Act permits (Eilperin 2012).

2012: The Braidwood nuclear plant in Illinois had to get special permission from the U.S. Nuclear Regulatory Commission to continue operating after the temperature of the water in its cooling pond rose to 102°F (Eilperin 2012).

2012: The Powerton coal plant in central Illinois had to temporarily shut down a generator during peak summer heat when water in the cooling pond became too warm for effective cooling (Bruch 2012).

2006: One unit at American Electric Power's D.C. Cook Nuclear Plant was shut down because the high summer temperatures raised the air temperature inside the containment building above 120°F, and the temperature of the cooling water from Lake Michigan was too high for cooling intake. The plant could not be returned to full power until the heat wave passed five days later (Krier 2012).

2006: Two units at Exelon's Quad Cities Generating Station had to reduce electricity production to less than 60% electricity capacity because the temperature of the Mississippi River was too high to discharge heated cooling water from the reactors (USNRC 2006).

Thermoelectric power plants are also vulnerable to flooding. Winter and spring precipitation for much of the Midwest could increase by 20% or more by the end of the century, although summer rainfall is projected to decline (NOAA 2013b, USGCRP 2014). In addition, more intense rainfall events are expected, increasing the chance of flooding from rapid runoff channeled from farm fields and urban areas. Power plants are typically located near rivers or other sources of water and may be susceptible to physical damage and disruption from flooding. Many areas in the Midwest have experienced increasing frequency and magnitude of flooding events (Hirsch and Ryberg 2012), and this trend is projected to continue (Figure 6-1) (USGCRP 2014).

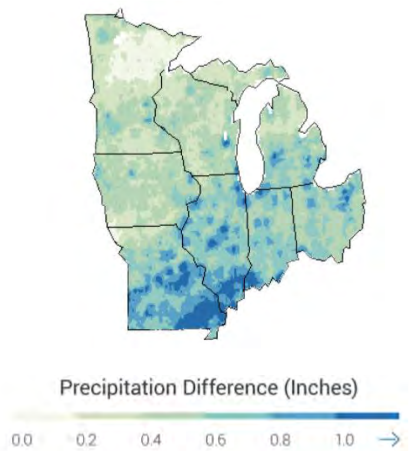

Figure 6-1. Rainfall increase during the wettest five-day period over a year by mid-century[1]
Source: USGCRP 2014

While annual average precipitation and heavy rainfall events are expected to increase, summer rainfall is projected to decline, and the number of consecutive days with no precipitation is projected to rise (Figure 6-2) (USGCRP 2014).Models indicate more precipitation when it rains but increased duration between rainfall events, which increases the chance of seasonal drought. Over 90% of electricity generation in the Midwest requires freshwater for cooling (UCS 2012), and low flow conditions in rivers and lakes pose an operational risk to thermoelectric facilities that require cooling water. Summer droughts can also contribute to warmer surface water temperatures, exacerbating power plant vulnerabilities associated with higher temperatures.

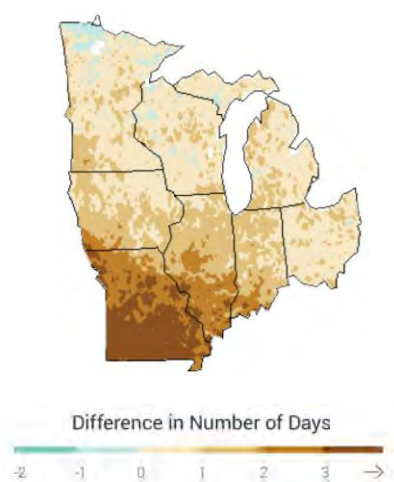

Figure 6-2. Increase in the number of consecutive dry days over a year by mid-century[1]
Source: USGCRP 2014

[1] Projected changes for mid-century (2041–2070) relative to the end of the last century (1971–2000) under an A2 emissions scenario

Thermoelectric Power Generation

Resilience Solutions

New generation capacity can help address falling capacity due to decreased plant efficiency. Capacity expansion with low water requirements (e.g., thermoelectric power plants with dry cooling or wet–dry hybrid cooling technology) or no water requirements (e.g., wind and solar photovoltaics) would help make the region's power sector more resilient to climate change. Programs that reduce total and peak electricity demand can also reduce the water needs of thermoelectric generators.

Technologies such as wind energy that are more resilient to climate change impacts can play an important role in future capacity additions. The region has abundant wind resources, and new generation is likely to include expanded wind capacity (NREL 2014a). For example, Illinois, Iowa, and Minnesota are among the top five states in the nation in existing and planned wind capacity additions in 2014 and 2015 (Figure 6-3). Policy measures play an important role in encouraging wind energy development. Michigan's wind capacity is among the fastest growing in the nation and is boosted by Michigan's Clean, Renewable, and Efficient Energy Act, which requires that all electricity providers obtain at least 10% of their power from renewable resources (EIA 2013e). Illinois' renewable portfolio standard requires that investor-owned electric utilities with more than 100,000 Illinois customers obtain 25% of retail sales from renewable resources by May 2026, with at least 75% of the requirement from wind (EIA 2015).

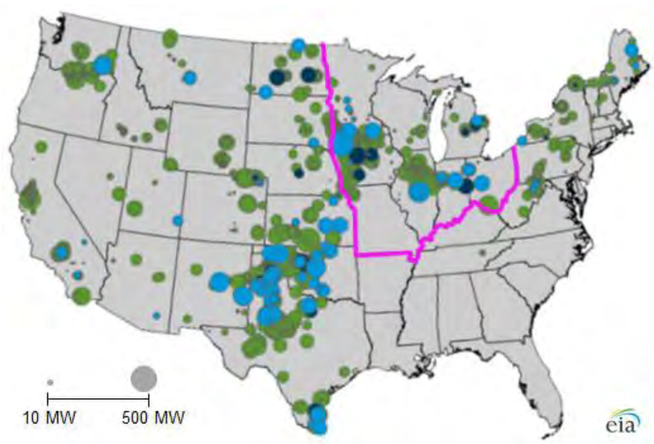

Figure 6-3. Existing wind capacity (green) and planned wind plant installations in 2014 (dark blue) and 2015 (light blue)
Source: Adapted from EIA 2014j

Engineered barriers such as levees can be effective in protecting vulnerable thermoelectric power plants from flooding during heavy precipitation events. Utilities may also elevate critical equipment to protect against flooding or upgrade plants with submersible equipment or watertight doors. Planners can protect new capacity by locating new generators at higher elevations or outside of flood plains.

To better understand the implications of changing water availability for cooling thermoelectric generation, advances are being made in modeling and projecting future impacts. For example, Exelon is developing tools to predict near- and long-term (decades) changes in water availability, including impacts linked to climatic changes, increased population density, and upstream use (Exelon 2013). In 2013, Exelon completed a pilot hydrological/climate modeling study of the Kankakee River in northern Illinois, which supplies water to the Braidwood nuclear plant. The facility had to suspend its withdrawals for several days during the summer of 2012 because flows in the river dipped below the threshold specified in the facility's public water withdrawal permit from the Illinois Department of Natural Resources. The Braidwood study was conducted as an analytical pilot to determine the extent to which watershed flows could be predicted and the extent to which climate change could potentially alter future water availability. In addition, Exelon and the U.S. National Oceanic and Atmospheric Administration (NOAA) are examining approaches to "downscale" NOAA climate models, which would be required before such models could be applied to operational decision making on a facility level.

Fuel Transport

Subsector Vulnerabilities

The Midwest is reliant on rail, barge, pipeline, and truck transport of energy products, notably coal. The region produces about 11% of the coal produced in the United States and imports significant quantities from the Northern Great Plains and Northeast regions (EIA 2013a). The Midwest depends heavily on coal for electricity, with coal-fired generation making up 58% of all electricity generated in the region (EIA 2013d). Rail is the primary means of transporting coal, but another key fuel transportation method is shipping of coal (and other energy products) by barge, utilizing the Mississippi and Ohio Rivers, as well as the Great Lakes. Energy commodities make up the largest proportion of total inland U.S. waterborne cargo traffic, and waterborne commerce is essential to the energy sector (USACE 2012). New domestic energy production is spurring rapid growth in the waterborne transport of energy commodities and related products, increasing the demands on waterborne traffic.

Midwest refineries and consumers rely on supplies of crude oil and refined petroleum products imported from other regions by barge and pipeline. In 2013, almost 580 million barrels of crude oil and refined petroleum products were moved via pipeline from PADD 3 (a region including the Gulf Coast states) to PADD 2 (which includes the Midwest, as well as some Great Plains and Southeast states) (EIA 2014k). As supplies of crude oil from the Northern Great Plains and Canada continue to grow, the Midwest is becoming less dependent upon pipeline shipments of crude oil from the Gulf Coast. Movements by barge or tanker are smaller but still important. In 2013, 80 million barrels of crude oil and petroleum products were shipped from PADD 2 to PADD 3 by barge and tanker, and 18 million barrels of petroleum products were moved in the opposite direction (EIA 2014f). In 2012, crude oil, refined petroleum products, and coal accounted for 55% of all U.S. waterborne cargo traffic by weight (DOE 2015c).

Climate change is projected to have the following impacts on energy transport in the Midwest:

- Expected increases in extreme precipitation events will increase the frequency of associated floods, which could damage and disrupt transport infrastructure (DOE 2013, NOAA 2013b, USGCRP 2014).
- More frequent and intense heat waves could damage rail infrastructure, increasing the likelihood of rail congestion and disruption to energy commodities transport (DOE 2013, NOAA 2013b, USGCRP 2014).
- Barge transport of energy products on rivers and lakes faces increased risk of disruption from changes in water levels due to flooding, droughts, and evaporation (DOE 2013, USGCRP 2014).

Both heavy precipitation events and extended periods of rainfall that saturate the soil can lead to regional flooding events (NOAA 2013b, USGCRP 2014). High water levels increase flow velocities and make river navigation by barge difficult or dangerous (Posey 2014, USGCRP 2009). Heavy precipitation events can also cause high runoff and flooding that can disrupt train traffic and submerge track and roadbed, causing extensive damage (Figure 6-4) (Union Pacific 2011). High streamflows during heavy precipitation events erode track beds, especially where railroads run in low-lying areas adjacent to rivers and streambeds (DOE 2013, USGCRP 2014). Higher current velocities can also affect river crossings, including rail and pipeline bridges, by scouring bridge piers (Posey 2014). Buried pipelines are less vulnerable to flooding impacts but may be subject to damage from flood-borne debris, as high streamflow could erode the soil and expose pipelines buried in riverbanks or

Figure 6-4. A railroad bridge is partially swept away by Cedar River floodwaters in Waterloo, Iowa, in 2008
Source: NOAA 2015

under the riverbed (GAO 2014). For example, in 2011, flooding along the Missouri River in Iowa submerged and damaged a pipeline, causing the pipeline to spill over 800 barrels of natural gas liquids into the river (EPA 2012, Gebrekidan 2011).

As the frequency, length, and intensity of heat waves increase, railroads and roadbeds are more susceptible to material stress and damage (Posey 2012). Heat waves also increase the likelihood of rail buckling, and railroads may reduce the loading of rail cars and issue “slow orders" to prevent derailments due to rail buckling (CCSP 2008, FRA 2011, USGCRP 2014). These measures can be costly, as they lead to delays, consume rail capacity, increase operating costs, and require railroads to maintain larger fleets of rolling stock (CCSP 2008). Heat waves can also cause bridges to expand, stressing thermal expansion joints and causing a need for more frequent maintenance (Posey 2012).

Fuel transport during the 2008 Midwest floods

Parts of Illinois, Indiana, Iowa, and Wisconsin received more than a foot of rain over 15 days in 2008, causing widespread flooding along the Mississippi River and regional rivers. The floods caused extensive damage to the region and disrupted barge, truck, and rail transport of energy products (NOAA 2008). The U.S. Army Corps of Engineers was forced to close locks on a 250-mile stretch of the upper Mississippi River, disrupting transport of petroleum products, coal, and ethanol (Iowa DOT 2008). Major rail infrastructure in the region was destroyed by floodwaters as railroad bridges were swept away, disrupting rail service in Iowa and other portions of the Midwest (DOE 2008). Damage to the railroad system in Iowa was estimated to be between $68 and $83 million and repairs lasted up to 12 months. In addition, 125 miles of primary highway were washed out, and 1,500 miles of road needed replacement (NOAA 2009).

Increasing episodes of flooding (see text box) and drought affect waterway levels and may have an impact on barge transport of energy commodities in the region, particularly along the Mississippi River. For example, during the 2012 drought, Mississippi River levels were near historic lows, and the U.S. Army Corps of Engineers allowed barges to move in only one direction for eight hours a day and closed the river to barge traffic for the remaining 16 hours for dredging operations (Fears 2013). In December 2012, total barge cargo in the portion of the Mississippi River running from St. Louis to Cairo, Illinois, was down more than 1,100 kilotons compared to December 2011. By February 2013, barges that typically run 12 feet deep were only allowed to run 8–9 feet deep (Rizzo 2013). A tow (chain of barges pulled or pushed as a group) on the upper Mississippi, Illinois, and Ohio Rivers typically has 15 barges, each capable of carrying more than 1000 tons. A one-inch drop in river level reduces tow capacity by 255 tons, resulting in transport delays and higher costs (NOAA 2012).

There is still considerable uncertainty in projections for Great Lakes water levels (USGCRP 2014). Increasing temperatures may lead to drops in lake levels due to increased evaporation, but increases in precipitation may offset this effect (Posey 2012). While lower water levels could reduce the amount of cargo ships could transport, if lake ice levels decline, the St. Lawrence Seaway may remain open longer and increase the shipping season (USGCRP 2014, Posey 2012).

Fuel Transport

Resilience Solutions

Measures to harden fuel transportation infrastructure to better withstand flooding include building or improving the design of dams and levees, some of which failed to hold during the 2008 floods in the Midwest. The dams and levees along the upper Mississippi River were not constructed according to a comprehensive plan, and the level of protection provided by these structures varies, ranging from protection from flood events occurring once in 5 years or less up to once in 500 years (CRS 2009). To improve resilience to drought conditions, increased maintenance dredging can increase river depths, reducing the likelihood of barge transport restrictions.

Risks to railroads from flooding can be mitigated through system and track upgrades, but these can be costly. Resilience solutions include upgrading drainage systems, ensuring culverts can handle increased runoff from heavy precipitation events, and increasing pumping capacity in tunnels (DOT 2009). Policy measures that restrict new rail line development in floodplains, revise standards for drainage capacity or elevating tracks, or require more frequent track inspection can also improve resilience. Track integrity inspection is shifting from visual methods to sophisticated sensing techniques operated from vehicles such as hi-railers (trucks that ride on rails).

Riverbank transport assets, including railroads and buried pipelines, can be protected through the use of manmade or natural barriers to reduce the risk of erosion. Pipelines under river crossings can be protected by using horizontal drilling techniques to bury the pipe significantly deeper than traditional trenching methods (Brown 2013, Miller and Bryski 2012). Pipelines at risk from erosion can also be replaced with materials that are less likely to leak or rupture from impacts (e.g., coated steel rather than cast iron or bare steel).

Rails are designed to withstand temperature gradients based on expected ambient temperatures and heat generated from railcar traffic (FRA 2011, Volpe 2003). New or replacement tracks can be installed to function at higher temperatures, reducing the likelihood of derailment. Railroad companies that are incorporating considerations of higher temperatures from climate change into their planning would most likely upgrade tracks when they are replaced for other reasons, including normal wear and tear, upgrades for traffic reasons, or damage from other extreme events, including flooding (CCSP 2008).

To increase resilience to disruptions in fuel supply, utilities may also consider increasing fuel stockpiles. For example, Ameren is implementing new fuel inventory policies and developing alternative delivery options at facilities to mitigate the risk of fuel supply disruption (Ameren 2013).

Electricity Demand

Subsector Vulnerabilities

The Midwest on the whole is an electricity exporter, providing power to adjacent states in the Northeast (USGCRP 2014). However, several states in the region, including Indiana, Michigan, Minnesota, Ohio, and Wisconsin, are net importers of power from neighboring states and Canada (EIA 2014a, EIA 2012b). Some localities in the Midwest, as well as adjacent states in the Northeast, may be affected if electricity demand in the region grows.

Winters in the region are cold, and in most cities, total energy demand for winter heating is five to seven times greater than energy demand for cooling (USGCRP 2014). But since heating is traditionally provided by fossil fuels, including natural gas and heating oil, utilities in the region are typically summer peaking, with summer peak demand an average of 14% higher than winter peak demand (EIA 2013c). The region is highly energy-intensive and more industrial than the rest of the country, with 34% of total electricity consumption in the industrial sector (EIA 2013c, USGCRP 2014).

Climate change is projected to have the following impact on electricity demand in the Midwest:

- Higher maximum temperatures, longer and more severe heat waves, higher humidity, and higher overnight lows are likely to increase electricity demand for cooling in the summer (NOAA 2013b, USGCRP 2014).

As shown in Figure 6-5, an increase of 300–900 CDDs is projected by mid-century for most of the region, with the exception of the northern portions of Minnesota and Wisconsin and the upper peninsula of Michigan (NOAA 2013b). Relative to historical climate, and depending on the region, these increases represent up to a doubling of CDDs by mid-century (NOAA 2013b).

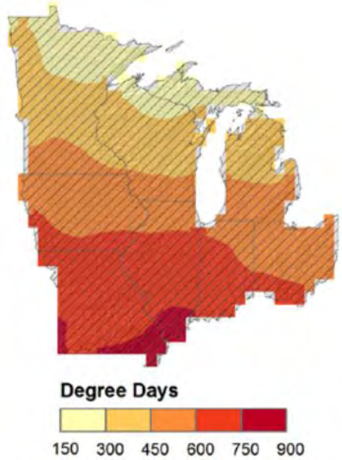

Figure 6-5. Increase in annual total CDDs by mid-century[2]
Source: NOAA 2013b

Additional CDDs will likely impel consumers to use more air conditioning as daytime and nighttime temperatures rise. In addition, it is likely that warmer temperatures will increase the number of homes and businesses with air conditioners in the region, which would amplify the electricity demand effects of increasing CDDs. One study projects that temperatures in much of the Midwest will be similar to current temperatures in the South by the end of the century, including more days over 95°F each year in Chicago than the average Texas resident experiences today (RBP 2015). Market penetration of air conditioners in the South is currently 98%, compared to 91% in the Midwest (EIA 2011b). As temperatures increase, the market penetration of air conditioners in the Midwest may approach that of the South. These changes could contribute to rapid increases in total and peak energy demand.

Demand for cooling energy depends on not only temperature but also humidity (Beecher and Kalmbach 2012). Projected changes for the region include increasing heat waves coinciding with increased humidity, compounding factors driving growth in peak energy demand (USGCRP 2014).

Increasing use of air conditioning is likely to heighten power sector vulnerability to service disruptions unless it is offset by demand management programs, improvements in air conditioner energy efficiency, or new generation and transmission capacity (refer to Thermoelectric Power Generation and Electric Grid sections).

In the winter, increasing temperatures are expected to reduce demand for heating. One study found that heating degree days may decrease by 15% across the Midwest by mid-century (CMAP 2013). Having fewer heating degree

[2] Projected changes for mid-century (2041–2070) relative to the end of the last century (1980–2000) under an A2 emissions scenario

days is likely to reduce demand for heating fuel, primarily natural gas (EIA 2013f).

Electricity Demand

Resilience Solutions

Energy efficiency, load management, and capacity expansion (including more climate-resilient technologies) all play roles in reducing the exposure of the Midwest's power sector to increasing electricity demand. One study found that increased demand in the Midwest associated with climate change could exceed 10 GW, which would require more than $6 billion in infrastructure investments (Gotham et al. 2012).

As changes to electricity demand depend on not only climate but also population change, economic growth, and the deployment of new technologies, investments in capacity expansion will likely be made as part of an integrated planning process. Growth in power consumption in the region has been slower than the national average over the last two decades and has fallen in several states (Beecher and Kalmbach 2012). This decrease is partly due to slow population growth, which has been slower than any other region over the same period (U.S. Census Bureau 2014).

Energy efficiency, load management, and other programs administered by regional power producers can help reduce total electric power demand and peak loads (Beecher and Kalmbach 2012). Midwest utilities have already implemented a number of demand-side management (DSM) practices to reduce loads and improve energy efficiency. For example, Hoosier Energy is expanding DSM efforts targeting water heaters, air conditioners, and heat pumps, contributing to lower costs and better reliability in times of high energy demand. The utility also offers incentives to encourage installation of higher efficiency heating and cooling systems, helps customers meet enhanced energy efficient design and construction standards to lower energy costs, and supports appliance recycling programs to remove inefficient refrigerators and freezers (Hoosier Energy 2014).

Increasing resilience through flexible demand

Columbia Water & Light (CWL) in Missouri offers a load shedding program to commercial and industrial customers. Customers who reduce their electric demand during peak demand periods can receive a credit of $36 per year per kilowatt based on the average reduction in demand during requested periods. Customers can receive credits for up to 50% of the customer's normal base load demand prior to load shedding (CWL 2014b).

DSM programs have so far achieved peak load reductions of over 3,700 MW and enrolled over 5,000 industrial customers, 32,000 commercial customers, and 1.2 million households in price responsive programs (EIA 2013c). A survey of 37 Midwest Independent System Operator (MISO) utilities indicated a peak load reduction potential of over 4,700 MW from retail demand response programs (LBNL 2008).

Capacity expansion can also help alleviate the stresses that increasing peak electricity demand will place on the region's electricity supply. In addition, new capacity investments

2003 Blackout: A lesson in regional interdependencies

On August 14, 2003, a major blackout struck the northeastern United States and parts of Canada, including areas in Connecticut, Maryland, Michigan, New Jersey, New York, Ohio, Vermont, and the Canadian provinces of Ontario and Quebec. Some 50 million people were affected. The blackout occurred on a hot summer day, with temperatures exceeding 87°F and elevated power demand throughout the region (DOE 2004).

Figure 6-6: New York City skyline during the 2003 blackout that was initiated in the Midwest

Source: DHS 2013

The blackout was initiated by outages on transmission lines operated by First Energy (FE) in Ohio. High ambient temperatures and high demand caused a 345 kV transmission line to sag low enough to arc to a tree, causing the line to trip (DOE 2004). This outage caused increased loads on other lines, causing those lines to trip, and soon a surge of power propagated throughout the northeastern grid. While management practices allowed the outage to spread across the region, the sensitivity of FE's transmission lines to elevated temperatures were also to blame (DOE 2004). Subsequent investigations found that FE made optimistic assumptions about transmission line cooling when setting summer emergency ratings, and that FE had failed to trim trees in its rights-of-way, precipitating the line strike (DOE 2004).

may be needed to replace a substantial number of baseload coal plants that may be retiring (see Thermoelectric Power Generation section) (EIA 2014l).

Electric Grid

Subsector Vulnerabilities

The Midwest region includes portions of MISO and PJM Interconnection, as well as a small part of the Southwestern Power Pool (SPP). The region's grid is dense, with total regional power production and consumption second only to the Southeast and significant mileage of 345 kV lines (EIA 2013b, EIA 2013c, EIA 2014a).

Climate change is expected to have the following impacts on the electric grid in the Midwest:

- Higher average and extreme air temperatures and higher nighttime temperatures reduce the capacity of transmission lines and substations, increasing the likelihood of disruption (DOE 2013, USGCRP 2014).
- Higher extreme temperatures may reduce the lifetime transformers and reduce transformer overloading capacity (Hashmi et al. 2013, USBR 2000).

Higher temperatures can cause transmission operators to decrease the current-carrying capacity of transmission lines in order to protect the equipment (Sathaye et al. 2013). High temperatures cause thermal expansion of transmission line materials, and sagging can permanently damage lines and increase the likelihood of power outages when the lines make contact with other lines, trees, or the ground (see sidebar) (DOE 2013). In Ohio, heat events have resulted in transmission outages for about 25,000 customers from 1992–2009 (DOE 2015b). The combined impacts of increasing demand and reduced capacity increase the likelihood that transmission operators will be forced to impose brownouts (Sathaye et al. 2013). Additionally, in the summer, overheated power lines rely on cooler overnight temperatures to reduce thermal load. Projected climate changes include heat waves with higher nighttime temperatures that hinder overnight cooling and may lead to more overheated power lines (DOE 2013, USGCRP 2014).

Reduced transmission capacity, when combined with projected increases in demand for cooling energy and reductions in available generating capacity associated with higher air and water temperatures, can also affect regions that depend on power imports from the Midwest.

Higher ambient temperatures can increase the likelihood that power transformers will be damaged, especially on extremely hot days when electricity demand is highest (Hashmi et al. 2013, USBR 2000). Power transformers are typically rated for 24-hour average ambient temperatures of 86°F (when temperatures do not exceed 104°F) (PJM 2011). Above a transformer's rated temperature, its paper insulation breaks down at exponentially higher rates, so even incremental increases in ambient temperature can harm transformers, especially if high temperatures occur during grid emergencies when transformers must be overloaded for safety or reliability purposes (Bérubé 2007, Hashmi et al. 2013, USBR 2000). To protect transformers, operators may be forced to reduce loading capacity (USBR 2000).

Electric Grid

Resilience Solutions

New and existing transmission infrastructure can be made more resilient through the use of smart technologies that better respond to grid emergencies by isolating outages before they can cause cascading failures (Ameren 2013, DOE 2004, DOE 2013). These advanced technologies provide increased redundancy in transmission networks and substations. New transmission lines can also be designed to accept emergency loading conditions at higher temperatures, and operators can use realistic assumptions about weather conditions when defining emergency conditions (DOE 2004, DOE 2013).

Building a resilient electric grid in Chicago

Commonwealth Edison, a unit of Exelon Corporation, has partnered with American Superconductor Corporation (AMSC) on the Resilient Electric Grid (REG) effort, a plan to deploy AMSC's high-temperature superconductor technology (AMSC 2014). This technology will be used to build a superconducting cable system to connect substations in Chicago's grid and build redundancy that allows multiple substations to share the extra load in the event of a substation going offline (AMSC 2014, DHS 2015). By splitting the load among operational substations, REG can help prevent outages (DHS 2015). REG is a part of the U.S. Department of Homeland Security Science and Technology Directorate's efforts to improve the security and resilience of electric grids in the United States, and was validated at Oak Ridge National Laboratory (AMSC 2014, DHS 2015).

Improved operations can also increase grid resilience. Vegetation management is an important means of preventing line outages caused by tree strikes, as well as fires that can be started by such events (DOE 2013). For example, American Electric Power (AEP) has invested more than $1 billion in vegetation management around transmission lines and is designing new and replacement poles to withstand damage greater than its National Electric Safety Code (NESC) requirement in the service territory (AEP 2014). In some cases, grid resilience can be improved through undergrounding of lines, although it is costly. For example, Ameren is burying power lines in the region to increase physical resilience and is working to incorporate smart technology such as intelligent switches that can isolate outages and respond to failures when damage occurs (Ameren 2013).

The resilience of transformers to higher air temperatures and higher nighttime temperatures can be increased by installing or upgrading forced-air or forced-oil cooling in transformers (Hashmi et al. 2013, USBR 2000). Operators can derate transformers during periods of elevated ambient temperatures to lower the thermal loading and protect the transformers from damage (USBR 2000). In the long term, operators can replace existing transformers with thermally upgraded transformers to increase resilience (Bérubé et al. 2007).

Local power generation can improve resilience by reducing reliance on long-distance delivery of electricity via the grid. Local or distributed generation, such as onsite solar panels or small-scale wind power (Figure 6-7), reduces exposure to grid outages. In addition, critical facilities such as emergency response services and water utilities can install backup power generators with sufficient capacity to operate continuously for extended outages.

Figure 6-7: Small scale wind turbines at Dull Homestead Farm in Brookville, Ohio
Source: DOE 2015a

Bioenergy

Subsector Vulnerabilities

As a major producer of agricultural products, the Midwest is critical to the nation’s supply of biofuels. Ethanol production from corn dominates regional bioenergy production and consumption. It also includes a small amount of biodiesel production from canola oil, and captured landfill and wastewater gases are used to generate electricity and produce renewable natural gas (biomethane).

The Midwest region is home to over half of the nation's ethanol refining capacity, with operational facilities capable of producing 7.3 billion gallons of ethanol per year (NEO 2014). Of the 121 ethanol biorefineries in the region, all but one rely on corn as a feedstock (RFA 2014). While corn is a commodity and is grown in almost every state, corn production for biofuel is an especially important product in the Midwest. Led by Iowa and Illinois (ranked first and second among states in corn production, respectively), the region harvested 58% of the nation's corn acres in 2013 (USDA 2014).

Climate change is expected to have the following impacts on bioenergy in the Midwest:

- Moderately higher temperatures may benefit crops, but extreme temperatures may harm them; warmer temperatures may also benefit weeds, disease, and pests (USGCRP 2014).
- Lower numbers of freezing days and a lengthening of the frost-free growing season may extend the range where biofuel crops can be grown (Bjerga 2012, NOAA 2013b, Roberts and Schlenker 2011).
- Moderate increases in seasonal precipitation may benefit crops, but an increasing probability of seasonal drought and floods may harm them (NOAA 2013b, USGCRP 2014).

The projected impacts of climate change on corn growth are complex, with a mix of outcomes depending on region and climate uncertainty, and are expected to evolve over time. Changes in the length of the frost-free season are projected to be large and positive, aiding corn cultivation, with increases of 15–30 days per year by the middle of the century, depending on the location (NOAA 2013b). Plant growth can also be aided by increased CO_2 levels. In the long run, however, temperature increases are projected to shorten the duration of reproductive development of corn and lead to declines in yield (USGCRP 2014). Additionally, any beneficial effects to crops may be outpaced by increased weeds, diseases, and pests, making cultivation more difficult and less productive (USGCRP 2014).

Projected increases in winter and spring precipitation may also benefit agricultural productivity, as soil moisture is recharged. However, springs that are too wet may also reduce crop yields, forcing growers to switch to shorter-season varieties. The region is expected to experience increased intensity of extreme precipitation events, which can erode soils and flood fields. Finally, higher temperatures (which increase evapotranspiration), declining summer precipitation, and an increase in the average number of days without precipitation may increase the region's vulnerability to periodic seasonal drought (USGCRP 2014).

Crop yields in the Midwest will be more strongly influenced by anomalous weather events than by changes in average temperature and annual precipitation. Increasing intensity, frequency, and length of heat waves may also reduce yields by preventing the effective pollination of crops (Figure 6-8) (USGCRP 2014).

Figure 6-8. Drought-stressed corn
Source: Station 2012

Figure 6-9 shows the effects of changes in maximum summer temperature on yields for two major crops in the region.

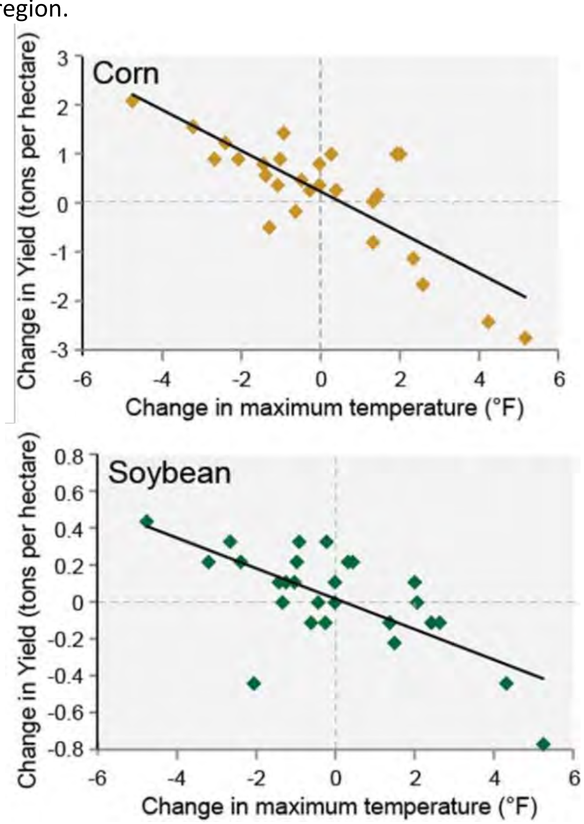

Figure 6-9. Differences in corn (top) and soybean (bottom) yields based on maximum summer temperatures in Illinois and Indiana
Source: USGCRP 2014

Biorefineries may also be vulnerable to climate change impacts. Biorefineries—which convert biomass (predominately corn) to ethanol or other fuel—can use a substantial amount of water. Water needs in biorefineries have fallen significantly over a ten-year timeframe from an average of 6 gallons of water per gallon of ethanol produced down to 2.7 (Wu and Peng 2011). Declines are largely due to new efficient designs; however, similar to petroleum refineries, biorefineries could face water shortfalls if seasonal droughts occur more frequently (DOE 2013, USGCRP 2014).

Bioenergy

Resilience Solutions

A number of resilience-building options are available to growers of biofuel crops. In the Midwest, a longer freeze-free season could allow more northern farmers to grow corn. Nationally, adaptation strategies for agriculture include diversification of crops and crop rotation (including heat- and drought-tolerant varieties), increased use of pesticides, and additional practices associated with sustainable agriculture, such as improving soil quality and minimizing off-farm flows of nutrients and pesticides (USGCRP 2014). Bio-refining technologies that use less water to produce fuels can also help increase resilience in cases of seasonal water shortages.

Wind Energy

Subsector Vulnerabilities

The Midwest region has over 15,000 MW of operational wind generating capacity, or 5% of total capacity in the region (EIA 2013b). In the Midwest, 146 utilities and producers operate 261 wind farms (EIA 2013b). Some of the best onshore wind resources in the country are located in Illinois, Iowa, and Minnesota, and all of the states in the region except Indiana incentivize wind power with renewable portfolio standards (EIA 2012a, NREL 2014a).

Although some models have suggested that climate change may lead to declines in average wind speeds, there is not yet substantial agreement among researchers as to how a changing climate will ultimately affect wind resources in the United States (DOE 2013). It is uncertain whether wind power production will be disrupted by climate-driven changes to wind patterns or if it will see an increase in available capacity.

Wind Energy

Resilience Solutions

Various measures can be taken to increase the resilience of wind energy. In general, if wind speeds decline, operators can increase the resilience of wind energy by increasing the efficiency of operating turbines, although these improvements would be beneficial regardless of reductions in wind resources. Generation by a single turbine can be increased by increasing turbine height and blade length (AWEA 2014). A wind farm can also operate more efficiently if turbines are sited to reduce the impact of a single turbine's wake on other turbines (NREL 2014b).

Advances in wind turbine technology can also enhance resilience to more extreme wind conditions. For example, because utilities cannot control when wind is available, it has been difficult to fully incorporate wind power into the electricity grid, but innovative battery designs and other grid-scale storage technologies designed to store energy produced by wind could enhance the use of wind turbine technology.

Regional Climate Change Observations and Projections in Detail

Higher Temperatures

Historical observations

- **Since 1895, average temperatures have increased 0.14°F per decade, or almost 1.5°F** (NOAA 2013a).
- **Spring temperatures have increased 0.17°F per decade, or almost 1.9°F** (NOAA 2013b).
- **Frost-free season has been lengthening**: The average length of the frost-free season across the Midwest region increased by about nine days (comparing 1991–2012 to 1901–1960) (USGCRP 2014).
- **Water temperatures on the Great Lakes have increased by more than 5°F from 1968 to 2002** (NOAA 2013a).
- **Ice coverage on the Great Lakes has decreased**: The average annual maximum ice coverage during 2003–2013 was less than 43%, whereas the average ice coverage during 1962–2013 was 52% (USGCRP 2014).

Future projections

- **Average temperatures are projected to increase at a faster rate**: Depending on the region and greenhouse gas emissions, increases of 4.5°F–9.5°F are projected by 2070–2099 compared to 1971–1999 levels, with the largest increases in Michigan, Minnesota, and Wisconsin (NOAA 2013b).
- **Extremely hot days are projected to become more common**: Across most of the region, up to 25 more days with daily maximum temperatures >95°F are projected by mid-century (2041–2070, compared to 1980–2000); portions of southern Missouri and Illinois are likely to be the most affected and may see as many as 30 more extremely hot days per year (NOAA 2013b).
- **Consecutive number of days of extreme heat are expected to become longer:** The annual maximum number of consecutive days with a daily high >95°F is projected to increase by up to 16 days by mid-century (2041–2070, compared to 1980–2000) across the region; the southern portion of the region is likely see the greatest increases (NOAA 2013b).
- **Extremely cold nights are projected to become less common**: Across the region, 5–25 fewer days with daily minimums <10°F are projected by mid-century (2041–2070, compared to 1980–2000) (NOAA 2013b).
- **Frost-free season is projected to lengthen**: The frost-free season is projected to be 15 to more than 30 days longer by mid-century (2041–2070, compared to 1980–2000) across the region, with the largest increases in Michigan (USGCRP 2014).
- **Cooling degree days (CDDs) are expected to increase**: Across the region, an increase of 150–900 CDDs is projected by mid-century (2041–2070, compared to 1980–2000) (NOAA 2013b).
- **Heating degree days (HDDs) are expected to decrease**: Across most of the region, declines of 700–1,300 HDDs are projected by mid-century (2041–2070, compared to 1980–2000); Michigan is projected to be the most affected, with declines of up to 1,500 HDDs by mid-century (NOAA 2013b).

Changing Water Availability

Historical observations

- **Since 1895, annual precipitation has increased by 0.31 inches per decade, or almost 3.4 inches** (NOAA 2013b).
- **Across the Midwest, extreme precipitation events have occurred more frequently**: An index of two-day extreme precipitation events expected to occur once every five years shows a statistically significant upward trend since 1895 (NOAA 2013a).

Future projections

- **Annual precipitation is projected to increase:** By the end of the century (2070–2099), precipitation in the northern portion of the region is projected to increase by 3%–9% under a high emissions scenario (compared to the period 1971–1999); Minnesota is projected to be the most affected and may see an increase as high as 12% (NOAA 2013b).
- **Winter and spring precipitation is projected to increase; summer precipitation may decline**: Midwest winters, springs, and falls are projected to see increased precipitation by mid-century (2071–2099, relative to 1971–2000) under a higher emissions scenario, while summer precipitation may decline by 10% or more in southwestern parts of the region (USGCRP 2014).
- **Extreme precipitation events are projected to increase, particularly in the northern portion of the region:** The number of days per year with precipitation greater than one inch is projected to increase by 10%–50% by mid-century (2041–2070, compared to 1980–2000) under a high emissions scenario; Minnesota is projected to be the most affected, and portions of the state may see an increase of over 50% (NOAA 2013b).
- **Consecutive number of days with little or no precipitation are likely to become longer**: The annual maximum number of consecutive days with less than 0.01 inches of precipitation is expected to increase by mid-century (2041–2070, relative to 1971–2000), with Missouri and Illinois projected to experience the largest changes (USGCRP 2014).

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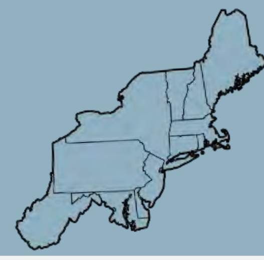
Chapter 6 Endnotes

[a] CDD projections under A2 scenario; mid-century refers to average for period (2041–2070). Source: NOAA 2013b
[b] Source: DOE 2013
[c] Sources: NOAA 2013b, USGCRP 2014
[d] Sources: DOE 2013, USGCRP 2014
[e] Sources: Beecher and Kalmbach 2012, DOE 2013, USGCRP 2014
[f] Source: USGCRP 2014
[g] Sources: DOE 2008, DOE 2013, NOAA 2013b, Posey 2012, Posey 2014, USGCRP 2014
[h] Sources: DOE 2013, EIA 2013b, EIA 2013d, USGCRP 2014
[i] Source: DOT 2009
[j] Sources: DOE 2013, NOAA 2013b, USGCRP 2014
[k] See detailed climate impacts. Sources: NOAA 2013b, USGCRP 2014

Chapter 7: Northeast

Climate Change and the Energy Sector



Overview

The Northeast consists of a number of large and densely populated urban and industrial areas, as well as wide-ranging rural areas and deciduous forestland. The climate is characterized by cold winters and warm, humid summers. The region relies primarily on thermoelectric power, including natural gas-fired, nuclear, and coal-fired plants. The Northeast produces large amounts of coal, mainly in West Virginia and Pennsylvania, and has a significant number of natural gas wells. Major climate change impacts projected to increasingly threaten the region's energy infrastructure include the following:

- **Temperatures are projected to increase, and heat waves are projected to occur more frequently and last longer.**[a] Warmer temperatures and longer, more frequent, and more severe heat waves are expected to increase both average and peak demand for cooling energy, while causing available generation and transmission capacity to decline.[b]
- **Atlantic hurricane intensity is projected to increase, and the most intense hurricanes (Category 4 and 5) are projected to occur more frequently. Combined with projected sea-level rise, hurricane-associated storm surge is likely to cause greater coastal damage.**[c] Coastal power plants, electrical grid components, and fuel transport infrastructure are at risk of damage from more intense hurricanes and sea level rise-enhanced storm surges.[d]
- **Heavy precipitation events are projected to occur more frequently, with the number of days with more than one inch of rain increasing 12%–30% by mid-century.**[e] Inland flooding from increasingly frequent and intense heavy precipitation events heightens the risk of damage and disruption to roads, railroads, power lines, pipelines, and other low-lying infrastructure.[f]

QUICK FACTS

Northeast States:	Connecticut, Delaware, District of Columbia, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, West Virginia

Population (2013)	65,000,000	(21% of U.S.)
Area (square miles)	198,000	(6% of U.S.)
Energy expenditures		$257 billion

ENERGY SUPPLY & DEMAND		**Annual Production**	**Annual Consumption**	***% for electric power***
Electric power	*TWh*	665	599	*n/a*
Petroleum	*MMbbls*	7	1,050	*<1%*
Coal	*million tons*	178	95	*89%*
Natural gas	*Bcf*	2,820	4,270	*39%*

ELECTRIC POWER	**Annual Production (TWh)**	***% of Total Production***	**Capacity (GW)**	**Power plants >1 MW***
Natural gas	215	*32%*	69	280
Coal	186	*28%*	48	86
Nuclear	199	*30%*	26	17
Hydroelectric	37	*6%*	8	369
Wind	8	*1%*	4	84
Biomass	13	*2%*	3	163
Solar	<1	*<1%*	<1	129

CRITICAL INFRASTRUCTURE

Petroleum		**Electric Power**	
Wells (>1 boe/d):	2,360	Power plants (> 1 MW):	1,270
Refineries:	10	Interstate transmission lines:	37
Liquids pipelines:	12	**Coal**	
Ports (>200 tons/yr):	20	Mines:	520
Natural Gas		**Waterways**	
Wells:	113,000	Coal and petroleum routes:	25
Interstate pipelines:	25	**Railroads**	
Market hubs:	2	Miles of freight track:	16,200

Note: Table presents 2012 data except for the number of oil wells, which is 2009 data.
*Some plants use multiple fuels, and individual generating units may be <1 MW.
Sources: AAR 2014, EIA 2011, EIA 2013b, EIA 2013c, EIA 2013d, EIA 2014a, EIA 2014b, EIA 2014c, EIA 2014e, EIA 2014f, EIA 2014g, USACE 2014, US Census Bureau 2014

Table 7-1: Examples of important energy sector vulnerabilities and climate resilience solutions in the Northeast

Subsector	Vulnerability	Magnitude	Illustrative Resilience Solutions
Energy Demand and Thermoelectric Power Generation	Higher temperatures reduce system efficiency and increase total and peak electricity demand[g]	Air temperature increases of 3.5°F–6.5°F and CDD increases of 100–700 projected by mid-century[h]	Capacity additions, demand-side load management, energy efficiency
Electric Grid	Increased intensity of storms and heavy rainfall, causing wind damage and flooding to power lines and low-lying substations[i]	Recent hurricanes resulting in wide-spread regional power outages to more than 8 million customers[j]	Physical hardening, submersible equipment, redundant transmission, smart grid and distributed generation, and vegetation management
Fuel Transport and Storage	Increased exposure to damage and disruption from flooding during heavy precipitation events and sea level rise-enhanced storm surge during more intense hurricanes[k]	Sea level rise expected to exceed global average of 1–4 feet by 2100 and coastal flooding impacts from higher frequency of intense hurricanes[l]	Reinforcing shorelines of critical waterways; dredging to maintain shipping access; elevating or rerouting critical rail, road, or pipeline arteries

Regional Energy Sector Vulnerabilities and Resilience Solutions

Key energy subsectors and illustrative examples of resilience solutions in the Northeast are discussed below. System components that are most vulnerable to climate change are described first.

Electricity Demand

Subsector Vulnerabilities

With cold winters and warm, humid summers, the Northeast relies on energy for both heating and cooling. The region's electricity consumption is distinctly seasonal. Summer peak demand served by the average utility in the region is about 30% higher than winter peak demand (EIA 2013a). More than four out of five households in the region report using air conditioning, although they use it significantly less frequently than the national average (EIA 2013e).

Winter space heating in the region is provided primarily by natural gas and fuel oil (EIA 2014h). The region hosts the oldest building stock in the nation, and therefore recent improvements in energy codes for new buildings may not benefit a large share of consumers (DOE 2008, NAHB 2012, USGCRP 2014).

Climate change is expected to have the following impacts on electricity demand:

- Higher average temperatures (including warmer overnight lows) and extreme high temperatures, including more frequent, more severe, and longer-lasting heat waves, are expected to increase average and peak electricity demand for cooling (NOAA 2013, USGCRP 2014).

By the end of this century, average temperatures in the Northeast are projected to increase by 3.5°F–8.5°F (compared to 1971–1999). By mid-century, increases of 2.5°F–5.5°F could produce 400–700 additional CDDs per year in the southern portion of the region and along the coasts from Massachusetts to Maryland (i.e., the location of the region's largest metropolitan areas). Changes in CDDs in the interior of New York and New England are projected to be smaller, adding 100–400 CDDs by mid-century (NOAA 2013).

Changes to temperature extremes, including heat waves, are expected to increase peak electricity demand in the region. This may limit the electricity sector's ability to deliver energy when it is most needed (DOE 2013a). Across most of the region, extremely hot days are expected to occur more often, and heat waves are expected to occur more frequently and last longer (USGCRP 2014, NOAA 2013). Conversely, warmer winter temperatures and fewer numbers of days below freezing are expected to reduce demand for heating energy (NOAA 2013, USGCRP 2014).

The projected increase in CDDs in the Northeast is comparable to CDD increases in most of the northern United States. However, the region hosts many densely populated metropolitan areas that magnify the intensity of summer heat through the urban heat island effect. Temperatures in densely populated towns and cities can be significantly higher than surrounding areas (EPA 2014). An example of this effect can be seen in a heat map of New York City (Figure 7-1). This effect, combined with the region's relatively humid summertime climate, is expected to amplify the region's electricity demand for cooling (USGCRP 2014).

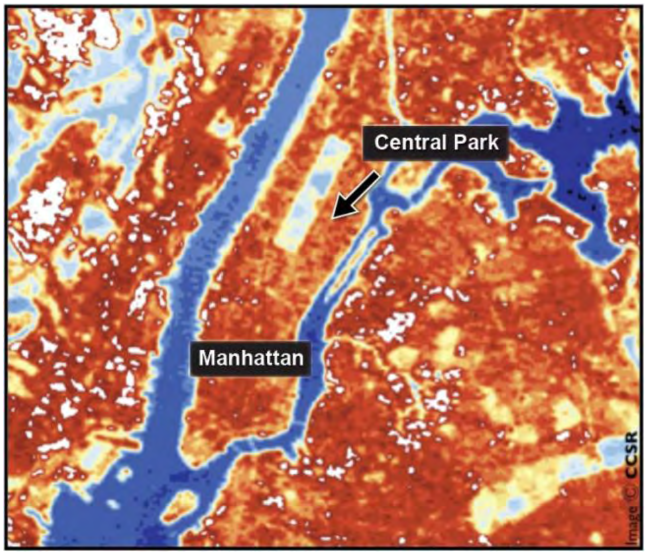


Figure 7-1. Urban heat islands magnify ambient temperatures. In this example, temperatures in urban areas of New York City are approximately 10°F warmer than the forested parts of Central Park

Source: USGCRP 2014

Increases in CDDs will likely cause homeowners and businesses to use air conditioning more often, as warmer daytime and nighttime temperatures will occur more frequently (DOE 2013a). More households and businesses may install air conditioning or upgrade from window units to whole-building systems. Large increases in summer air conditioning—along with associated technology and structural investments—could be a transformational change for much of the region. These changes could contribute to nonlinear increases in total and peak electricity demand (Auffhammer 2011). The New York Independent System Operator (NYISO) expects peak demand to grow an average of five times faster than total demand over the next decade (NYISO 2014).[1] The most significant changes in the projected number of extremely hot days occur in and near coastal areas where the region's populations are concentrated (Figure 7-2).

[1] Peak demand is forecast to grow 0.83% per year on average, while overall electricity demand is forecast to grow 0.16% per year on average from 2014 to 2024 in New York State.

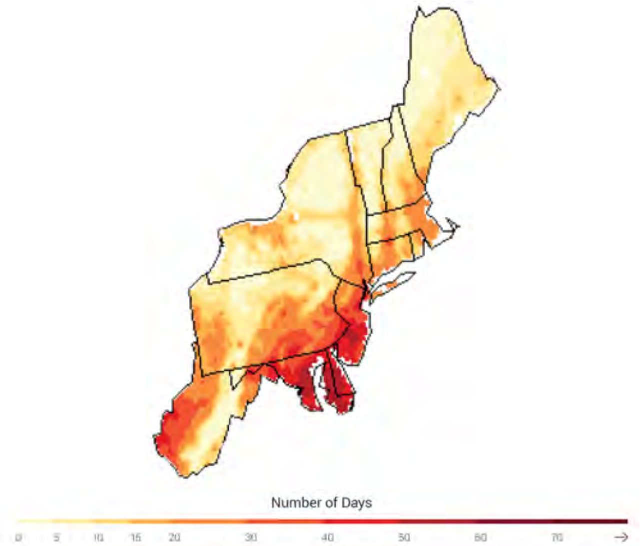


Figure 7-2. Average mid-century increases in hot days (>90°F) per year[2]
Source: USGCRP 2014

Growth in electricity demand will reduce power system resilience unless mitigated by successful demand side management or increased generation capacity. These increases in peak and annual demand heighten the risk of service outages, particularly when combined with the impacts of climate change on electricity generation and transmission infrastructure (see Thermoelectric Power Generation and Electric Grid sections).

Electricity Demand

Resilience Solutions

Energy efficiency, capacity expansion, and market mechanisms such as demand response could improve the electric power sector's resilience to future increases in electricity demand.

Energy efficiency can help reduce total electricity demand, even as the need for cooling energy increases. Federal energy efficiency programs such as the U.S. Department of Energy's (DOE's) Weatherization Assistance Program reduce energy demand by partnering with utilities (including the Northeast Utility System) to provide weatherization services to low-income families. Through DOE's Better Buildings Challenge, organizations in the region and across the country are taking on important commitments to improve the energy intensity of their buildings by at least 20% over 10 years and sharing strategies that work. Nationwide, more than 190 organizations are participating in the Challenge, representing more than 3 billion square feet of building space, over 600 manufacturing facilities, and close to $2 billion in energy efficiency financing (DOE 2014f).

In addition to future energy savings from federal energy efficiency programs, many Northeast states have adopted aggressive energy efficiency resource standards for investor-owned utilities and other power producers. Massachusetts, in particular, has one of the most ambitious targets for energy savings, requiring utilities to achieve annual savings of 2.4% per year through 2015, resulting in energy efficiency investments that are projected to reduce energy demand by over 3,700 GWh in 2015 (ACEEE 2014). New York requires a 20% energy efficiency improvement in buildings owned or managed by the state by the year 2020 (BuildSmartNY 2015).

Capacity expansion can alleviate the pressure that increasing peak electricity demand from warmer temperatures will place on the region's electricity generators. Population shifts, economic growth, and new technologies, such as electric vehicles, could also contribute to increasing electricity use. In addition to meeting increased electricity demand, the electric power sector in the Northeast may need to replace a substantial number of baseload coal plants that are nearing retirement and nuclear plants that are approaching the end of their operating license and may not apply for renewal (ISO-NE 2014). The bulk of new capacity is likely to come from natural gas. This transition from coal to gas can potentially reduce both greenhouse gas emissions and water withdrawals for cooling thermoelectric power plants. Between 2000 and 2012, the Northeast added more than 30 GW of natural gas capacity, while retirements of coal and petroleum power plants resulted in a net decrease from those fuels (Figure 7-3) (EIA 2013c).

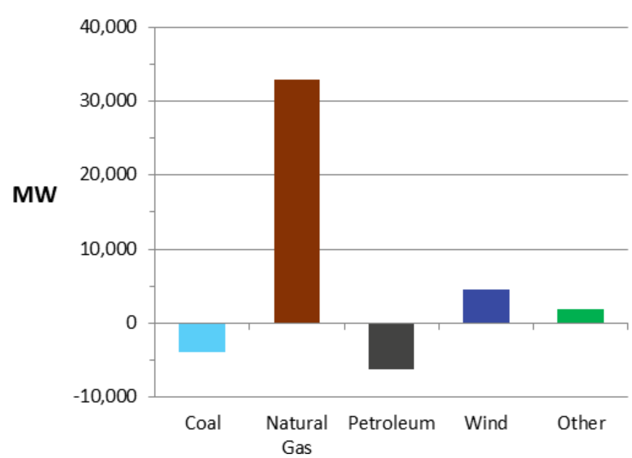


Figure 7-3. Recent changes in Northeast electricity generation nameplate capacity by fuel type, 2000–2012
Source: EIA 2013c

Renewable energy represents a significant potential resource for new capacity. For example, wind power provided 11% of new capacity additions between 2000 and 2012 (EIA 2013c). DOE has used loan guarantees to support deployment of innovative technologies that enable greater use of regional wind generation (see text box). Efforts also

[2] Projected changes for mid-century (2041–2070) relative to the end of the last century (1971–2000) under an A2 emissions scenario.

include enhanced hydropower deployment, including efficiency upgrades of existing hydropower infrastructure. For example, more than 70% of the electricity New York Power Authority (NYPA) produces is from hydropower facilities (NYPA 2013). NYPA has conducted significant efficiency improvements over the last several years, including replacing and refurbishing major components and equipment, such as pump-turbines, that will enable the plants to operate at maximum efficiency well into the 21st century (NYPA 2013).

Electric trading with other regions, including across the border with Canada, allows pooling of resources and can improve electric reliability. Although power imports can introduce vulnerabilities, as seen in the 2003 blackout that was triggered by an event in the Midwest, on balance interconnection improves reliability, both in sharing reserves and in guarding against cascading outages. Peak power use in Canada is during the winter, which enables additional imports to the United States in the summer (EIA 2012b).[3]

Examples of U.S. Department of Energy support for deployment of wind generation technologies

- In August 2011, DOE issued a loan guarantee enabling Record Hill Wind to build a 50 MW wind farm in Maine. This plant uses new technology that reduces the need for curtailments and allows consistent power output during extreme wind conditions, reducing wear and tear on the turbines and preserving the lifetime of the turbine components (DOE 2014a).
- In September 2011, DOE issued a partial loan guarantee to Brookfield Renewable Power to construct the Granite Reliable wind power generation facility in New Hampshire. The facility is one of only a few land-based wind farms in the United States that use a 3.0 MW wind turbine (rather than a 1.7 MW turbine), reducing project costs on a per-megawatt basis (DOE 2014b).

Demand response in the power market is a strategy that reduces the risk from increasing peak electricity demand. Many operators in the Northeast are already leveraging demand response to address increasing peak demand. Compared to all other independent system operators (ISOs) and regional transmission organizations (RTOs) surveyed by the Federal Energy Regulatory Committee in 2012, the New England ISO had the highest rate of demand response capacity as a percentage of total peak load (10.7%), and PJM Interconnection had the largest absolute response capacity, with 10,825 MW in reserve (FERC 2013).

Thermoelectric Power Generation

Subsector Vulnerabilities

The Northeast region generates almost all of its power from thermoelectric power plants. The region's fuel mix is relatively evenly split between natural gas, nuclear, and coal, but important differences exist between New England and the Mid-Atlantic states (Table 7-2). Coal is the largest source of power for the Mid-Atlantic (33%) but is a small (3%) fraction of New England's fuel mix, which relies on natural gas for more than half of its total electricity. Nuclear energy supplies 30% of the region's power, a greater fraction than in any other region in the United States (EIA 2013c).

Table 7-2. Electric power generation in the Northeast by technology

Generator Type	New England	Mid-Atlantic	Total Northeast
Coal	3%	33%	28%
Natural Gas	52%	28%	32%
Nuclear	30%	30%	30%
Hydroelectric	6%	6%	6%
Biomass	6%	1%	2%
Wind	1%	1%	1%
Solar	<1%	<1%	<1%
Other	2%	1%	1%

Source: EIA 2013c

Over the next several decades, the region's fuel mix is expected to change. Many of the nuclear power plants in the region are scheduled to retire. The contribution of coal to the region's generation mix is also expected to decline as more plants are closed (ISO-NE 2014, NYISO 2014).

Climate change is projected to have the following impacts on thermoelectric power generation in the Northeast:

- Increasing air and water temperatures could reduce the available generation capacity of thermoelectric power plants (DOE 2013a).
- Increased hurricane intensity, and more frequent intense (Category 4 and 5) hurricanes, combined with the effects of sea level rise, increase the vulnerability of coastal power plants to wind and coastal flooding damage (DOE 2013a, USGCRP 2014).
- More frequent and intense heavy precipitation events increase the vulnerability of low-lying inland and coastal power plants to damage and disruption from flooding (DOE 2013a, USGCRP 2014).
- Higher temperatures, decreasing summer precipitation, and increasing periods of time between precipitation events may increase the likelihood of thermoelectric

[3] Although it is outside the scope of this study, it is plausible that warmer temperatures in Canada will affect summer electricity demand and reduce the amount of power available for export to the United States.

power plants experiencing water shortages (DOE 2013a, NOAA 2013, USGCRP 2014).

The majority of thermoelectric power plants in the Northeast use fresh surface water for cooling (UCS 2012, Figure 7-4). Although many of the coal and nuclear power plants in the Northeast use advanced cooling technologies that recirculate cooling water, approximately 30% of generating capacity in the region (including one third of coal-fired plants and a quarter of nuclear plants) use once-through cooling systems that draw from and discharge into freshwater sources (UCS 2012).[4]

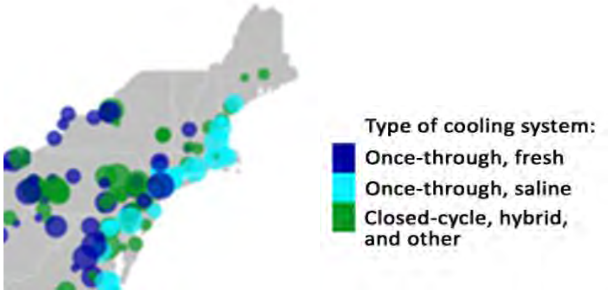


Figure 7-4. Distribution of thermoelectric power plants greater than 70 MW by type of cooling system; larger circles on the map indicate higher net summer capacity
Source: EIA 2012a

Climate change is expected to increase the temperature of bodies of water used for cooling (NOAA 2013). Higher surface water temperatures decrease generation efficiency and, therefore, available capacity. This effective decrease in generation capacity may increase the likelihood of power disruptions; power plants may be forced to shut down to avoid exceeding the thermal water discharge limits imposed by law to protect ecosystems (DOE 2013a).

Warmer surface water temperatures may also increase the likelihood of forced shutdowns of nuclear power plants. Nuclear plants are licensed to operate under a range of conditions. If water temperatures exceed this range, they may be required to shut down. For example, in 2010, and again in 2012, nuclear plants in the region faced mandatory curtailments or shutdowns in response to elevated cooling water temperatures (DOE 2013a).

In addition to warmer water temperatures, higher air temperatures also reduce efficiency in power plants. For example, natural gas power plants may lose 0.3%–0.7% of power output for every 1.8°F increase in air temperature (DOE 2013a).

Climate change is projected to increase the frequency of intense hurricanes, hurricane-associated storm and rainfall intensity, and heavy precipitation events (USGCRP 2014). Intense hurricanes can cause significant wind and flood damage to coastal power plants. In addition, hurricane-associated storm surge will likely be intensified by rising sea levels (USGCRP 2014). Estimates suggest that 19 power plants in the Northeast are located less than four feet above sea level (Climate Central 2014).

Inland power plants are threatened by more frequent heavy precipitation and increased rainfall during the heaviest downpours (NOAA 2013, USGCRP 2014). Flooding in mountain valleys and floodplains can inundate vulnerable power plants and disrupt surface cooling water sources (DOE 2013a, USGCRP 2014).

While more frequent heavy downpours are expected to increase the likelihood of flooding, total summer precipitation is projected to decline (NOAA 2013, USGCRP 2014). The largest changes are projected for western Pennsylvania and West Virginia, where rainfall may decline by 4%–8% in the summer (NOAA 2013). Combined with higher temperatures that lead to greater evaporation rates, the likelihood of seasonal water shortages may increase. Decreasing surface water availability resulting from lower summer rainfall, increased evaporation rates from higher temperatures, and competing uses (e.g., irrigation for agriculture and municipal water for metropolitan areas) may reduce the available generation capacity of thermoelectric power plants in the summer (DOE 2013a, USGCRP 2014).

The once-through freshwater cooling systems used by many Northeast power plants (Figure 7-4) require a significant and consistent supply of water from lakes, rivers, and streams. Plants using these types of cooling systems are more vulnerable to deratings or outages due to low water levels. During periods of drought, plants using these cooling systems can become nonoperational if the water level drops below water intake structures (NERC 2013).

Thermoelectric Power Generation

Resilience Solutions

Reduced efficiency and capacity from higher air and water temperatures can be addressed by capacity additions or through demand reduction measures such as load management and energy efficiency. New generation capacity with sources and supply chains less affected by increasing temperatures and decreased water availability (e.g., wind and solar photovoltaics) can help make the region's power sector more resilient to climate change.

[4] Excluding oil-fired capacity.

Hardening power generation in New York City

By 2050, 97% of New York City's power plants are projected to be in the 100-year flood plain. New York City has developed a plan to work with plant owners, utilities, and regulators to harden assets against 100-year floods. The City has called on the New York Public Service Commission to require that new and upgraded generation facilities be hardened if they cannot demonstrate they would be able to remain operational during a 500-year flood event (NYC 2013).

Figure 7-5. Projected increase in FEMA 100-year flood zone for New York City
Source: NOAA 2014

Engineered barriers such as levees can be effective in protecting thermoelectric power plants that are vulnerable to flooding from hurricanes and heavy precipitation events. For example, ConEdison has installed new floodgates and doors in new walls and moats to access isolation zones at three generating stations in New York City and has installed new flood pumps on mobile skids that can remove excess water from isolation zones and moats (ConEd 2014b). Utilities may also elevate critical components to protect against flooding or upgrade plants with submersible equipment. Long-run changes to planning processes account for sea level rise, and increased storm surges are necessary to protect future power plants from coastal flooding.

Introducing more advanced cooling technologies into the region's power production infrastructure may be an effective strategy to reduce its vulnerability to periodic drought. For example, American National Power installed a dry cooling system in a natural gas-fired plant in Connecticut, cutting projected water consumption by 70% (UCS 2011).

Generators can also pursue alternative water supplies for once-through power plants. For example, to mitigate the risk of low river levels in the region, Exelon Generation is a co-owner of the Merrill Creek Reservoir in New Jersey, which acts as water storage for Exelon's generating stations when river flow on the Delaware River is low (Exelon 2014).

Electric Grid

Subsector Vulnerabilities

Energy transmission and distribution infrastructure in the Northeast is both extensive and aging (ISO-NE 2014, Pepco 2014). The region's population and electric power infrastructure are concentrated in coastal cities and low-lying river valleys (USGCRP 2014), making the Northeast electric grid vulnerable to flooding from both heavy precipitation events and coastal storm surge during hurricanes, both of which are projected to increase as a result of climate change.

The Northeast region's electric grid is operated by three independent system operators: the New England ISO, New York ISO, and PJM Interconnection. In many areas, the electric grid is characterized by an extensive network of older, lower-capacity transmission lines serving as feeder lines to transformers and other critical system components (ISO-NE 2014).

Climate change is projected to have the following impacts on the electric grid:

- Increasing hurricane intensity (and frequency of Category 4 and 5 storms) and frequency of heavy precipitation events will increase the likelihood of wind damage, flooding, and inundation of coastal and inland electric grid infrastructure (DOE 2013a, USGCRP 2014).
- Sea level rise is expected to magnify the height and reach of storm surges, exacerbating the impact of hurricanes on coastal transmission and distribution infrastructure (DOE 2013a, USGCRP 2014).
- Increasing air temperatures and higher nighttime temperatures are projected to reduce the electric grid's transmission capacity and increase the risk of damage to transformers (Bérubé 2007, DOE 2013a).
- Increasing frequency of extreme temperatures will increase the risk of physical deformation of power lines and disruptions to service (DOE 2013a, USGCRP 2014).

Components of the electric grid may be damaged by flooding and storm surge during extreme precipitation events and hurricanes (see Figure 7-6 and sidebar on next page: Northeast hurricanes and electric grid infrastructure), and overhead power lines are vulnerable to wind damage from intense storms (DOE 2013a, USGCRP 2014). For example, transmission lines damaged by hurricanes resulted in outages for almost 1.5 million Maryland customers from 1992–2009 (DOE 2015a). In coastal areas, substations may be flooded, critically undermining electric grid operations. When components of electric transmission and distribution infrastructure are flooded with seawater during storm surge events, the salt water may permanently damage electrical components (ConEd 2013). In general, more frequent and intense coastal flooding is expected to result in an increased frequency of longer-term localized outages due to flooded and corroded equipment, as well as increased damage from saltwater encroachment and structural damage due to wave action (USGCRP 2014). More severe storms and flooding also impair the ability of repair crews to respond and restore service (DOE 2013d).

Figure 7-6. Significant damage to New Jersey distribution infrastructure caused by Hurricane Sandy
Source: DOE 2014e

Average sea levels are projected to rise between one and four feet by the year 2100, compounding the coastal flooding impacts of storm surge from intense hurricanes (USGCRP 2014). Moreover, local land subsidence is expected to increase the local rate of sea level rise across much of the northeastern coastline, especially in the southern portion of the region (USGCRP 2014). States in the southern portion of the region have relatively flat (low-sloping) coastlines and are particularly vulnerable to the amplifying effect of sea level rise on the height and reach of hurricane storm surge (USGCRP 2014). Although states farther north, such as Massachusetts and New York, have higher sloping coastlines, the presence of major cities and the high concentration of infrastructure bordering the coast increase the potential for storm surge-related damage and disruption to essential electric grid infrastructure (USGCRP 2014).

Extremely high temperatures can force transmission operators to reduce the current-carrying capacity of transmission lines (DOE 2013a, Sathaye et al. 2013). Hot weather conditions also reduce the capacity of power substations and increase the risk of damaging transformers (Bérubé 2007, DOE 2013a). These effects can be exacerbated by higher nighttime temperatures, which prevent power lines and other grid infrastructure from cooling off. Higher temperatures cause thermal expansion of transmission line materials, and sagging lines increase the risk of damage to the lines and cause outages if they

Northeast hurricanes and electric grid infrastructure

Hurricanes Sandy and Irene had severe impacts on the electric grid in the Northeast. During Sandy, more than 100 electric substations in four states were inundated, and almost 9 million customers were left without power (Table 7-3). Substation flooding during Hurricanes Sandy and Irene led to outages and severe disruptions to electric power service in the region (Figure 7-6 and Figure 7-7) (ConEd 2013, USGCRP 2014).

Figure 7-7. Areas of New York metro region inundated by Hurricane Sandy
Source: DOE 2013b

The damage to the electric grid from Hurricane Sandy rippled through other sectors, including transportation, communications, wastewater treatment, and health care. For example, loss of power to pipelines in the region temporarily disabled pipeline transport of critical fuels to the region (Table 7-3, DOE 2013b). Subsequently, power outages also prevented gas stations from being able to pump gasoline, resulting in widespread fuel shortages in New York and New Jersey (see Fuel Transportation and Storage section). In addition, power outages at treatment plants sent billions of gallons of raw and partially treated sewage into the region's waterways, affecting public health and aquatic habitats (Climate Central 2013).

Table 7-3. Energy impacts of Hurricane Irene and Hurricane Sandy

Impact	Irene	Sandy
Electric Customer Outages (millions)	6.69	8.66
Petroleum Refining Capacity Shut Down (barrels per day)	238,000	308,000
Petroleum Product Terminals Shut Down (number)	57	25

Source: DOE 2013b

make contact with other lines, trees, or the ground (DOE 2013a).

The risk of damage to transformers from higher ambient temperatures and higher nighttime temperatures can also force operators to reduce the capacity of transformers (USBR 2000). Typical power transformers in the region are rated to 24-hour average ambient temperatures of 86°F, with a maximum of 104°F (PJM 2011). Above the rated ambient temperature, the paper insulation used in transformers begins to break down at an exponentially increasing rate (Bérubé 2007, Hashmi et al. 2013). Transformers are critical to system operations and may be overloaded during system emergencies, pushing temperatures to critical limits. Elevated ambient temperatures on the hottest days of the year may limit the emergency overloading capacity available to operators (Hashmi et al. 2013, USBR 2000).

Electric Grid

Resilience Solutions

A number of measures are available for grid operators to improve the resilience of transmission and distribution infrastructure to extreme weather and temperatures. Measures include physical and engineering modifications to hardware to better withstand the impacts of climate change (hardening) and improvements in the tools available to grid operators to improve flexibility and response options during extreme weather events.

In flood-prone areas, infrastructure owners may choose to replace existing equipment with submersible equipment or elevate components above expected flood stages (NY Storm Recovery 2014). For example, ConEdison has installed submersible switches on the distribution grid (NEMA 2013). Additionally, ConEdison considers a number of modeled and observed flooding scenarios to set the minimum elevation of new and existing grid infrastructure (ConEd 2013). Public Service Electric & Gas Company (PSE&G) is elevating or physically hardening 21 transmission switching stations that would benefit from flood and/or storm surge mitigation, such as those located below the newly defined Federal Emergency Management Agency (FEMA) advisory base flood elevations.

System-wide resilience to reduced capacity and increased risk of disruption from elevated temperatures can be improved by adding additional capacity and redundancy to the transmission grid (DOE 2013a). Transformers can be protected from higher ambient temperatures by installing or upgrading cooling systems, or by replacing existing units with thermally upgraded transformers (Bérubé 2007, USBR 2000). Operators can increase transformers' resilience to increasing air temperatures by derating transformers when air temperatures are high to prevent damage (Hashmi et al. 2013).

National Grid focuses on microgrids

National Grid has partnered with Clarkson University on an underground microgrid pilot project in Potsdam, New York, that would increase the resilience and efficiency of New York's electricity grid. The microgrid could be islanded in an emergency and would serve critical loads with local generation from existing natural gas, fuel oil, hydroelectric, and photovoltaic sources (National Grid 2014).

The deployment of improved system controls can enable more flexible and targeted grid operator response to critical events, regardless of their cause. Grid sectionalizing is one solution that infrastructure managers can use to increase the resilience to climate change. ConEdison is implementing an overhead system upgrade in the region that will reduce the number of customers served by a single circuit to fewer than 500. It is anticipated that 15%–20% fewer homes and businesses will lose power during major storms as a result of the measure (ConEd 2014b). The use of isolation switches at local levels, for example, enables operators to section off vulnerable locations during emergencies without disrupting the larger network. Iberdrola USA has adopted the goal of increasing the number of distribution circuits in order to decrease the number of customers served per circuit. Grid sectionalizing will also improve resilience to impacts of extreme heat on overhead transmission and distribution lines (ConEd 2013).

In May 2014, the New Jersey Board of Public Utilities approved an investment program of resilience solutions to be implemented by PSE&G. The program includes efforts to harden infrastructure and restore service to customers quicker following major storm events. In the approved program, 29 switching and substations that were damaged by water in recent storms will be raised, relocated, or otherwise protected, and smart grid technologies will be deployed to better monitor system operations and facilitate swifter mobilization of repair teams.

In Maine, Central Maine Power's (CMP's) smart metering network allows for remote verification and diagnosis of outages reported by customers, speeding the assessment and restoration and reducing the recovery times.

New York's vision for a future "Energy Highway" is one example of an integrated approach to system resilience. The state's long-term plan for its transmission grid includes a number of strategies to prepare for climate change and higher peak energy demand. New York plans to increase its investment in smart grid systems to improve resilience through enhanced power systems operation, security, and energy storage. The plan also includes increasing the capacity of power transmission lines to allow access to new generation sources, particularly wind power (NYEHTF 2012).

DOE and Sandia National Laboratories are collaborating with the New Jersey Board of Public Utilities, City of Hoboken, and PSE&G to develop and implement a plan for the first-ever transit system microgrid as part of Hurricane Sandy recovery efforts (City of Hoboken 2013, DOE 2013c, NJ Transit 2014). NJ TransitGrid (NJT) is being designed as a dynamic microgrid spanning rail lines and critical stations and maintenance facilities across New Jersey Transit's busy northeastern corridor between Newark and New York City. NJT will help to ensure trains keep running even if the centralized grid goes down (City of Hoboken 2013, DOE 2013c, NJ Transit 2014). Beyond being America's third-largest transportation system and serving nearly 900,000 passengers daily, the stretch of rail covered by NJT is both an important access point to Manhattan and one of the most at risk from flooding.

Fuel Transport and Storage

Subsector Vulnerabilities

Transportation and storage infrastructure are integral to the Northeast's energy systems. The region imports very nearly all of the petroleum it consumes, and while production of natural gas is growing in the Marcellus shale, significant quantities are still imported. Coal transportation is also critical to meeting the region's energy demand.

Petroleum transportation infrastructure varies within the region. Maryland, New Jersey, New York, Pennsylvania, and West Virginia receive most refined petroleum products by pipeline from the Gulf Coast and Midwest or from local refineries. Refineries in northwest Pennsylvania rely on imports of crude oil by pipeline from Canada, while refineries in Delaware, New Jersey, and around Philadelphia rely on shipments by tanker from other countries and increasingly on crude-by-rail shipments from shale formations in the United States and Canada (EIA 2014b). New England has no product pipelines from outside the region and is entirely reliant on marine terminals to receive petroleum products, which are then transported further inland by rail, truck, pipeline, and barge. Road infrastructure in the Northeast is also critical for delivery of retail petroleum products.

The Northeast, particularly New England, relies on aboveground liquefied natural gas (LNG) storage more than any other region in the United States (DOE 2014d). New England does not contain any underground natural gas storage sites but is home to almost 75% of the nation's aboveground LNG storage capacity (DOE 2014d, EIA 2014d). Natural gas storage is critical for meeting peak winter gas demand for heating and is increasingly important for electricity generation (NERC 2011).

Coal is transported from domestic producing regions by rail and is imported from South America by ship (EIA 2014b). Coal is also transported through the region for export: the Port of Baltimore is the third largest coal export port in the United States (EIA 2014b). Coal is brought to the port by rail from mines in the Appalachian region (EIA 2014b).

Climate change is projected to have the following impacts on transport of energy products:

- Projected increases in the storm intensity of hurricanes and frequency of intense the most intense hurricanes (Categories 4 and 5) are expected to heighten the risk of damage and disruption of coastal transportation and storage infrastructure, including ports, refineries, and pumping stations (DOE 2013a, USGCRP 2014).
- More frequent extreme precipitation events can cause flooding and damage to transportation infrastructure running along rivers and in low-lying areas, leading to service disruptions (DOE 2013a, USGCRP 2014).

Coastal energy transportation infrastructure across the Northeast seaboard is vulnerable to storm surge and heavy winds associated with hurricanes (DOE 2013a, EIA 2014b). Included are petroleum, LNG, and coal terminals, port facilities, aboveground storage facilities, pipeline pumping stations, and petroleum refineries. Over this century, models project a slight decrease in the average annual number of tropical storms but an increase in hurricane-associated storm intensity and rainfall rates, as well as in the number of Category 4 and 5 hurricanes (USGCRP 2014). Storm surges associated with hurricanes will likely be enhanced by rising global sea levels, which are projected to rise between one and four feet by the end of the century, with even higher local rates of relative sea level rise (USGCRP 2014). Storm surge can cause structural damage (due to wave impact and erosion) and saltwater corrosion and lead to extended service disruptions to critical facilities (CCSP 2008, USGCRP 2014).

Inland flooding caused by extreme precipitation events is a major threat to Northeast transportation infrastructure and systems (USGCRP 2014). Roads and bridges, railroads, pipelines, and other energy transportation and storage infrastructure located alongside rivers or in river floodplains are vulnerable to disruption of service and damage from flooding and debris. For example, two pipeline ruptures in April 2015 in Marshall County, West Virginia, were caused by shifting soil after heavy rains (AP 2015). Natural forces are the leading cause of damage to petroleum product pipelines in West Virginia (DOE 2015b). The Northeast has already experienced significant increases in the amount of rain that falls during the heaviest downpours. Compared to the middle of the last century, extreme precipitation events in the Northeast are already 70% heavier (USGCRP 2014).[5] By the middle of this century, the average number of days per year with precipitation of more than one inch is

[5] Comparison is between 1958 and 2010. Extreme precipitation events are defined as the heaviest 1% of all daily events.

projected to grow 12%–30% under continued emissions growth (compared to the 1980–2000 average) (NOAA 2013). Intense hurricanes can also contribute to inland flooding as hurricane-associated rainfall increases (USGCRP 2014).

Through wave action and erosion, storm surges affecting port and terminal facilities can knock down terminal buildings and dislodge cargo containers, damage specialized terminal equipment, and damage wharf and pier structures and undermine the foundation of terminals (CCSP 2008). Facilities can also be inundated, rendering them inoperable and damaging equipment with saltwater contamination. High winds can damage refinery structures, aboveground tanks at storage terminals, and retail outlets (API 2014, DOE 2010). For example, during Hurricane Rita in 2005, approximately half of the cooling towers at refineries in Port Arthur, Texas, and Port Neches, Texas, were damaged, some with fan blades that were dislodged and launched by intense winds (DOE 2010).

Terminals and aboveground facilities are forced to stop or delay operations prior to and during hurricanes, affecting the transport of oil and gas throughout the region (CCSP 2008). Storm-associated currents and flood debris can block or render inoperable navigation channels, extending delays (CCSP 2008). One analysis of U.S. Department of Transportation data found that 28 intermodal freight terminals across the region were located less than four feet above sea level, with 13 of these terminals located in New Jersey (Climate Central 2014).

Many of the key highways and railroads in the Northeast are located in areas prone to coastal flooding and are vulnerable to damage and disruption from more frequent intense hurricanes (USGCRP 2014). By one estimate, more than 4,500 miles of roads in the region lie below four feet above sea level (Climate Central 2014). Short-term impacts of coastal flooding may temporarily take roads out of service and damage culverts and bridge decks, but prolonged flooding may weaken roadways over the long term (CCSP 2008). Similarly, railroads are susceptible to long-term damage from flooding, including erosion of the track subgrade that will weaken the track's foundation. Saltwater inundation of coastal rail infrastructure can also damage infrastructure, causing corrosion of rail lines, electrical distribution systems, and signaling equipment (Figure 7-8) (USGCRP 2014).

Figure 7-8. Corroded electrical substation equipment damaged by saltwater following Hurricane Sandy
Source: Port Authority of NY & NJ 2015

Further inland, increasing frequency of heavy precipitation events may lead to washout of roads and railroads and damage to rail yards and bridges important for the transportation of energy products (see sidebar: Coastal and inland flooding: A Tale of Two Storms) (DOE 2013a).

Coastal and inland flooding: A Tale of Two Storms

Successive tropical storms struck the Northeast in 2011 and 2012, unleashing both inland and coastal flooding on the region's transportation infrastructure. Hurricane Irene dumped more than 10 inches of rain on large areas of New Jersey, upstate New York, and southern Vermont in a short period of time, causing record-breaking flood stages in mountain valleys across the region (NOAA 2011). While coastal impacts were less severe than expected, the inland floods destroyed or damaged nearly 2,400 roads and over 300 bridges, including major interstates, as well as over 200 miles of railroad in Vermont alone (NOAA 2011, VANR 2014). Subsequent efforts to restore power were hampered by widespread road closures, leading to lengthy delays in full power restoration (NJBPU 2011).

Hurricane Sandy made landfall in New Jersey and brought tropical storm conditions and record storm surges to a large portion of the East Coast. As tides well above 13 feet were measured across New York Harbor, coastal flooding associated with Hurricane Sandy damaged buildings, equipment, and cargo at ports in New York and New Jersey. Flooding and power outages closed fuel terminals in New York City for four days to more than a week following the storm, resulting in long-term delays (ICF 2014, NYC 2013). Ocean water flooded and heavily damaged three of the four major tunnels into Manhattan, and two Class I railroads with service into the Northeast, CSX and Norfolk Southern, embargoed traffic into the region (Progressive Railroading 2012, USGCRP 2014). The Colonial Pipeline (a major source of gasoline and petroleum products for the New York City metropolitan area) was shut down for four days, and National Grid's natural gas distribution mains in portions of New York were severely damaged and had to be rebuilt (DOE 2013a, NYC 2013). Extensive power outages from Sandy also caused crippling fuel shortages in New Jersey, New York City, and Long Island, leading to fuel rationing. Even after many stations were resupplied, electricity was not available to power pumps (Nahmias 2013).

Flooding of river valleys can wash out road and railroad culverts and embankments, bridge piers, and pipelines that follow river courses or cross underneath riverbeds. For example, flooding has already been a problem for important coal railroads in the Appalachian Mountains that follow riverbanks (DOE 2013a). Hurricane Irene was a major precipitation event that produced destructive flash flooding across upstate New York and southern Vermont in 2011 (Figure 7-9) (NOAA 2011). Resulting floods damaged hundreds of miles of roads and rail and significantly disrupted transportation in the region (USGCRP 2014, VANR 2014).

Figure 7-9. Vermont Route 131, washed out from flooding following extreme precipitation during Tropical Storm Irene
Source: USGCRP 2014

Some climate change impacts may benefit energy sector transportation in the future. Winter temperatures are expected to increase, reducing cold weather risks to transportation infrastructure and winter pipeline congestion (NERC 2013, USGCRP 2014). For example, increasing average temperatures and decreasing heating degree days may alleviate constraints on natural gas pipeline capacity during the winter months as heating energy demand falls (NERC 2013). Furthermore, freezing temperatures can interrupt gas wells and pipelines; naturally occurring hydrates can freeze wellheads, pipelines, and pipeline equipment, causing temporary shutdowns in extremely cold weather (NERC 2011).

Fuel Transport and Storage

Resilience Solutions

Similar to other low-lying and coastal infrastructure, some fuel storage and transport assets can be hardened to better withstand more intense hurricanes and associated storm surge, and management measures can reduce the risk of damage and shorten resulting disruptions. Examples of hardening measures include elevating critical equipment, using submersible equipment, building or improving the design of levees and floodwalls, and installing watertight doors on vulnerable structures. For example, the Port Authority of New York and New Jersey is installing waterproof doors at flood elevation levels and increasing the height of retaining walls by four to six feet in the Holland Tunnel to prevent future flooding (NY Storm Recovery 2014). At fuel terminals and pipeline pumping stations, critical equipment, including substations, control rooms, and pumps, can be elevated or sealed in waterproof structures (DOE 2010). In preparation for expected flooding, small pump motors can be wrapped for protection or mounted on skids to allow operators to lift the motors prior to flooding events (DOE 2010). To prevent tank movement during flood events, operators can anchor tanks or add product to increase the tanks' weight and prevent floating, and ensure that containment dike drainage valves are opened to allow flood waters to exit the diked area (DOE 2010). ConEdison has undertaken several measures to harden its LNG peak-shaving facility in New York, such as installing dockside auxiliary diesel pumps for use after storm events and constructing elevated corrosion-resistant platforms to install transformers, the diesel-driven backup pump, and a diesel black start generator (ConEd 2014a).

Fuel shipping operations can be protected by hardening the shorelines of critical waterways to prevent and offset erosion, and dredging can be employed to maintain shipping access and accelerate a return to normal operations.

To protect infrastructure from wind impacts, refineries can ensure that fan blades are secured prior to storms. Installing girders on storage tanks to reinforce their structural integrity can harden the tanks against hurricane-force winds (DOE 2010).

Natural gas and steam distribution systems can be hardened to better withstand flooding events and intense hurricanes. Example measures include replacing cast iron and bare steel distribution pipes with coated steel pipes, upgrading low-pressure facilities to high-pressure facilities to minimize water infiltration, and developing devices that customers can use to mitigate water infiltration in flooded homes. Utilities may also harden infrastructure surrounding distribution systems. For example, the First Avenue Tunnel in New York City, which contains both steam and gas mains and high-voltage electric feeders, was flooded with 500,000 gallons of water during Hurricane Sandy (ConEd 2013). ConEdison is designing vent cover plates for the First Avenue Tunnel and replacing head houses on other tunnels with hardened and reinforced concrete structures to prevent damage from future flooding (ConEd 2013). PSE&G is replacing and modernizing 250 miles of low-pressure cast iron gas mains in or near flood areas, and protecting an LNG station and five natural gas metering stations located in flood zones.

To prevent power outages from leading to temporary fuel shortages, pipeline and storage facility operators and fuel retailers can ensure adequate backup is available at critical locations. For example, Colonial Pipeline operators prepositioned the company's mobile generators to New Jersey in anticipation of Hurricane Sandy (GAO 2014). States can also ensure that gas stations and fuel retailers have sufficient access to backup generation.

Fuel station resilience in New York

In 2013, New York State passed a law that requires retail fuel stations located adjacent to evacuation routes and controlled access routes to maintain fueling operations. Stations must have equipment allowing them to connect to generators during power outages and must enter into supply contracts for emergency generators (NYS 2013).

The Northeast is home to federal reserves of both heating oil and gasoline, established to minimize the region's vulnerability to shortages and disruptions in fuel product supply. The reserves store almost two million barrels of petroleum products at sites in Connecticut, Maine, Massachusetts, and New Jersey. In the aftermath of Hurricane Sandy, the U.S. Department of Defense distributed diesel fuels from the heating oil reserve to state, local, and federal responders in New York and New Jersey to fuel emergency equipment such as generators and vehicles (DOE 2013a). New York State, NYPA, and other entities are planning to set up a strategic fuel reserve with 2.5 million gallons of gasoline and diesel fuel to provide emergency short-term supply. In the event of a shortage, the fuel reserves will be dispersed at strategic locations in New York to ensure sufficient fuel is available for emergency responders, including transmission and repair crews (NY Storm Recovery 2014, NYPA 2014).

Resilience solutions for inland infrastructure include design changes and upgrades to prevent erosion, improve drainage, and harden assets. Road and rail bridges and culverts can be protected from erosion and scour by improving flow around bridge foundations, increasing the size of hydraulic openings, and increasing culvert capacity, or by installing riprap to protect piers and abutments (DOT 2009, State of New York 2013). Improved drainage can reduce flooding of road surfaces and railbeds, and increased pumping capacity can protect tunnels (DOT 2009). River embankments can be protected with manmade or natural barriers to erosion to prevent undercutting of road and track beds or exposure of buried pipes. Pipelines under river crossings can be protected by using horizontal drilling techniques to bury the pipe significantly deeper than traditional trenching methods, and by upgrading pipes with more robust materials that are less likely to leak or rupture from impacts (Miller and Bryski 2012).

FEMA recently awarded New York State $74 million to improve the resilience of 29 bridges across the state to scour of bridge foundations due to increasing flooding impacts (State of New York 2013). The State is planning to upgrade a total of 105 scour- and flood-prone bridges by elevating and improving flow around bridge piers at a projected total cost of $518 million (State of New York 2013).

Management measures can also improve the resilience of infrastructure to inland flooding. By performing adequate maintenance and reducing repair backlogs, managers can reduce the risk of damage to assets (DOT 2009). Managers can also prepare contingency plans, undertake risk assessments of existing assets, and use flood monitoring sensors to improve their understanding of risks (DOT 2009).

Regional Climate Change Observations and Projections in Detail

Higher Temperatures

Historical observations

- **Since 1895, average temperatures have increased 0.16°F per decade, or almost 1.8°F** (NOAA 2013).
- **Since 1895, summer temperatures have increased 0.11°F per decade, or almost 1.2°F** (NOAA 2013).
- **Frost-free season has been growing**: The average length of the frost-free season across the Northeast has increased by about ten days (1991–2012, compared to 1901–1960) (USGCRP 2014).

Future projections

- **Average temperatures are expected to increase at a faster rate**: Depending on the location and emissions scenario, increases of 3.5°–8.5°F are projected by 2070–2099 compared to 1971–1999 levels (NOAA 2013).
- **Extremely hot days are projected to become more common**: Across most of the region, up to 15 more days with a daily maximum temperature >95°F are expected by mid-century (2041–2070, compared to 1980–2000); West Virginia and Maryland are likely to be the most affected and may see as many as 20 more extremely hot days per year (NOAA 2013).
- **Consecutive number of days of extreme heat are expected to become longer in West Virginia and Maryland**: The annual maximum number of consecutive days with a daily high >95°F is projected to increase by 4–8 days by mid-century (2041–2070, compared to 1980–2000) in southern portions of the region (NOAA 2013).
- **Extremely cold nights are expected to become less common**: Across the region, 5–25 fewer days with daily minimums <10°F are expected by mid-century (2041–2070, compared to 1980–2000) (NOAA 2013).
- **Freeze-free season is expected to lengthen**: The freeze-free season is expected to be 20–30 days longer by mid-century (2041–2070, compared to 1980–2000) across the region (NOAA 2013).
- **Cooling degree days are expected to increase**: Across most of the region, an increase of 200–600 CDDs is expected by mid-century (2041–2070, compared to 1980–2000) (NOAA 2013).
- **Heating degree days are expected to decrease**: Across most of the region, declines of 900–1,500 HDDs are expected by mid-century (2041–2070, compared to 1980–2000) (NOAA 2013).

Changing Precipitation Patterns

Historical observations

- **Since 1895, annual precipitation has increased by 0.39 inches per decade, or almost 4.3 inches** (NOAA 2013).
- **Between 1958 and 2010, the region saw over a 70% increase in the amount of precipitation falling in very heavy events** (USGCRP2014).

Future projections

- **Annual precipitation is projected to increase**: By the end of the century (2070–2099), precipitation across the region is expected to increase by 3%–12% across most of the region compared to the period 1971–1999 (NOAA 2013).
- **Drier summers are expected in Pennsylvania and West Virginia**: Summer precipitation is expected to decrease by 5%–10% by the end of the century (2071–2099, compared to 1971–1999) under a high emissions scenario (USGCRP 2014).
- **Extreme precipitation events are projected to increase**: The number of days per year with precipitation greater than one inch is projected to increase by 12%–30% by mid-century (2041–2070, compared to 1980–2000) under a high emissions scenario across most of the region (NOAA 2013).
- **Seasonal drought risk is projected to increase in summer and fall**: High temperatures are expected to lead to greater evaporation and earlier snowmelt, resulting in seasonal drought (USGCRP 2014).

Hurricanes and Sea Level Rise

Historical observations

- **Relative mean sea level has risen because of a combination of global sea level rise and land subsidence in the region**: Relative mean sea level on the Northeast coast rose 0.07–0.22 inches per year, depending on the location, between the beginning and middle of the 20th century and 2013 (NOAA 2015).

Future projections

- **Sea level rise is expected to accelerate**: Between 1992 and 2050, sea level on the coast in the Northeast is projected to rise at an average rate of 0.06–0.27 inches per year (no ice sheet melt) or 0.21–0.41 inches per year (ice sheet melt), depending on the location (USGCRP 2014).
- **Frequency of intense hurricanes (Category 4 and 5) is projected to increase** (USGCRP 2014).
- **Hurricane-associated storm intensity and rainfall are projected to increase:** Rainfall rates within 100 km of tropical storm centers are projected to increase by 20% by 2100 (USGCRP 2014).

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Chapter 7 Endnotes

[a] Sources: NOAA 2013, USGCRP 2014
[b] Sources: DOE 2013a, NOAA 2013, USGCRP 2014
[c] Source: USGCRP 2014
[d] Sources: DOE 2013a, USGCRP 2014
[e] Projection is under A2 emissions scenario; mid-century refers to average for period (2041–2070). Source: NOAA 2013
[f] Sources: DOE 2013a, NOAA 2013, USGCRP 2014
[g] Sources: DOE 2013a, NOAA 2013, USGCRP 2014
[h] Sources: DOE 2013a, NOAA 2013, USGCRP 2014
[i] Sources: DOE 2013a, USGCRP 2014
[j] Source: DOE 2013b
[k] Sources: DOE 2013a, USGCRP 2014
[l] Source: NOAA 2013, USGCRP 2014

Chapter 8: **Southeast**

Climate Change and the Energy Sector

Overview

The Southeast region, characterized by hot and humid summers and mild winters, is predominantly powered by coal, natural gas, and nuclear power plants. The region contains extensive oil and gas infrastructure that is essential to the nation's energy supply. Primarily located near the Gulf Coast, this infrastructure includes oil refineries, natural gas processing plants, offshore platforms, and energy transport infrastructure. Major climate change impacts projected to increasingly threaten the region's energy infrastructure include the following:

- **Hurricane storm intensity and rainfall are projected to increase, and the most intense hurricanes (Category 4 and 5) are projected to occur more frequently. Coastal flooding is likely to worsen as sea level rise and local land subsidence enhance hurricane-associated storm surge.**[a] Critical oil and gas wells, refineries, and ports located along the Gulf Coast, as well as coastal power plants, transmission lines, and transportation infrastructure, are at risk of damage from intense hurricanes and sea level rise-enhanced storm surges. Heavy rainfall and high winds may damage power lines, power plants, and other energy assets. Transportation infrastructure such as ports, major roads, and rail lines along the Gulf and Atlantic coastlines are vulnerable to storm surges enhanced by rising sea levels.[b]
- **Average and extreme temperatures are projected to increase, and heat waves are likely to become more severe, occur more often, and last longer.**[c] Electricity demand for cooling rises with increasing air and water temperatures, yet higher temperatures reduce the capacity of thermoelectric power plants and transmission lines.[d]

QUICK FACTS

Southeast States:	Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, Virginia
Population (2013)	79,000,000 (25% of U.S.)
Area (square miles)	503,000 (14% of U.S.)
Energy Expenditures	$343 billion

ENERGY SUPPLY & DEMAND		**Annual Production**	**Annual Consumption**	***% for electric power***
Electric power	*TWh*	1,170	1,120	*n/a*
Petroleum	*million barrels*	116	1,680	*2%*
Coal	*million tons*	140	208	*94%*
Natural gas	*Bcf*	4,640	6,410	*49%*

ELECTRIC POWER	**Annual Production (TWh)**	***% of Total Production***	**Capacity (GW)**	**Power plants >1 MW***
Natural gas	432	*37%*	155	325
Coal	399	*34%*	103	134
Nuclear	275	*24%*	39	22
Hydroelectric	30	*3%*	23	214
Wind	<1	*<1%*	<1	2
Biomass	24	*2%*	6	166
Solar	<1	*<1%*	<1	51

CRITICAL INFRASTRUCTURE

Petroleum		**Electric Power**	
Wells (>1 boe/d):	12,400	Power plants (> 1 MW):	1,024
Refineries:	31	Interstate transmission lines:	32
Liquids pipelines:	18	**Coal**	
Ports (>200 tons/yr):	27	Mines:	516
Natural Gas		**Waterways**	
Wells:	62,300	Coal and petroleum routes:	56
Interstate pipelines:	60	**Railroads**	
Market hubs:	5	Miles of freight track:	32,800

Note: Table presents 2012 data except number of oil wells, which is 2009 data.
*Some plants use multiple fuels, and individual generating units may be <1 MW.
Sources: AAR 2014, EIA 2011, EIA 2013a, EIA 2013b, EIA 2013c, EIA 2014a, EIA 2014c, EIA 2014d, EIA 2014e, EIA 2014f, EIA 2014g, EIA 2014h, US Census Bureau 2014, USACE 2014

Table 8-1. Examples of important energy sector vulnerabilities and climate resilience solutions in the Southeast

Subsector	Vulnerability	Magnitude	Illustrative Resilience Solutions
Oil and Gas Exploration and Production	Increased exposure to damage and disruption from an increasing frequency of powerful hurricanes combined with sea level rise[e]	Increasing number of Category 4 and 5 hurricanes by the end of the century[f]	Elevating and hardening infrastructure, improving emergency preparedness protocols, restoring coastal habitats[g]
Fuel Transport	Increased exposure to damage and disruption from sea level rise-enhanced storm surge during intense hurricanes[h]	Increasing sea level rise by 0.06–0.48 inches per year from 1992–2050, depending on the location and magnitude of ice sheet melt[i]	Reinforcing shorelines of critical waterways; dredging to maintain shipping access; elevating or rerouting critical rail, road, or pipeline arteries[j]
Thermoelectric Power Generation; Electric Grid; Electricity Demand	Higher temperatures resulting in increased average and peak electricity demand and reduced generation and transmission capacity[k]	Increasing air temperatures by 2.5°F –8.5°F and increasing numbers of cooling degree days (CDDs) by 450–1,150 degree days by mid-century[l]	Increasing energy efficiency, demand-response programs, installing new generation and transmission capacity

Regional Energy Sector Vulnerabilities and Resilience Solutions

Key energy subsectors and illustrative examples of resilience solutions in the Southeast are discussed below. System components that are most vulnerable to climate change are described first.

Oil and Gas Exploration and Production

Subsector Vulnerabilities

The Southeast region contains extensive oil and gas exploration and production infrastructure, with almost a quarter of the nation's oil refining and natural gas processing capacity. Some of the United States' largest oil fields are located off the coast of Louisiana. Most of this offshore production, which constituted 17% of all oil production in the United States in 2013, comes onshore in Louisiana (EIA 2014a).

Climate change is projected to have the following impacts on the Southeast's oil and gas industry:

- Increasing frequency of the most intense hurricanes increases the risk of damage and disruption to coastal and offshore oil and gas facilities (DOE 2013, USGCRP 2014).
- Rising sea level combined with projected increases in hurricane and associated storm intensity, storm surge, and heavy rainfall may lead to intensified flooding along coasts (USGCRP 2014).
- Decreasing water availability may increase the cost of onshore unconventional oil and gas production (DOE 2013).

Offshore oil and gas platforms are vulnerable to high winds and damaging surf caused by hurricanes. One study found that approximately 3%–6% of offshore platforms exposed to hurricane-force winds typically experience damage that could take anywhere from less than a month to at least 6 months to repair, and an additional 2%–4% are typically destroyed (Kaiser and Yu 2009). As the frequency of Category 4 and 5 hurricanes increases, the risk of damage from these intense storms is likely to increase as well.

Offshore platforms typically follow the design specifications of the American Petroleum Institute (API), which sets performance standards for withstanding stresses such as wind speeds and wave heights for a 100-year storm. However, some of these threshold limits have been significantly surpassed in recent years (Cruz and Krausmann 2008). Furthermore, as oil exploration and production operations move farther offshore into deeper waters, the potential for damage increases (DOE 2013).

Oil and gas infrastructure affected by 2005 hurricanes

Hurricanes Katrina and Rita disrupted production operations and caused widespread damage along the Gulf Coast in 2005. The storms temporarily took offline 100% of Gulf of Mexico oil production and more than 88% of Gulf of Mexico natural gas production, and power outages knocked out three major petroleum pipeline systems (Colonial, Plantation, and Capline) (DOE 2009, Grenzeback and Lukmann 2008). The hurricanes caused significant damage to parts of the Port of New Orleans and silted in nearby waterways, preventing deep-draft ships from passing through. Parts of the Lower Mississippi River were closed to traffic for over a week, and more than 300 barges along the river were significantly damaged, set adrift, or sunk. Damaged vessels and power outages disrupted freight transport along the Gulf Intracoastal Waterway. Commercial barge traffic could not use locks, as they were being operated for floodwater drainage. Together, Hurricane Katrina and Rita led to a $15 billion loss to energy markets, two-thirds of which was associated with physical damage to infrastructure (Grenzeback and Lukmann 2008).

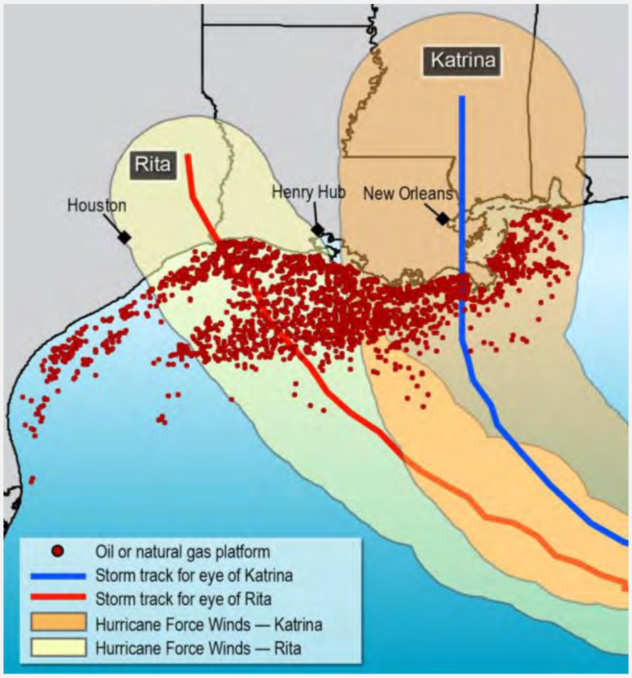

Figure 8-1. Hurricanes Katrina and Rita destroyed 113 offshore platforms, damaged another 52 platforms, and damaged more than 450 pipelines.
Source: USGCRP 2014

Coastal energy infrastructure—including processing plants and refineries—are vulnerable to physical damage from inundation and waterborne and airborne debris during hurricanes. Storm surges associated with intense hurricanes destroy equipment, damage building foundations, and knock buildings down. Even if exploration and production facilities are not physically damaged, they can be forced offline for extended periods following hurricanes when damage to refining and processing infrastructure and the electric grid prohibits access to crude oil, natural gas, and/or power (EIA 2009).

Hurricanes can destroy wetlands and other natural features that help protect coastal infrastructure (Figure 8-2). Natural barriers absorb hurricane-generated storm surges and waves, and their destruction increases the vulnerability of coastal and inland infrastructure to future storms. Coastal development can also destroy natural barriers, and Louisiana has lost 1,880 square miles of land along the coast in the past 80 years owing to management of river flow, dredging, and other natural and manmade problems (USGCRP 2014).

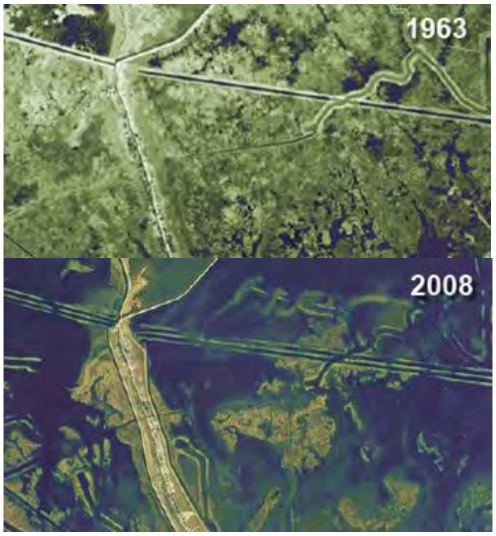

Figure 8-2. Aerial photos of Isle de Jean Charles in Louisiana taken in 1963 (top) and 2008 (bottom) show the effects of sea level rise, land subsidence, and human development on the Gulf Coast

Source: USGCRP 2014

The exposure of coastal energy facilities to hurricanes is magnified by sea-level rise, which amplifies the height of storm surges. Depending on location, relative mean sea level in some locations along the Gulf Coast has already increased by almost three inches per decade because of a combination of global sea-level rise and land subsidence (NOAA 2009). Future sea-level rise is projected to climb between one and five inches per decade in the first half of the 21st century and to accelerate over time (USGCRP 2014). In the Southeast, 187 major energy facilities are located below four feet above sea level; 148 of these facilities are located in Louisiana (Climate Central 2014).

Shale oil and gas exploration and production may face decreasing water availability. Shale oil production in the United States requires between 4.2 and 8.5 million gallons of water per day to produce 2.1 million gallons of oil per day. Production in the Haynesville Shale in Louisiana and Texas requires about 3.75 million gallons of water per well (Burke 2013, Stark et al. 2012), most of which is used for hydraulic fracturing. More than 2,600 wells have been drilled in this shale as of September 2014 (LDNR 2014). About 20% of the water that is used in shale production in the Haynesville Shale is groundwater. Louisiana requires permits for groundwater withdrawals. Production in the Fayetteville Shale in Arkansas requires closer to 3 million gallons of water per well (Stark et al. 2012).

Oil and Gas Exploration and Production

Resilience Solutions

Oil and gas operators along the Gulf Coast, experienced with risk management from natural hazards, can adopt a number of solutions to enhance resilience to more frequent Category 4 and 5 hurricanes and associated storm surge. These solutions include expanding the use of mobile equipment (Entergy 2010) and practices for improving resilience of offshore platforms to hurricanes. Floating production systems are already in use in deepwater drilling operations in the Gulf of Mexico (BSEE 2014); these systems can be disconnected and removed from a site in advance of a hurricane, reducing the risk of damage and destruction to the platform. New engineering and operations guidance developed by the American Petroleum Institute provides modified design specifications for new platforms; operations protocols for hurricane season, such as positioning platform decks higher above the sea surface, methods for securing platform equipment to rigs, and locating mobile "jack-up" rigs on more stable areas of the sea floor; improved data for wind, wave, current, and surge conditions at higher spatial resolution; and protocols for post-hurricane structural assessment (API 2014a).

Engineered barriers such as levees can be effective in protecting vulnerable coastal areas. In addition, wetland restoration and development of other natural barriers may be a cost-effective resilience technique (TNC-DOW 2012). These types of structures—natural and manmade—help protect coastal infrastructure from storm surges and wave impacts (DOE 2013). Historically, the economic value of coastal protection and other ecological services provided by natural landscape features has not been consistently incorporated into the risk management decisions involved in the planning and construction of coastal infrastructure. Recently, however, projects undertaken between private industry and natural resource conservation stakeholders have shown that collaboration and data sharing can be successful strategies for integrating the value of environmental features into coastal facilities planning (TNC-DOW 2012).

Shell efforts to harden offshore oil platforms

Shell researched damage done to the Mars platform in the Gulf of Mexico during Hurricane Katrina to develop measures to increase resilience of offshore platforms to hurricane damage. Most of the above-water damage to the platform occurred when clamps holding the rig's structure failed under 270-kilometer-per-hour winds. Shell installed re-designed clamp systems on all offshore platforms in 2006; the new systems are four times stronger than the older ones (Shell 2013).

As competition for limited water resources increases in some areas, oil and gas companies can take measures to reduce vulnerability to water scarcity. Resilience solutions include water recycling and reuse as well as utilizing sources of lower-quality water, such as degraded water, wastewater, or brackish groundwater. These sources do not compete with irrigation and municipal needs, but they do require additional treatment steps and add to costs.

Fuel Transport and Storage

Subsector Vulnerabilities

The Southeast region is home to critical oil and gas transport and storage infrastructure, including ports, terminals, storage facilities, highways, railroads, and pipelines. In the central Gulf Coast region, 72% of ports, 27% of major roads, and 9% of rail lines are at or below 4-foot elevation (CCSP 2008).[1]

The region contains 27 petroleum ports and energy fabrication ports—which build the structures used in offshore oil and gas exploration and production—including the Port of South Louisiana, the largest port in the United States. The region also includes Port Fourchon, Louisiana, an energy supply port that serves as the launching point to supply rigs producing about 90% of the deepwater oil in the Gulf of Mexico and the land base for the Louisiana Offshore Oil Port (LOOP) (Figure 8-3) (DHS 2011). LOOP is the only deepwater port in the United States and the single largest point of entry for crude oil coming into the United States via tanker (EIA 2014a).

Five of the ten currently-operating LNG import terminals in the United States are located in the Southeast, and many are in the process of applying to export LNG (EIA 2014a, FERC 2012). Louisiana is also the location of Henry Hub, a major natural gas market hub where more than a dozen pipelines converge and that serves as the national benchmark for natural gas pricing (EIA 2014a).

Figure 8-3. LOOP's two onshore facilities, the Clovelly Dome Storage Terminal (above) and Fourchon Booster Station, which are located in coastal Louisiana
Source: DOTD 2015

Louisiana hosts two of the nation's four Strategic Petroleum Reserve (SPR) storage sites. The SPR provides the United States with energy and economic security through the emergency stockpile of crude oil.

Climate change is projected to affect fuel transport and storage in the Southeast in the following ways:

- Projected increases in the frequency of the most intense hurricanes (Category 4 and 5) and associated storm surge and intense winds increase the risk of damage and disruption to coastal and offshore oil and gas transport and storage infrastructure (DOE 2013, USGCRP 2014).
- Rising sea levels and land subsidence combined with projected increases in hurricane intensity and associated storm surge and heavy rainfall, are expected to increase flood regimes along coasts, affecting coastal transportation and storage infrastructure (USGCRP 2014).
- Barge transport of energy products on inland waterways may be at increased risk of disruption from lower water levels associated with decreasing precipitation, increasing evapotranspiration, and competing demand for water (DOE 2013, Ingram et al. 2013).

Coastal ports and facilities are vulnerable to high wind speeds and storm surge associated with intense hurricanes. Storm surge has the capacity to knock down terminal buildings, dislodge cargo containers, damage terminal equipment, and damage wharf and pier structures (CCSP 2008). When terminals and aboveground facilities are forced to stop or delay operations, oil and gas markets nationwide can be affected.

The impact of intense hurricanes on coastal ports and facilities in Florida may be particularly acute, as Florida is entirely dependent on petroleum products delivered by tanker and barge and has no interstate crude oil or petroleum product pipelines (EIA 2014a). During previous hurricanes, petroleum supplies have been delivered by

[1] In the referenced study, the Central Gulf Coast includes the coast between Galveston, TX and Mobile, AL (CCSP 2008).

truck and rail to compensate for closures of ports and terminals (DOE 2005).

Accelerating sea-level rise (Figure 8-4) and more intense hurricanes are likely to further affect coastal facilities through damage to low-lying roads that provide access to coastal energy infrastructure. Sea-level rise contributes to more damaging storm surges by amplifying their height and reach. In the short term, roads may be closed, but prolonged flooding can weaken roadways over the long term. Over half of the interstate and arterial-road miles along the Gulf Coast are vulnerable to a storm surge of 18 feet (CCSP 2008). An 18-foot storm surge would inundate 98% of the Gulf Coast's ports (CCSP 2008). A storm surge of 23 feet has the ability to inundate 66% of interstate highways, 57% of arterial roads, and almost half of the railroad miles along the Gulf Coast (CCSP 2008). These levels are below the storm surge levels of 25–28 ft produced by Hurricane Katrina in 2005 along the Mississippi coast (NOAA 2014a).

Figure 8-4. Relative risk from sea level rise according to a Coastal Vulnerability Index, which is based on coastal system susceptibility to change and the area's natural ability to adapt
Source: USGCRP 2014

Due to sea level rise and land subsidence, Louisiana State Highway 1, the only road that provides land access to Port Fourchon, Louisiana, could be inundated and inaccessible more than 155 days by 2040, and more than 300 days per year by 2050 (Figure 8-5) (DHS 2011, Needham et al. 2012). An analysis by the Department of Homeland Security found that a 90-day washout of Highway 1 in Louisiana, due to either washout of the road following a storm or gradual submersion due to sea-level rise and land subsidence, would reduce production by 120 million barrels of oil and 250 billion cubic feet of gas over a 10-year period (DHS 2011). Other ports would be able to replace only approximately 25% of the service provided by Port Fourchon (DHS 2011).

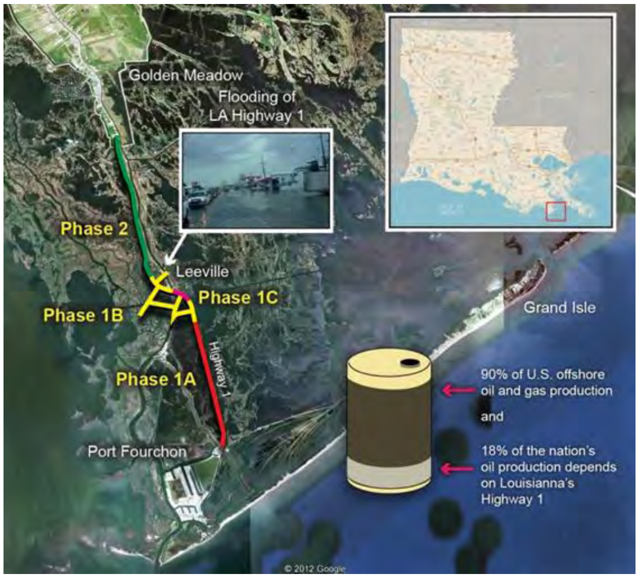

Figure 8-5. Highway 1 in Louisiana, which provides the link to a critical U.S. oil facility, Port Fourchon, and is vulnerable to climate impacts
Source: USGCRP 2014

Sea level rise may pose the greatest danger to the dense network of marine and coastal facilities in the central Gulf Coast region between Mobile Bay, AL, and Galveston, TX. An increase in relative sea level of 2 feet has the potential to affect 64% of the region's port facilities, while a 4-foot rise in relative sea level would affect nearly three-quarters of port facilities (CCSP 2008). By 2100, global average sea levels are expected to rise 1–4 feet above current levels, and rates of increase are expected to be even higher in the Southeast (USGCRP 2014).

Offshore pipelines that provide crude oil and natural gas to Gulf Coast refineries from offshore production are vulnerable to large surface waves and strong near-bottom currents associated with hurricanes. The currents scour the seafloor, creating underwater mudslides that damage subsea pipes and other equipment that rests on the seafloor. During the 2005 hurricane season, most of the damage to offshore pipelines occurred at the interface between pipelines and offshore platforms and subsea pipelines were identified by industry experts as the major cause of delays in bringing production back online (Cruz and Krausmann 2008, DOE 2015). Onshore pipelines are vulnerable to damage from coastal and inland flooding events, which can expose buried pipe that can then be impacted by flood-borne debris (GAO 2014, CCSP 2008). Onshore pipes are also vulnerable to corrosion as rising sea levels and coastal flooding increase saltwater intrusion of groundwater, and aboveground structures associated with pipelines may be damaged by high winds and flooding during hurricanes (DOT 2014).

The Gulf Intracoastal Waterway is a key asset in the distribution of petroleum products (CCSP 2008). Increasing intensity of hurricanes and sea level rise-enhanced storm surge may increase the risk of damage and disruption to waterway assets and operations. Storm debris can block navigation channels, and markers and barrier islands can be affected (CCSP 2008). Rail terminals, docks, and ships located along the coast in the Southeast are also vulnerable to high winds and storm surge from intense hurricanes.

Aboveground storage facilities are also vulnerable to storm surge and high winds associated with intense hurricanes. Storm surge and flooding can inundate facilities, and high winds can damage aboveground tanks at storage terminals and lead to spills in hazardous materials (API 2014a, Santella et al. 2010). Additionally, aboveground storage tanks can float off of their foundations during hurricanes, leading to spills (DOE 2015a). For example, flooding associated with Hurricane Katrina dislodged and damaged an above-ground storage tank at the Meraux Refinery in St. Bernard Parish, Louisiana, resulting in a release of more than 25,000 barrels of crude oil that impacted an adjacent residential neighborhood (EPA 2014).

During Hurricane Ike in 2008, the SPR site in West Hackberry, Louisiana, was flooded with debris, and the electrical systems sustained significant damage. Two additional SPR sites in Texas were damaged by storm surge from the hurricane, and costs for the repairs to all three SPR sites amounted to about $22 million (DOE 2010a). Supply disruptions during hurricanes can cause natural gas and petroleum product spot prices to spike (API 2014b, DOE 2009). Damage and disruption to the region's oil and gas infrastructure associated with a projected increase in intense hurricanes and accelerating sea level rise may contribute to short-term price volatility throughout the country (API 2014b, DOE 2009).

Coastal Virginia vulnerable to sea level rise and storm surge

In the Norfolk, Virginia, metropolitan area, a Category 4 storm in conjunction with a one-foot sea level rise could inundate critical energy assets. Under such a scenario, a DOE analysis identified exposure of the following fuel transport infrastructure: 11 petroleum terminals (>100,000 bbl), two natural gas pipelines, an LNG storage facility, and a petroleum pipeline. In addition, 39 substations (>230kV) and four power plants (>100 MW) are threatened in such a scenario (DOE 2014).

Lower waterway levels may disrupt barge transport of energy commodities, particularly in the western portion of the region where some models project an increasing likelihood of drought (DOE 2013, Ingram et al. 2013). Less rainfall and increasing evapotranspiration due to higher temperatures contribute to reduced runoff into navigable waterways. In addition, withdrawals for competing uses, such as agricultural, industrial, and municipal use, can contribute to lower water levels. In August 2012, the Mississippi River approached historically low water levels in several places and barges ran aground in the main river channel near Greenville, Mississippi (NASA 2012). Water availability may decline by 2.5%–6.4% by 2060 for most of Alabama, Arkansas, Kentucky, Louisiana, Mississippi, and Tennessee (USGCRP 2014). One study found that the largest decrease in river flow magnitude is projected to occur in the Appalachian-Cumberland subregion, which includes, Kentucky and Tennessee, and the Mississippi Alluvial Valley, which spans the Mississippi River from Kentucky to the Gulf Coast (Ingram et al. 2013). Low flow conditions along rivers may cause barge operators to reduce their loads, with estimates suggesting that in some cases a one-inch drop in river level could reduce tow capacity by 255 tons (DOE 2013).

Fourchon beach repair and renourishment project

In 2013, the Greater Lafourche Port Commission initiated a $5.4 million project to restore 6 miles of beach and dunes on Fourchon Beach to provide storm surge protection to Port Fourchon and the surrounding area (Houma Times 2012, Buskey 2013). The Federal Emergency Management Office (FEMA), Shell, and the Port Commission provided funding for the Fourchon Beach Repair/Renourishment Project, also known as the GeoTube Project (Shell 2012). Under this initiative, contractors installed geotubes, large tubes that are made of fabric and filled with sand, along the beach and covered the geotubes with sand to create an over-10-foot dune (Houma Times 2012).

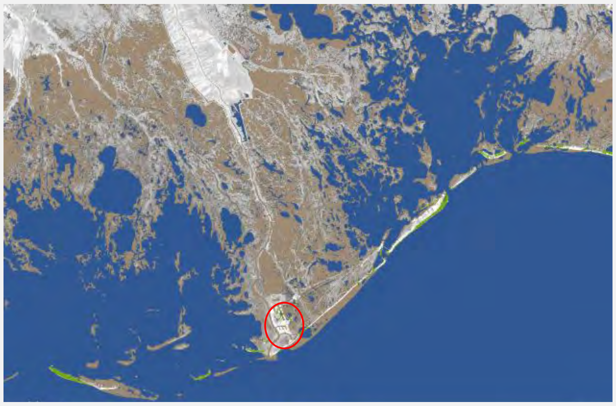

Figure 8-6. The landscape of coastal Louisiana, including the Port Fourchon area (red circle), which has been significantly altered since 1932
Brown indicates land that was lost or converted to water from 1932–2010 and green indicates land that was gained from 1932–2010 through coastal improvements such as shoreline revetments and beach enrichment. Blue indicates open water.
Source: NOAA 2012

Fuel Transport and Storage

Resilience Solutions

In many cases, fuel storage and transport assets can be hardened to better withstand more intense hurricanes and storm surges. Examples of infrastructure hardening include installing water-tight doors, elevating critical equipment, using submersible equipment, and building or improving the design of levees. Railroad and road bridges can be raised above storm surge levels or engineered to withstand lateral and uplift forces resulting from flooding and wave action (Cauffman 2006, DOT 2014). Shorelines of critical waterways can be hardened to prevent and offset erosion. Dredging, flood control, and water management practices can be employed to maintain shipping access, including appropriate upstream reservoir management to maintain water levels for shipping without impacting the other purposes of the reservoirs.

Portions of Louisiana State Highway 1 were elevated in 2009 to protect the road from 100-year flood events, and bridge designers used restraining devices and anchor bolts to protect the road from storm surge forces. The raised segment of the road was unaffected by Hurricane Isaac, however the bridge approaches—the portions of the road to the north and south of the raised section—and adjacent land were inundated by storm surge and suffered damage from erosion (GAO 2013).

Strategies for improving resilience of onshore pipelines include installing manmade or natural barriers to reduce risk of erosion, which could expose buried pipes. Another risk reduction measure is upgrading pipes with more robust materials that are less likely to leak or rupture from seawater-induced corrosion—such as coated steel pipes instead of cast iron or steel.

Barge transport of energy commodities can be more resilient to disruptions from low flow conditions by implementing dredging and water management practices, such as upstream reservoir management to maintain river flow levels (Ingram et al. 2013).

Electric Grid

Subsector Vulnerabilities

Most of the Southeast electricity markets operate under a traditional vertically integrated utility model, with the exception of Virginia, which is part of the PJM Interconnection, and parts of Louisiana, Mississippi, and Arkansas, which are part of the Midcontinent Independent System Operator (MISO) market. For states dominated by the traditional utility model, utilities own the transmission network. Many transmission investments in the Southeast are driven by future load growth and reliability needs rather than by power plant retirements or connecting to distributed renewables, which are important drivers in other regions (EEI 2013).

Climate change is projected to have the following impacts on the electric grid in the Southeast:

- Increasing hurricane intensity and frequency of the most intense hurricanes (Category 4 and 5), along with hurricane-associated storm surge enhanced by sea level rise, may increase the risk of physical damage or disruption to transmission and distribution infrastructure, including substations and transformers, near the coast (DOE 2013, USGCRP 2014).
- Increasing average and extreme temperatures reduce transmission efficiency, increase the risk of damage to transformers, and may reduce available transmission capacity (Bérubé et al. 2007, DOE 2013, USBR 2000, USGCRP 2014).

Table 8-2. Damage to the electric grid from recent hurricanes

	Katrina (2005)	Rita (2005)	Wilma (2005)	Gustav (2008)	Ike (2008)
Customers Affected (in millions)	2.7	1.5	3.5	1.1	3.9
Utility Poles Destroyed	72,447	14,817	~14,000	11,478	10,300
Transformers Damaged	8,281	3,580	NA	4,349	2,900
Transmission Structures Damaged	1,515	3,550	NA	241	238
Substations Offline	300	508	241	368	383

Source: DOE 2009

Intense hurricanes produce high winds and increase incidents of damage and disruption to power lines (Figure 8-7 and Table 8-2). Severe weather is the leading cause of electric power disturbance events in the United States, and as intense hurricanes (Category 4 and 5) become more common as a result of climate change, the Southeast region's electric transmission and distribution infrastructure will be increasingly threatened (DOE 2013, EOP 2013, USGCRP 2014). Transmission outages from hurricanes and tropical storms affected more than 10 million customers in Florida from 1992–2009 (DOE 2015b).

Substations and underground distribution systems are vulnerable to damage from storm surge and coastal flooding during hurricanes. The most prevalent cause of damage to substations in coastal regions is flooding from storm surge (DOE 2009). According to one study, projected sea level rise by 2030 could increase the number of substations exposed to storm surge from a Category 1 hurricane by 82 (from 255 substations in a scenario without sea level rise to 337 substations in a scenario with a 10 inch sea level rise) (DOE 2015a). Any significant increase in hurricane intensities would greatly exacerbate exposure to storm surge and wind damage. During Hurricanes Katrina and Rita, low-lying power substations in Mississippi and Louisiana suffered significant damage to controllers, switches, and other components as a result of storm surge and waves (DOE 2009). Even equipment that was pressure-washed with fresh water immediately after the storm was destroyed from salt water exposure (NIST 2006). More than one million distribution poles were damaged during Hurricane Katrina, and during Hurricane Gustav, damage to high-voltage transmission lines caused the transmission system south of Lake Pontchartrain, including the city of New Orleans, to be islanded from the supply network for two days (DOE 2009, DOT 2014).

Figure 8-7. High winds and flooding during Hurricane Katrina downed power lines and poles in New Orleans
Source: FEMA 2005

During periods of high air temperatures, operators reduce the carrying capacity of transmission lines and power substations, and higher air temperatures may compound capacity constraints during extreme heat events when demand for power for air conditioning is the highest (DOE 2013). This effect can be exacerbated by higher nighttime temperatures, which prevent power systems from cooling off. Higher temperatures also cause thermal expansion of transmission line materials, and sagging lines increase the risk of power outages when the lines make contact with other lines, trees, or the ground (DOE 2013).

Higher temperatures can damage power transformers and force operators to reduce transformer loading on extremely hot days (Bérubé et al. 2007, USBR 2000). Power transformers in the United States are typically designed to operate at an average ambient temperature of 86°F over a 24-hour period where maximum temperatures do not exceed 104°F (PJM 2011, Hashmi et al. 2013). As temperatures increase above the rated temperature, the paper insulation in traditional power transformers begins to break down. Transformers are critical to system operation, and during emergency conditions, they may be overloaded forcing temperatures as high as 284°F and causing breakdown to occur as much as 100 times faster than normal (USBR 2000, Bérubé et al. 2007). Higher ambient temperatures increase the likelihood of transformers reaching critical temperatures during emergency overloading (Hashmi et al. 2013).

Electric Grid

Resilience Solutions

Resilience could be improved through hardening measures that help the grid withstand higher winds and flooding, as well as additional capacity in the transmission networks (DOE 2013). In some circumstances, new conductor technologies could be installed that withstand higher temperatures with fewer losses and less sag (NARUC 2011).

Although it is expensive, undergrounding power lines is one measure that can protect power lines from wind impacts. In order to protect its distribution system from storm impacts, Dominion Virginia Power initiated a decade-long program in 2014 to place underground approximately 4,000 miles of the utility’s most outage-prone distribution lines: about 7 percent of the 57,100-mile system. This $175 million-per-year undergrounding program is expected to substantially increase system reliability and resilience to climate change and extreme weather (Dominion 2014).

For infrastructure located near the Gulf Coast, hardening measures include activities such as replacing wood power poles with steel, concrete, or composite structures, burying critical power line segments, and relocating equipment away from flood zones or building levees around equipment (EOP 2013). For example, Entergy has invested in elevating substation control equipment, such as the Leeville substation in southern Louisiana, above the 100-year flood level (Entergy 2013, Kusnetz 2012). Elevating critical equipment such as substations is a common hardening practice to protect against storm surge (Figure 8-8). To determine how high to elevate substations, control rooms, and other vital assets, utilities often use the Seas and Lakes Overland Surges (SLOSH) model (DOE 2010). SLOSH is a computerized model developed by the National Oceanic and Atmospheric Administration (NOAA) that estimates storm surge heights and winds from hurricane scenarios (NOAA 2014b).

Figure 8-8. Elevated substation in Vermilion Parish, Louisiana
Source: DOE 2010b

Florida Power & Light Electric Infrastructure Storm Hardening Plan

Following the damaging 2004–2005 hurricane season, Florida Power and Light (FPL) announced their Storm Secure Plan to strengthen the electric grid against hurricanes. FPL announced that they would be adopting extreme wind velocity zone criteria (up to 150 mph) as a new standard for distribution construction and system upgrades. This plan also includes encouraging undergrounding of distribution lines by investing in local government-sponsored overhead-to-underground conversion projects, and calls for increasing pole inspections and line clearing and vegetation management activities (FPL 2006).

In 2013, FPL announced the 2013–2015 Electric Infrastructure Storm Hardening Plan. The company expects to invest $428 million to $646 million to improve the resilience of its electric infrastructure (FPL 2013a). This plan includes an initiative to protect 15 above-grade vaults in the Miami downtown electric network distribution system (FPL 2013b). The vaults will be retrofitted with submersible equipment, and existing equipment will be replaced with new sealed, stainless steel equipment (FPL 2013b). FPL is also accelerating its program to replace wood transmission structures with concrete structures and upgrade ceramic post insulators with polymer material, and replaced over 4,000 wood transmission structures and upgrade more than 3,600 ceramic post insulators from 2007–2012 (FPL 2013a).

Entergy and America's Wetland Foundation collaborated on the development of a framework to inform economically sensible approaches to address risks and to build a resilient Gulf Coast (Entergy 2010). The study covered a wide region, including Texas, Louisiana, and coastal counties in Mississippi and Alabama, and was comprehensive across key economic sectors, including fuel supply, electricity generation, and residential and commercial demand sectors. The study projected that by 2030 there may be nearly $1 trillion in energy assets at potential risk from rising sea levels and more intense hurricanes. Based on an analysis of hazards, assets, and vulnerabilities, the Gulf Coast energy sector faces an average annual loss from climate change and extreme weather of $8 billion in 2030 (Entergy 2010). The study identified key "no regrets" options for adaptation that have low investment needs, high potential to reduce expected losses, and additional strong co-benefits such as wetlands restoration. The study also concluded that supporting and enforcing a range of actions to reduce the risks that individuals bear (e.g., through building codes and development decisions) and to unlock barriers to increasing industry resilience would be important elements of a coordinated response (Entergy 2010).

To increase the resilience of transformers to high ambient temperatures, operators may derate existing transformers or install or upgrade forced-air or forced-oil cooling in transformers (Hashmi et al. 2013, USBR 2000). When replacing existing transformers, operators can increase system resilience to increasing temperatures by installing thermally upgraded transformers (Bérubé et al. 2007).

Thermoelectric Power Generation

Subsector Vulnerabilities

Fossil fuel-fired power plants dominate the electricity source mix in the Southeast, with coal and natural gas accounting for about 70% of total generation and nuclear representing about a quarter of total generation (Table 8-3). The source fuel varies within the region, with natural gas supplying the majority of electric power to states along the Gulf Coast. For example, about 68% of Florida's power is generated from gas-fired power plants. Other states in the Southeast have a higher contribution from coal and nuclear power. Coal-fired generation makes up 92% of generation in Kentucky and provides the majority of generation in Arkansas, Tennessee, and North Carolina. About half of South Carolina's power comes from nuclear plants.

Table 8-3. Electricity generation fuel mix in the Southeast

	Gulf Coast States*	Other Southeast	Total Southeast
Coal	22%	44%	**34%**
Natural Gas	57%	20%	**37%**
Nuclear	15%	30%	**24%**
Hydroelectric	2%	3%	**3%**
Other	4%	2%	**3%**

* Alabama, Florida, Louisiana, and Mississippi
Source: EIA 2013a

Climate change may have the following impacts on thermoelectric power generation in the Southeast:

- Increasing air and water temperatures decrease the efficiency and the available capacity of thermoelectric power plants (DOE 2013).
- Increasing water temperatures could cause thermoelectric power plants to exceed thermal discharge limits and force temporary curtailments at plants (PNNL 2012).
- Decreasing summer precipitation in some locations and higher evaporative losses from surface water resources could reduce water available for cooling (USGCRP 2014, NOAA 2013, NETL 2010).
- Increasing hurricane intensity and frequency of intense hurricanes, sea-level rise-enhanced storm surge, and

heavy rainfall threaten low-lying and coastal power generation facilities (GAO 2014, DOE 2013).

As the temperatures of ambient air and water used for cooling increase, the thermal efficiency of power generation decreases (DOE 2013). Reduced thermal efficiencies can result in reduced power output and/or additional fuel consumption. With more than 90% of the electricity in the Southeast generated from thermoelectric power plants (Table 8-3), such decreases in power output or increases in fuel consumption will hinder system flexibility or increase costs across the region (EIA 2013a, DOE 2013).

Higher surface water temperatures heightens the risk that power plants will exceed thermal discharge limits mandated to protect aquatic ecosystems, which could cause plants to temporarily reduce their power generation. For example, Browns Ferry Nuclear Plant was forced to curtail operations after heat waves in 2007, 2010, and 2011 caused the temperature of the Tennessee River to exceed 90°F, as cooling water discharge from the plant would exceed the thermal limit (PNNL 2012).

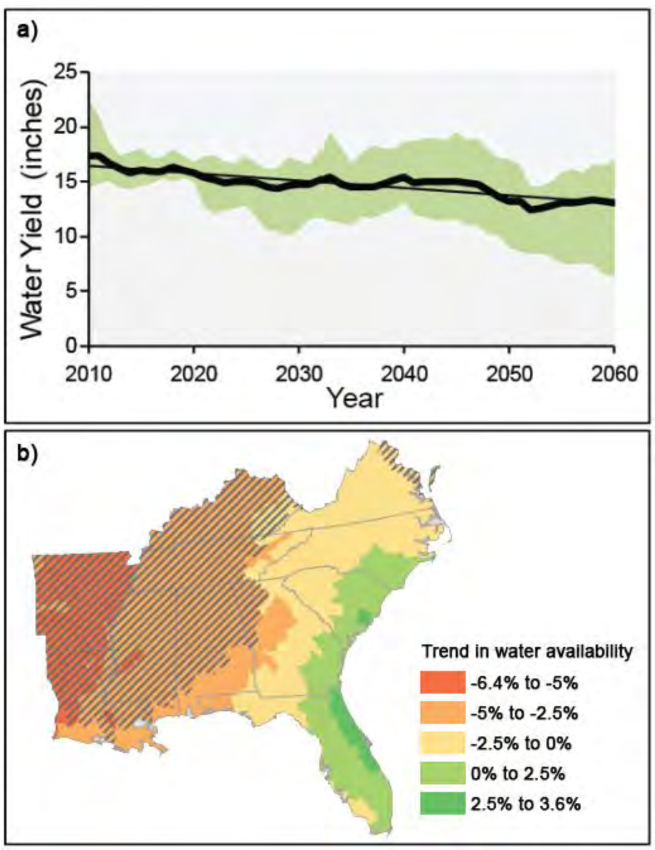

Figure 8-9. a) Projected trend in water availability in the Southeast; green area indicates range of emission scenarios and b) decadal trend for 2010–2060 relative to 2010; hatching indicates projected negative trend is statistically significant
Source: USGCRP 2014

Water availability for most of the Southeast is trending downward, particularly for the areas in the region west of the Appalachian Mountains and west of the Chattahoochee River (Figure 8-9). Decreasing surface water availability resulting from lower rainfall, increased evaporation rates, and competing uses (e.g., irrigation for agriculture and municipal water for a growing population) may threaten the available generation capacity of thermoelectric power plants. Drier summers are expected across most of the region (NOAA 2013, USGCRP 2014).

Many power plants in the Southeast region use once-through freshwater cooling systems (Figure 8-10), and because of their need to withdraw large amounts of water from lakes, rivers, and streams, these plants are more vulnerable to deratings or outages due to low water. During periods of drought, plants using these cooling systems can become nonoperational if the water level drops below water intake structures (NERC 2013).

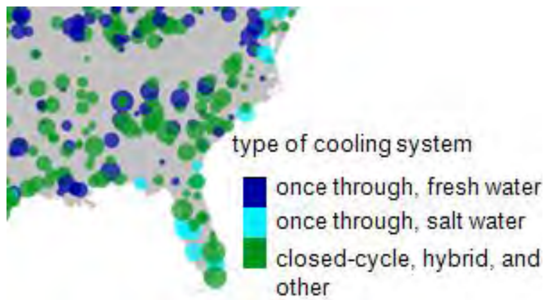

Figure 8-10. Distribution of thermoelectric power plants greater than 70 MW by type of cooling system in the Southeastern United States; larger circles on the map indicate higher net summer capacity
Source: EIA 2012a

Changes in the number of intense hurricanes could increase the vulnerability of low-lying and coastal power plants to flooding and inundation. Flooding can interfere with power plant operations and floodwaters and flood-borne debris can damage structures that draw cooling water from rivers (DOT 2014, GAO 2014). Rising sea levels will magnify the destructive power of hurricanes. One study estimates that even with no sea-level rise, there are 69 electricity generation facilities in the Southeast potentially exposed to a Category 1 hurricane storm surge and 291 facilities exposed to a Category 5 storm (Maloney and Preston 2014).[2,3] However, with just 1.6 feet of relative sea-level rise, the number of facilities vulnerable to a Category 1 storm surge increases by 41%. Depending on the sea-level rise scenario (ranging from 1.6 feet to 2.7 feet) and the

[2] Southeast region as defined in the study differs from the region definition in this profile. The study includes Texas but excludes Virginia.

[3] The capacity of the 69 power plants exposed to a Category 1 storm is about 15,000 MW, and the capacity of the power plants exposed to a Category 5 storm is about 86,000 MW.

intensity of the hurricane, the number of exposed power plants increases by 6%–60% (Maloney and Preston 2014).

More intense hurricanes can also increase the risk of flooding to power plants in low-lying inland locations. Hurricanes can bring massive amounts of rainfall hundreds of miles from the coast. The rainfall produced by Atlantic hurricanes may increase by as much as 20% as a result of climate change (USGCRP 2014).

Thermoelectric Power Generation

Resilience Solutions

New generation capacity with sources and supply chains less affected by increasing temperatures and decreased water availability, such as wind power and solar photovoltaic (PV), may help make the region's power sector more resilient to climate change.

Introducing more advanced cooling technologies into the region's power production infrastructure may also be an effective strategy to reduce its vulnerability to decreasing water availability or generation reductions due to discharge water temperature restrictions. A large number of the power plants in the region rely on older once-through cooling systems. Nuclear and coal-fired power plants using these systems require the largest amounts of water compared to other fuels (DOE 2013). A transition to natural gas-fired power plants, which require relatively less cooling water, will enhance resiience. Equipping power plants with cooling ponds, recirculating systems, or advanced cooling technologies such as hybrid wet–dry and dry cooling systems will also reduce power plant exposure to water scarcity-related vulnerabilities. For example, Plant Yates, a coal-fired generator in Georgia that operated using a once-through system, added cooling towers and cut water withdrawals by 93%, dropping withdrawals to 32 million gallons per day (UCS 2011). Additionally, Duke Energy is modifying equipment and procedures at nuclear and coal-fired generating plants to reduce drought-related risks to generation (Duke Energy 2014).

Policy measures could also help address water availability issues. Some areas have established market-driven solutions to address the vulnerability of critical shortages in supply.

Coastal thermoelectric power plants can be hardened against hurricanes and heavy precipitation events and associated flooding through relocating or elevating critical equipment, upgrading plants with submersible equipment or watertight doors, and building improved levees around existing infrastructure. Planners can protect new capacity by locating new generators at higher elevations which are not at risk of flooding due to hurricanes or increased precipitation.

Evaluating the risk of sea level rise to nuclear reactors in Florida

Florida Power & Light (FPL) has begun incorporating sea level rise into siting and hazard assessments for nuclear reactors. In June 2009, FPL submitted an application to evaluate the construction of two new nuclear reactor units at Turkey Point that incorporated potential sea level rise over the next 100 years. In a 2013 reevaluation of flooding hazards for two existing nuclear reactor units at Turkey Point, FPL incorporated projected sea level rise over the next 20 years (GAO 2014).

Electricity Demand

Subsector Vulnerabilities

Among regions, the Southeast is the greatest energy consumer and has the highest per capita electricity use in the United States (EIA 2014a). On average, more than 10% of the energy consumed in homes is used for air conditioning in the Southeast, compared to a national average of 6% (EIA 2014a). Hotter temperatures and a higher frequency of extreme temperatures are projected for the region, which is expected to increase use of air conditioning and contribute to an overall increase in net energy use (USGCRP 2014).

Climate change is expected to affect electricity demand in the following way:

- Increasing average temperatures and occurrences of extreme temperatures are expected to increase average and peak demand for cooling energy (DOE 2013).

Although projected temperature increases are generally smaller for most parts of the Southeast than for other regions of the United States, higher temperatures are expected to be an important contributor to increased electricity use (USGCRP 2014). The Southeast may require the steepest increases in electricity transmission and distribution to meet cooling demand (USGCRP 2014). Climate change is expected to increase CDDs throughout the region, ranging from 450 to 750 additional CDDs in the northeastern part of the Southeast region to between 750 and 1,150 additional CDDs per year projected for Florida, the Gulf Coast, and the Mississippi River Valley by the middle of this century (compared to 1980–2000) (NOAA 2013). Florida is expected to see a sharp increase in the number of extreme temperatures (>95°F), quadrupling to over 60 days per year by mid-century (

Figure 8-11).

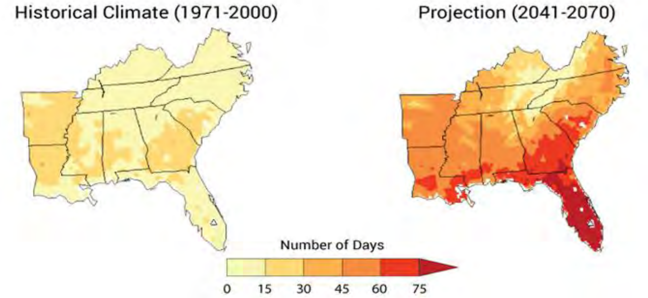

Figure 8-11. Number of days per year with daytime high temperatures exceeding 95°F historically (left) and by mid-century (right) under a higher emissions scenario
Source: USGCRP 2014

Market penetration of air conditioners in the South is currently 98% (EIA 2013d), so an increase in CDDs will likely drive an increase in the energy use of existing air conditioners, an increase in the hours of operation, or both. Higher temperatures could have significant repercussions for the power sector, as the predicted increases cooling energy demand may require major system upgrades to handle increases in peak load.

Higher temperatures can have a compounding effect on the water use in the region, as higher temperatures increase overall demand for water, increasing energy required for pumping, treatment, drainage, and desalination. For coastal communities that rely upon groundwater for their water supply, rising sea levels can contribute to saltwater intrusion of underground freshwater aquifers. Preventing saltwater intrusion requires additional energy for pumping. Energy demand for additional pumping in heavily managed water systems is projected to grow rapidly (Berry 2012).

Alongside technological change and economic growth, population growth is an important factor driving future electricity demand in the region. The population in the Southeast is projected to increase by 57% between 2000 and 2030, compared to a national average projected growth of 29% over the period (US Census Bureau 2005). The region has four of the ten fastest-growing metropolitan areas (Mackun 2010).

Increases in electricity demand could exacerbate vulnerabilities to the broader energy system in the region, particularly during peak demand for cooling. Periods of high temperatures coincide with reduced power plant and transmission line efficiency and capacity and potentially coincide with decreased water availability for cooling at power plants.

As temperatures increase, the demand for heating energy is expected to decline. Electricity is the primary fuel used for space heating in the Southeast (EIA 2013d), although with mild winters, the region's peak electricity demand is about 10% less in the winter than in the summer (EIA 2013e).

Electricity Demand

Resilience Solutions

Energy efficiency, demand-response programs, and capacity expansion play an important role in reducing the exposure of the Southeast's power sector to increasing energy demand.

Anticipating the need to increase system resilience, several states in the region have enacted legislation to reduce future demand for electricity by requiring energy efficiency measures. For example, Florida and Georgia—states which are expected to see the largest increases in extremely hot days in the region—require that new homes meet International Energy Conservation Code building standards (ACEEE 2014a). Only two of the region's thirteen states (Arkansas and North Carolina) have adopted an energy efficiency resource standard as a legislated target for energy savings. Arkansas requires a 0.75% annual reduction in investor-owned utility electricity sales, and North Carolina has a combined energy efficiency and renewable portfolio standard, requiring a 12.5% offset by 2021 from either efficiency savings or renewable energy (ACEEE 2014b).

Improving resilience to greater electricity demand

Entergy has worked to mitigate the effects of increasing electricity demand by investing in energy efficiency programs, including programs to weatherize low-income homes and distribute 1,500 weatherization kits. Entergy, which has service territory in Arkansas, Louisiana, Mississippi, and Texas, reduced demand by 40 MW in 2012 and has also added 2,080 MW of new capacity to meet future demand (Entergy 2013).

In Tennessee, the city of Knoxville was recognized by the White House as a Climate Action Champion—in part for its energy efficiency and demand reduction efforts (White House 2015). The city has adopted the latest available building energy codes and is developing a revolving loan pilot program for residential energy efficiency retrofits. The city is also reducing energy consumption by upgrading streetlights and deploying energy management programs (City of Knoxville 2014).

Load management programs include dynamic pricing, remote-controlled thermostats, and dispatchable demand programs. Several utilities in the Southeast—including Duke Power, Georgia Power, and the Tennessee Valley Authority—have offered demand management programs to their large customers for a decade or more. For example, participants in Georgia Power's real-time pricing program during the early 2000s reduced peak demand by 17%, or about 800 MW (MIT 2011). The Florida Public Service Commission establishes annual goals for seasonal peak demand and annual energy consumption reductions, and conservation and load management programs are projected to reduce Florida utilities' total summer peak demand by over 9,200 MW and annual energy consumption by over 14,500 GWh (FPSC 2013). Almost 2.6 million residential customers and 65,000 commercial and industrial customers in the Southeast were enrolled in demand response programs in 2013, resulting in energy savings of more than 99,000 MWh (EIA 2014i).

In addition to energy efficiency and load management programs, new electric generation capacity may help the Southeast region reduce its vulnerability to increasing energy demand. Virtually all of the new capacity additions to the electric power sector between 2000 and 2012 are natural gas-fired units (EIA 2013c). Natural gas-fired generating units are projected to constitute a majority of the generation additions through 2040.

Hydroelectric Generation

Subsector Vulnerabilities

The Southeast generates 3% of its electricity from 214 federally and privately-owned hydroelectric facilities in the region (Figure 8-12) (EIA 2013a). These facilities make up a combined 23 MW of installed capacity and are typically located in low-elevation areas with heavily vegetated land cover (DOE 2012a, EIA 2013c). Compared to other regions with federally-operated hydropower resources, the Southeast climate typically has the highest amounts of precipitation and runoff, but is also the hottest region with large evaporative losses (DOE 2012a). As in other regions, hydroelectric power generation in the Southeast is only one of many competing users of water resources. Other major uses of water in the region include agricultural use, ecological flows, navigation, and growing demand for municipal and industrial users—particularly in Atlanta and northern Georgia (DOE 2012a, 2012b).

Figure 8-12. The Raccoon Mountain project outside of Chattanooga, Tennessee, which is the Tennessee Valley Authority's (TVA's) largest hydroelectric facility where water is pumped to the reservoir on top of the mountain and then used to generate electricity when additional power is needed by the TVA system

Source: TVA 2015

Climate change may affect hydropower production in the following ways:

- Throughout the Southeast, dry years[4] are projected to occur more frequently, and the severity of low flow conditions[5] is projected to increase (DOE 2012a, 2012b).
- Decreasing precipitation, increasing evapotranspiration, as well as competing demand for water, may decrease water availability for hydropower generation (DOE 2012a, Ingram et al. 2013).

According to one study, the Southeast is projected to experience an increase in extremes in hydrology, primarily as a substantial increase in the number of dry years and decrease in the number of normal years, although some basins are projected to experience only a small change in the number of wet years (DOE 2012a).[6] According to the same study, future low-flow periods may be 10%–30% more severe than current low-flow periods. Despite these changes to runoff, annual hydropower generation in the Southeast is projected to decrease only slightly, with median annual federal hydropower in the region decreasing by 0.5% in the mid-term (2025–2039, relative to 1960-1999) (DOE 2012a, DOE 2012b). However, seasonal trends may be more relevant than annual trends in impacting hydropower generation. Projected hotter-drier summers amy result in more significant decreases in hydropower generation, coinciding with increases in electricity demand for cooling. Across the region, changes to inter-annual variability will likely have a greater effect on the region's hydropower resource than total reductions, as competition for water resources increases in dry years.

When considered in the context of other water users, the increasing occurrence of low-water years may have a larger impact than indicated by models that only consider hydropower resources. One water resource assessment of the Apalachicola-Chattahoochee-Flint (ACF) River basin considered both climate change impacts and current water management procedures. The study indicated that under various emissions scenarios, the basin may be vulnerable to severe stress resulting in deeper reservoir drawdowns and reduced firm hydropower generation (Ingram et al. 2013). Federal hydroelectric facilities in the basin—including the Buford Dam and W.F. George Dam—typically provide power during peak demand periods but would be unable to operate if water levels drop below water intake conduits due to decreased water availability (CRS 2007).

[4] Dry years are defined as those with annual runoff values in the lowest 20% of years in the baseline period (1960–1999)

[5] Low flow conditions are estimated by 10 year return-level quantiles of seasonal low runoff

[6] Comparing projected runoff in the period 2025–2039 to a baseline period of 1960–1999, based on a 2.7°F temperature increase.

Hydroelectric Generation

Resilience Solutions

To increase resilience to decreasing water availability, operators may consider hydropower generation as part of an integrated water management and planning approach. With competing demand from other users, hydropower may not be the highest-priority water user during periods of low flow. Operators may be able to maximize generation during low-flow periods by increasing efficiency of current facilities. For example, federal operators are working to replace older turbines with models that are more efficient at lower head levels (DOE 2012a). In addition, pumped storage can reduce vulnerabilities by pumping water to an elevated reservoir during low demand periods and then releasing the water to generate electricity when additional power is needed.

Operators may also benefit from improved monitoring and forecasting tools (DOE 2012a). Following the 2007 drought in North Carolina, which forced Duke Energy to cut hydroelectric generation 67%, Duke Energy established a drought mitigation team to monitor and forecast drought effects throughout Duke Energy Carolinas' service area (Duke Energy 2008). Duke Energy also partnered with public water system owners in the region to form the Catawba-Wateree Water Management Group to establish a groundwater monitoring network, modify water intakes at hydroelectric facilities, optimize water intake and return locations, and establish demand-side management goals for water (Duke Energy 2008).

Regional Climate Change Observations and Projections in Detail

Higher Temperatures

Historical observations

- **Since 1970, average temperatures have increased 2°F** (USGCRP 2014).
- **Frost-free season has been growing**: The average length of the frost-free season across the Southeast region increased by about six days (1991–2012, compared to 1901–1960) (USGCRP 2014).

Future projections

- **Average temperatures are expected to increase at a faster rate**: Depending on the location and GHG emissions, increases of 2.5°F–8.5°F are expected by 2070–2099 compared to 1971–1999 levels (NOAA 2013).
- **Extremely hot days are projected to become more common**: Across most of the region, 20–30 more days with a daily maximum temperature > 95°F are projected by mid-century (2041–2070, compared to 1980–2000); Florida is likely to be the most affected and may see as many as 40 more extremely hot days per year (NOAA 2013).
- **Consecutive number of days of extreme heat are expected to become longer:** The annual maximum number of consecutive days with a daily high > 95°F is projected to increase by up to 20 days by mid-century (2041–2070, compared to 1980–2000) across the region; the western portion of the region is likely to be the most affected (NOAA 2013).
- **Extremely cold nights are expected to become less common**: In the northern portion of the region, 2–10 fewer days with daily minimums <10°F are expected by mid-century (2041–2070, compared to 1980–2000) (NOAA 2013).
- **Freeze-free season is expected to lengthen**: The freeze-free season is expected to be 20–30 days longer by mid-century (2041–2070, compared to 1980–2000) across most of the region (NOAA 2013).
- **CDDs are expected to increase**: Across most of the region, an increase of 450–950 CDDs is expected by mid-century (2041–2070, compared to 1980–2000); Florida is likely to be the most affected with increases of up to 1,150 CDDs by mid-century (NOAA 2013).
- **Heating degree days (HDDs) are expected to decrease**: Across most of the region, declines of 100–900 HDDs are expected by mid-century (2041–2070, compared to 1980–2000); the northern portion of the region is likely to be the most affected, with declines of up to 1,100 HDDs by mid-century (NOAA 2013).

Changing Water Patterns

Historical observations

- **Since 1895, summer precipitation has decreased by 0.10 inches per decade, or 1.1 inches** (NOAA 2013).
- **Since 1895, fall precipitation has increased by 0.27 inches per decade, or almost 3 inches** (NOAA 2013).
- **Across the Southeast, extreme precipitation events have occurred more frequently:** An index of 2-day extreme precipitation events expected to occur once every five years shows a statistically significant upward trend since 1895 (NOAA 2013a).

Future projections

- **Depending on the emissions scenario and region, annual precipitation is projected to increase or decrease**: By the end of the century (2070–2099), annual average precipitation is expected to increase by 3%–6% in the northern portion of the region under a low emissions scenario compared to the period 1971–1999. Under a high emissions scenario, precipitation is projected to decrease by 3%–9% in the western and southern portions of the region compared to the period 1971–1999 (NOAA 2013).
- **Drier summers are expected across most of the region**: Summer precipitation is expected to decrease by up to 15% by mid-century (2041–2070, compared to 1971–2000) under a higher emissions scenario in the northern and far southern portions of the region (NOAA 2013).
- **Extreme precipitation events are expected to increase in the northern portion of the region**: The number of days per year with precipitation greater than one inch is expected to increase by up to 25% by mid-century (2041–2070, compared to 1980–2000) under a higher emissions scenario (NOAA 2013).
- **Consecutive number of days with little or no precipitation are likely to become longer in Louisiana**: The annual maximum number of consecutive days with less than 3 mm of precipitation is expected to increase up to 10 days by mid-century (2041–2070, compared to 1980–2000) (NOAA 2013).

Sea Level Rise and Hurricanes

Historical observations

- **Relative mean sea level has risen because of a combination of global sea level rise and land subsidence in the region**: Relative mean sea level on the coast of the Southeast region rose 0.03–0.38 inches/year between the middle of the 20th century and 2006, depending on the location (NOAA 2009).

Future projections

- **Sea level rise is expected to accelerate**: Sea level on the coast in the Southeast is projected to rise at an average rate of 0.06–0.27 inches/year (no ice sheet melt) or 0.21–0.48 inches /year (ice sheet melt) between 1992 and 2050 depending on the location (USGCRP 2014).
- **Frequency of intense hurricanes (Category 4 and 5), hurricane-associated storm intensity, and rainfall rates are projected to increase** (USGCRP 2014): Rainfall rates within 100 km of tropical storm centers are projected to increase by 20% by 2100 (USGCRP 2014).

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Chapter 8 Endnotes

[a] Source: USGCRP 2014
[b] Sources: DOE 2013, USGCRP 2014
[c] Sources: NOAA 2013, USGCRP 2014
[d] Sources: DOE 2013, USGCRP 2014
[e] Sources: DOE 2013, USGCRP 2014
[f] Source: USGCRP 2014
[g] Sources: API 2014a, DOE 2013, TNC-DOW 2012
[h] Sources: DOE 2013, USGCRP 2014
[i] Source: NOAA 2013
[j] Sources: Cauffman 2006, DOT 2014, GAO 2013
[k] Source: DOE 2013
[l] Under a higher emissions scenario in 2041–2070 compared to 1980–2000 (NOAA 2013)

Chapter 9: **Alaska**

Climate Change and the Energy Sector

Overview

Alaska consists of a vast, sparsely populated land area with over 30,000 miles of ocean coastline. Diverse ecosystems span the state, ranging from Arctic tundra in the far north to temperate continental in the interior to maritime coastal in the south. The state is a major oil and gas exporter, with critical oil production assets, pipelines and roads, and export facilities. Key climate change trends that may affect the energy sector in the region include the following:

- **Air temperatures in Alaska have increased rapidly over the last half-century and are projected to continue rising at a rate faster than anywhere else in the United States. Permafrost across much of the state is thawing, and permafrost loss is expected to continue in the future.**[a] Thawing permafrost alters the foundations of much of Alaska's infrastructure, such as the Trans-Alaska Pipeline System (TAPS), roads and airstrips, transmission lines, fuel storage tanks, and generators, and it can increase the vulnerability of riverbanks and coastlines to erosion.[b]
- **Arctic sea ice is retreating and is projected to decline substantially in the future.**[c] Sea ice protects coastlines from erosion and reduces the height of storm surge, reducing coastal flooding. Erosion of coastlines undercuts the structural footing of energy infrastructure, including barge landings, power lines, and fuel storage tanks. Reduced sea ice can increase the offshore oil drilling and shipping season but also increases the vulnerability of coastal communities to flooding during autumn storms.[d]
- **Wildfires may burn more extensively and frequently as projected higher temperatures, longer growing seasons, and drier conditions enable fires.**[e] Fire threatens infrastructure across Alaska's interior, including roads, transmission and distribution lines, and the TAPS. Wildfires and associated changes in vegetation cover can also lead to rapid, lasting permafrost thaw in some areas.[f]
- **Precipitation is projected to increase, and glaciers are expected to continue receding at increasing rates, likely increasing streamflow in the near term but causing long-term reductions.**[g] The continuing increase in river discharge from glaciers in southeastern and south central Alaska may increase hydropower potential but may also increase challenges associated with sedimentation and affect seasonal variability, complicating hydropower planning. In the long term, increases in rain (rather than snow) and associated changes in mountain snowpack, as well as the decline of glaciers, may reduce hydropower resources.[h]

QUICK FACTS

Population (2013)	740,000 (<1% of U.S.)
Area (square miles)	571,000 (16% of U.S.)
Energy expenditures	$8 billion

ENERGY SUPPLY & DEMAND		**Annual Production**	**Annual Consumption**	***% for electric power***
Electric power	*TWh*	7	6	*n/a*
Petroleum	*million barrels*	188	45	*2%*
Coal	*million tons*	2	1	*43%*
Natural gas	*Bcf*	351	332	*10%*

ELECTRIC POWER	**Annual Production (TWh)**	***% of Total Production***	**Capacity (GW)**	**Power plants >1 MW***
Natural gas	4	*52%*	1	13
Coal	1	*10%*	<1	5
Nuclear	0	*0%*	0	0
Hydroelectric	2	*23%*	<1	28
Petroleum	1	*15%*	<1	89
Wind	<1	*1%*	<1	4
Biomass	<1	*<1%*	<1	1
Solar	0	*0%*	0	0

CRITICAL INFRASTRUCTURE

Petroleum		**Electric Power**	
Wells (>1 boe/d):	1,284	Power plants (> 1 MW):	130**
Refineries:	6	Interstate transmission lines:	0
Liquids pipelines:	5	**Coal**	
Ports (>200 tons/yr):	7	Mines:	1
Natural Gas		**Waterways**	
Wells:	185	Coal and petroleum routes:	13
Interstate pipelines:	0	**Railroads**	
Market hubs:	0	Miles of freight track:	506

Note: Table presents 2012 data except number of oil wells, which is 2009 data.
*Some plants use multiple fuels, and individual generating units may be <1 MW.
**Total is less than sum of plants by fuel as some plants use more than one fuel.
Sources: AAR 2014, EIA 2011, EIA 2013b, EIA 2013c, EIA 2013d, EIA 2014a, EIA 2014b, EIA 2014c, EIA 2014d, EIA 2014e, EIA 2014f, EIA 2014g, U.S. Census Bureau 2014b, USACE 2014

Table 9-1: Examples of important energy sector vulnerabilities and climate resilience solutions in Alaska

Subsector	Vulnerability	Magnitude	Illustrative Resilience Solutions
Fuel Transport and Storage	Increased risk of damage to foundations of transportation infrastructure from thawing permafrost, erosion of coastal and riparian fuel systems[i]	Average annual shoreline erosion rates of 68 feet per year for the period 1954–2003 in Newtok, Alaska, due to reduced sea ice and thawing permafrost[j]	Maintenance of support structures and embankments, rerouting around permafrost, protection of shorelines, or relocation of assets[k]
Oil and Gas Exploration and Production	Reduced load-bearing of drilling pads due to permafrost thaw, shorter work season due to later freeze-up and earlier thaw of tundra[l]	Reductions of continuous permafrost load-bearing capacity of up to 20%; 100 fewer working days per year in 2002 compared to 1970s[m]	Appropriate structures for construction on "continuous permafrost," including insulation to protect from thaw
Hydropower Generation	Possible changes to snowpack, streamflow timing, and sediments; long-term decline of glaciers[n]	Glacier meltwater comprises approximately half of all streamflow volume in Alaska[o]	Water resource management practices, including monitoring and forecasting snowmelt availability[p]

Regional Energy Sector Vulnerabilities and Resilience Solutions

Key energy subsectors and illustrative examples of resilience solutions in Alaska are discussed below. System components that are most vulnerable to climate change are described first.

Fuel Transport and Storage

Subsector Vulnerabilities

Alaska's expansive territory separates its ample energy resources from rural communities and from easy access to wider energy networks. Alaska's remote communities rely on regular shipments of fuel–primarily by barge, but also by airplane–across long distances, often in difficult conditions (see sidebar). Highways and rail are used for fuel transport in Alaska's relatively populous Railbelt region, which spans from Fairbanks in the north to Anchorage, Valdez, and the Kenai Peninsula in the south. Oil products shipped by rail are increasingly important since the closing of the Flint Hills refinery in 2014, and petroleum products for Alaska's interior are now refined in Kenai and are shipped north to the Fairbanks area on the Alaska Railroad (Cole 2014).

Transport of fuel for export is critical for Alaska's economy, as Alaska is one of the top oil-producing states in the country (EIA 2014b). Most of Alaska's energy production operations are located on the North Slope of the Brooks Range along Alaska's northern coastline, although production has been falling steadily since 1988 as existing North Slope oil wells mature (EIA 2014a). The North Slope is one of the most remote places in the world, and oil produced from this region relies on the TAPS to access markets in Alaska and beyond. The TAPS consists of a network of gathering pipelines in the Prudhoe Bay area of Arctic Alaska, a single 48-inch-diameter pipeline stretching 800 miles south to the port of Valdez, and a series of 12 pumping stations and other support equipment and facilities located along its length. The pipeline carries nearly all of the oil produced in the North Slope each year (approximately 175 million barrels in 2014) (Alyeska 2014, EIA 2014a). Oil from the TAPS is transferred to tanker ships at the Valdez Marine Terminal.

Several Alaskan communities rely on natural gas pipelines for deliveries of locally produced natural gas, and some of the natural gas produced on the Kenai Peninsula is exported to Asian markets through a liquefied natural gas (LNG) export terminal in Nikiski (EIA 2012, EIA 2014b, EIA 2014d). Nikiski is also the likely location for a future export terminus of a proposed gas pipeline from the North Slope gas fields (Bradner 2013).

Figure 9-1. Map of Alaska

Alaska's multi-modal transport network delivering fuel and supplies to rural populations

Fuel transport for Alaska's remote rural communities outside of the Railbelt region requires significant effort and frequently comes at a high cost (Bradner 2012, USGCRP 2014). Over 80% of Alaska's communities have populations smaller than 1,000, many with no connection to wider energy or electrical networks (AFN 2012, US Census Bureau 2014a, USGCRP 2014). Heating fuel, transportation fuel and diesel for electricity generation are all critical supplies for these remote communities. Diesel generators supply the large majority of Alaska's electricity outside of the Railbelt (AEA 2013a).

Fuel shipments to Alaska's rural communities often require specialized equipment and multiple stages involving different vehicles (Bradner 2012). Over short distances, roads within and around towns serve as crucial links for Alaska's transportation networks. However, most remote communities are not connected via long-distance roads, and shipping by barge is the primary means of transporting fuel to Alaska's isolated coastal and interior riparian communities. For some communities beyond the reach of barge transport, fuel is shipped by air, often at extremely high cost (Bradner 2012, USARC 2003). For these communities, the local airstrip is an essential part of their energy transportation infrastructure. Furthermore, because of seasonal constraints and the high cost of shipments, communities rely on large storage containers to reduce the number of necessary shipments. Many communities receive only one fuel shipment per year.

Some long-distance roads serve as crucial transportation links for providing energy infrastructure support. For example, the Dalton Highway stretches 414 miles between Fairbanks and Deadhorse, located on Prudhoe Bay, and is used to carry supplies and heavy machinery for North Slope oil production as well as for servicing the TAPS (Alaska Geographic 2014).

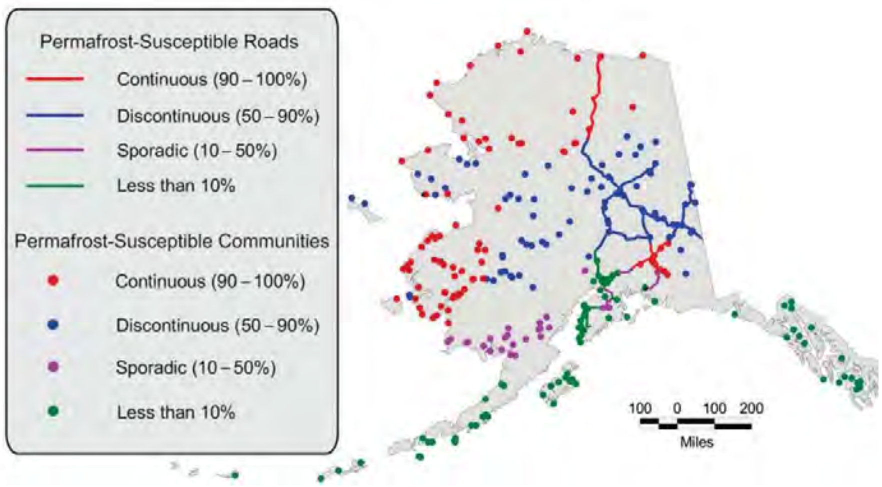

Figure 9-2. Extent of permafrost affecting Alaska's communities and highways
Source: USARC 2003

Climate change is projected to have the following impacts on fuel transport in Alaska:

- Warming temperatures are expected to contribute to the continued thaw of permafrost, compromising the structural stability of transportation and storage infrastructure, including oil and gas pipelines, storage tanks, runways, railroads, and roads in northern and interior Alaska (USARC 2003, USGCRP 2014).
- Reduced sea ice and thawing permafrost are expected to lead to accelerated rates of coastal and riparian erosion, affecting northern and western Alaska's shoreline energy assets, such as the extensive shipping infrastructure including ports and terminals; reductions in sea ice may also benefit shipping by extending the ice-free season (Alaska AAG 2010, DOE 2013, USGCRP 2014).
- Increased temperatures, drier conditions,[1] and increased vegetation are expected to increase the extent and severity of forest fires, which can disrupt road and rail transport and contribute to rapid local permafrost thaw (LTER 2006, USGCRP 2014).

Permafrost across the state is expected to experience continued warming, reduced thickness, and thawing, depending on the permafrost zone and soil factors. In zones of continuous permafrost[2] (primarily occurring north of the Brooks Range, including the North Slope; Figure 9-2), permafrost thickness is expected to decline (ACIA 2005). In discontinuous permafrost zones—where permafrost temperatures are much closer to 0°C, including most of the Alaskan interior and western coastline—permafrost may thaw much more rapidly, especially in the southernmost reaches of the zone (ACIA 2005). In one study of permafrost north of Fairbanks, researchers found that 38% of their sites indicated thawing or unstable permafrost layers (LTER 2006).

Almost the entire length of the TAPS is constructed in continuous or discontinuous permafrost zones. Thawing permafrost layers can reduce the load-bearing capacity of the ground under the TAPS supports, and frost heave and uneven settlement may damage TAPS segments (DOE 2013, USARC 2003). Segments of the TAPS that are elevated above permafrost layers (over half of the pipeline length) utilize heat pipes called thermosyphons that passively transfer heat from the permafrost layer into the air, thus stabilizing the permafrost foundation (Alyeska 2014, DOE 2013, USARC 2003). As ambient temperatures warm, existing thermosyphons may become insufficient to provide the necessary cooling to protect permafrost layers from thawing (ACIA 2005). The design of existing thermosyphons was based on the average permafrost and climate conditions of the period 1950–1970, a period featuring a much colder climate than today, and did not take a warming climate into account (NOAA 2013, USARC 2003, USGCRP 2014). A 2001 study indicated that upwards of one third of all vertical support members along the pipeline route had possible problems caused by climate change (USARC 2003).

Permafrost thaw is already affecting segments of the pipeline. In one case, a reduction in permafrost thickness caused a vertical support member to tilt by seven degrees over a period of approximately three years. The vertical support member was replaced in 2000 (USARC 2003).

In addition to structural vulnerabilities related to permafrost, climate change may also alter the stability of soil in the permafrost-free areas where the TAPS is buried. Changes in precipitation, temperature, and groundwater

[1] In Alaska's interior, landscapes have become drier even as precipitation has increased. While the relative importance of different mechanisms contributing to drier conditions is not clear (including permafrost thaw and increased evapotranspiration), the National Climate Assessment has expressed high confidence that landscapes are getting drier (USGCRP 2014).

[2] Continuous permafrost zones are defined as those with >90% of the land area underlain by permafrost. Discontinuous zones are those underlain by 50%–90% permafrost. Sporadic permafrost regions are those underlain by 10%–50% permafrost (ACIA 2005).

availability may affect the annual frost depth of the soil's active layer in these areas, affecting soil stability and load-bearing capacity (NOAA 2013, USARC 2003, USGCRP 2014).

One study projected that permafrost warming of 5°C at a 10-meter depth in Barrow, Alaska (in the continuous permafrost zone), would correspond to a decline in load-bearing strength of 23% (ACIA 2005). The study also projected that permafrost warming of only 2°C in Bethel, Alaska (in the discontinuous permafrost zone), could be sufficient to reach thawing temperatures, resulting in the potential complete loss of permafrost and a projected 40% drop in load-bearing strength (ACIA 2005).

Thawing permafrost also undercuts the stability of roads and airstrips. Most of Alaska's road miles are in Southcentral Alaska, which includes the Railbelt region and other areas where permafrost is less common (USARC 2003). However, many of Alaska's long-distance highways are located in interior regions with discontinuous permafrost, which is more vulnerable to thaw and resulting instability (see Figure 9-2 on previous page) (ACIA 2005, USARC 2003). Furthermore, a large number of Alaska's remote communities are in areas with continuous or discontinuous permafrost coverage, and local roads are vulnerable to permafrost thaw and land settling. Roads underlain with ice-rich permafrost (such as sections of the Dalton Highway) may require substantial rehabilitation or relocation if thawing occurs (USARC 2003). In zones of warm, discontinuous permafrost, thawing beneath road embankments may occur in the next 20–30 years, within the lifetime of most embankments (ACIA 2005). While roads built on lower-ice permafrost may not necessarily require relocation, expensive, continuous repairs are likely to be necessary (ACIA 2005, USARC 2003).

The state's only freight railroad company, the Alaska Railroad, operates a line that extends from Seward on the southern coast to the Fairbanks area in the state's interior. The railway line defines the relatively densely populated Railbelt region. The Alaska Railroad crosses sporadic and discontinuous permafrost zones and has historically been affected by differential frost heave and thaw settlement (USARC 2003). Continuing thaw of permafrost may increase these challenges, including increasing the risk of damage to track and railbed, as well as higher maintenance costs (USARC 2003).

For many of Alaska's rural communities, thawing permafrost also threatens inland fuel transport and storage infrastructure, including airstrips, roads, and fuel storage tanks. Alaska has over 160 communities in continuous or discontinuous permafrost zones (USARC 2003). In these communities, thawing permafrost can cause the foundations of structures to settle inconsistently, leading to loss of support or damage to the structures (ACIA 2005, DeMarban 2012). For example, in Newtok, Alaska, thawing permafrost is contributing to the subsidence of land under fuel tanks and generators (Figure 9-3) (ADEC 2013a, DeMarban 2012).

Figure 9-3. Shifting fuel tanks in Newtok
Source: Newtok Planning Group 2014

Runways face the same vulnerabilities to permafrost thaw as other terrestrial infrastructure, including the risk of uneven land settling and loss of foundation strength. Runways in communities built on discontinuous or continuous permafrost may require major repairs or may have to be entirely relocated (USARC 2003). The village of Noatak in Alaska's northwestern interior relies exclusively on air transport for fuel shipments since falling water levels in the Noatak River have made barge shipments impossible (ANTHC 2011, USA Today 2012). Because of the high cost of shipping fuel by air, Noatak also sees the highest electricity costs in Alaska's northwest region (NANA Regional Corporation 2010).

Air strips in coastal communities may also be vulnerable to coastal erosion and flooding. The community of Point Hope on the Bering Strait relocated to higher ground in the 1970s, but climate change-related erosion and flooding remains a threat to the community's air strip (ANTHC 2010, GAO 2003).

Thawing permafrost combined with declining sea ice can increase the rate of coastal erosion along Alaska's northern and western coastlines. Rapid coastal erosion can occur during severe storms when sea ice is not present to protect the shoreline from wave action and storm surge. Additionally, inland permafrost thaw can contribute to accelerated erosion of infrastructure along riverbanks (Alaska AAG 2010, USGCRP 2014). For Alaska's rural communities that rely on periodic shipments of fuel for heating, transportation, and electricity generation, permafrost thaw and erosion that damages transportation infrastructure can cause temporary or long-term disruptions to fuel deliveries and increase the costs of these essential products.

Coastal erosion exacerbated by receding sea ice in Alaska is threatening fuel transport infrastructure for numerous small native communities. Since consistent satellite imagery of Arctic sea ice became available in 1979, the extent and thickness of summer sea ice along Alaska’s coastlines has decreased substantially, and currently there is only about half as much as at the beginning of the record (USGCRP 2014). Decline of sea ice cover is expected to continue: summer sea ice may disappear completely before mid-century, and winter sea ice may no longer reach Alaska's southwest coast on the Bering Sea by the end of the century (ACIA 2005, USGCRP 2014). Coastal sea ice in the Arctic Ocean and Bering Strait protects shorelines from storm-driven wave action and flooding associated with storm surge (Alaska AAG 2010). As sea ice recedes earlier in the summer and returns later in the winter, communities are more vulnerable to storm-driven erosion. Permafrost thaw further allows greater coastal erosion, as coastal bluffs that have been historically "cemented" by ice-rich permafrost are beginning to thaw (USGCRP 2014). Some inland riparian communities may also experience greater erosion of riverbanks due to climate change as thawing permafrost allows more rapid erosion, especially if riverflows are increased by accelerating glacier melt or increased precipitation (ACIA 2005, Alaska AAG 2010, NOAA 2013, USACE 2006b, USARC 2003).

Coastal and riparian erosion can destroy barge landings, fuel connections, and other infrastructure used for offloading fuel shipments from barges. In cases in which fuel barges cannot offload, communities must transfer fuel to smaller, shallow draft ships capable of landing, adding to the cost (Bradner 2012, USGCRP 2014). In some cases, communities must rely on air shipments of fuel, which is extremely expensive (Bradner 2012, USARC 2003).

Declining sea ice may also aid fuel deliveries for some communities, as the ice-free season grows longer. For coastal villages that are ice-bound for some portion of the year, declining sea ice may allow more flexible or more frequent fuel deliveries.

Increasing incidence of forest fires may also affect the TAPS. The pipeline is designed to resist forest fires and is protected by a galvanized steel jacket and insulation, as well as its placement within a 64-foot wide right-of-way clear-cut of vegetation. Past fires have not affected the pipeline's operations; however, the costs associated with protecting the pipeline may increase, as climate change is projected to increase the risk of forest fires in Alaska (BLM 2007, D'Oro 2003, News-Miner 2014). For example, in response to a fire that approached the TAPS in 2014 near the Yukon River Crossing, pipeline operators mobilized sprinkler systems, water trucks, and bulldozers in case the fire threatened the pipeline or support structures (News-Miner 2014). Fires can also affect the health and depth of permafrost. By reducing insulating vegetation from the active layer of soil (the topmost layer that freezes and thaws annually) and by increasing soil drainage, fires can lead to rapid local permafrost thaw, or even long-term transition to permafrost-free soil (LTER 2006). When combined with warming, fire-related changes to local permafrost conditions may affect soil stability.

Newtok erosion leading to energy crisis

The Yup'ik Eskimo village of Newtok is facing erosion threats that have already destroyed its barge landing and disrupted fuel shipments (USACE 2008a, USGCRP 2014). Located on the tidal Ninglick River just inland of the western coast of Alaska on the Bering Sea, the village is experiencing thawing permafrost and loss of sea ice that increases its vulnerability to rapid erosion during storms (USACE 2008b, USGCRP 2014). In 2005, the village's barge landing on the Ninglick was destroyed, and in April 2006, a fuel barge was grounded for three days, after which deliveries were suspended and the fall 2006 fuel delivery was not made (USACE 2008a). The village experienced a fuel crisis in the winter of 2006–2007, and emergency shipments of fuel were flown in to supplement dwindling supplies until a solution could be found (D'Oro 2007, USACE 2008a). Fuel storage tanks—including tanks for the village's generator station and school, for home heating, and for marine and aviation fuel—are also threatened by erosion of both the Ninglick and the Newtok rivers (ADEC 2013a, DeMarban 2012).

Figure 9-4. Shoreline erosion in Netwok
Source: USACE 2008b

Fuel Transport and Storage

Resilience Solutions

As temperatures increase, the TAPS may require additional operational, maintenance, design, and construction techniques to prepare for rapid thawing permafrost. Currently, the TAPS and its supporting infrastructure are actively monitored for structural problems resulting from thawing permafrost, and vertical support members are inspected once every three years (Alyeska 2008, USARC

2003). The frequency or robustness of monitoring and inspecting may need to be increased in the face of climate change. In cases in which underlying permafrost has become insufficient to support the TAPS, new, deeper supports or rigid support structures can be used (USARC 2003). Additionally, proactive maintenance and upgrading of thermosyphons avoids damage to underlying permafrost (Figure 9-5) (Alyeska 2008). Currently, the majority of repairs to thermosyphons are done in the Copper River Basin, an area in the southern reaches of the pipeline's range that is undergoing a transition from a discontinuous permafrost zone to a sporadic permafrost zone (Alyeska 2008).

Figure 9-5. An elevated section of the Trans-Alaska Pipeline System uses thermosyphons, which draws heat out of the ground and vents it into the air to prevent permafrost thaw
Source: FBI 2012

For communities facing rapid erosion, options for protecting coastal fuel transport and storage infrastructure may be limited. Many communities have invested millions of dollars in walls to reduce or stop erosion. For example, Bethel, which has about 6,000 residents, has deployed an extensive seawall along 8,000 feet of its riverbank at a total estimated cost of $24 million (GAO 2003). Bethel serves as a major regional fuel hub for several rural communities on the Kuskokwim River, and the seawall protects storage tanks capable of holding over 20 million gallons from eroding riverbanks (ADEC 2013b, Bradner 2012).

In other communities, coastal energy assets may require relocation inland. For example, in Port Heiden and Levelock, fuel headers (connections used for refilling fuel storage tanks from barges) may need to be relocated inland, as shorelines are eroding (ADEC 2012, ANTHC 2014, LPB 2013). However, in other cases, the only solution to the challenges presented by erosion may be complete relocation of an entire community. Several communities, including Newtok, Kivalina, and Shishmaref, have voted to relocate, often at extremely high costs (GAO 2003). After efforts to build an erosion barrier from sandbags failed, the village of Newtok began the process of migration to a new village site in 2003 (GAO 2003). In the village of Shishmaref, various attempts to address erosion of coastal bluffs—including seawalls constructed from sandbags, gabions, and concrete mats—have failed to stop the threat to the community. The residents had to relocate 19 homes following storms in 1997 and 2002. After the latter storm, the village voted to relocate in its entirety (GAO 2003). Relocation is expected to take 15–20 years and cost at least $180 million (USACE 2006a). In the interim, the U.S. Army Corps of Engineers built additional seawall protection in Shimsharef in 2007 at an estimated cost of $6.5 million (Weyiouanna 2007).

Roads, railroads, and airstrips subject to shifting permafrost foundations may require increased maintenance, rehabilitation, rerouting, or relocation, depending on location-specific factors (USARC 2003). Future projects should take projected temperature increases into account when designing on or around permafrost. For example, new projects built on continuous permafrost can anticipate reduced load-bearing capacity and utilize thicker embankments when necessary (ACIA 2005). Because of the short summer building season, constructing a new rural airport in Alaska is an expensive and lengthy project, costing $15–$20 million and ordinarily taking 3–5 years—and sometimes as much as 10 years (TRB 2012). Alaska has an airport system planning process in place that seeks to continually monitor Alaska's airports and prioritize funding based on need and economic benefits (TRB 2012). For example, the Federal Aviation Administration provided $10.3 million to raise and lengthen the airstrip in Koyukuk, a village in Alaska's interior plagued by regular spring flooding (GAO 2003).

The Alaska Village Electric Cooperative (AVEC) serves many of Alaska's most remote rural communities. AVEC is expanding the use of village interties (low-voltage transmission lines between villages) to reduce the likelihood of power outages if fuel storage tanks and generating equipment are affected by flooding and erosion impacts (AVEC 2013). By connecting nearby villages, AVEC can centralize energy generation and reduce the need for bulk fuel deliveries and storage for difficult-to-reach communities (AVEC 2013). Development of local renewable energy resources such as wind and ocean power may also increase the resilience of rural communities by reducing the need for remote fuel deliveries (AVEC 2013).

Oil and Gas Exploration and Production

Subsector Vulnerabilities

For the last four decades, Alaska has been one of the top oil-producing states in the country, and oil production is a key driver of the state's economy. Alaska produced 8% of the nation's oil in 2012. Although that percentage is down from a peak of 25% in 1988 (EIA 2014a), Alaskan oil still serves a large share of the western United States' demand for oil, and Alaska's remaining oil reserves constitute 8.7% of the nation's proven reserves (EIA 2015a, EIA 2014b). As Alaska's North Slope oil fields mature, exploration and drilling is reaching farther inland, and new wells are located farther apart (DeMarban 2014).

Alaska's natural gas is produced primarily in the Cook Inlet, with additional production in the North Slope and outside Barrow. Unlike Alaska's oil sector, the state's natural gas resources are primarily used locally for electricity production, refining, and heating. Historically, 8%–15% of the state's total marketable gas production has been exported via the Kenai LNG export terminal, primarily to Japan (EIA 2012, EIA 2014b, EIA 2014d, EIA 2015b). Gas on the North Slope cannot be transported outside the region and is therefore consumed locally, or is reinjected.

Because of the dominant role Alaska's oil industry plays in the state's economy, climate change impacts that affect the sector's productivity are likely to have negative effects on Alaska's economy. Oil production and other extractive industries constitute the largest single share of Alaska's GDP (21% in 2012), and taxes and royalties affiliated with the industry contribute over 90% of the state's unrestricted revenue (ADCCED 2014).

Climate change is projected to have the following impacts on oil and gas exploration and production in Alaska:

- Warming temperatures are expected to contribute to the continued thaw of permafrost, weakening the soil and causing differential settling underneath drilling pads and supporting infrastructure (ACIA 2005, USARC 2003, USGCRP 2014).
- Increasing temperatures are likely to reduce the number of days of allowable road travel on frozen tundra, while dependence on ice roads for oil and gas production in the North Slope is increasing (ADNR 2004, DOE 2013).
- Declining sea ice may benefit offshore oil exploration off the North Slope by providing a longer ice-free season and expand the spatial extent of offshore exploration in the Arctic (DOE 2013).

Warming temperatures in the North Slope are expected to reduce the thickness of the permafrost layer and increase the depth of the active soil layer (the layer that freezes and thaws annually). North Slope drilling occurs on the colder, thicker tundra north of the Brooks Range that may not be as susceptible to thawing as the warm permafrost in Alaska's interior (USARC 2003). But even if permafrost is not completely lost, partial thawing of the permafrost layer can reduce the load-bearing capacity of soils and lead to differential settling, undermining the foundations of structures, including drilling pads, production installations, and supporting structures (DOE 2013, USARC 2003).

Off-road transportation in Alaska's far north is essential for oil exploration and production on the North Slope, but is limited to the winter season to protect the sensitive tundra ecosystems. The Alaska Department of Natural Resources (ADNR) determines the annual opening and closing dates for off-road travel on tundra, basing its decisions on the thickness and hardness of the ground frost (ADNR 2004). Higher temperatures and thawing permafrost can shorten the winter operating season, decreasing productivity and increasing costs (DOE 2013, NOAA 2014). Since the 1970s, both warmer conditions and changes in regulatory criteria have shortened the tundra travel season by an average of 100 days (Figure 9-6) (ADNR 2004, DOE 2013, NOAA 2014). The challenges of shorter winter working seasons are compounded by record demand for tundra travel as the extent of active North Slope oil and gas wells grows and becomes less geographically concentrated. In the winter of 2013–2014, a record-high number of miles of ice roads were approved for construction (DeMarban 2014).

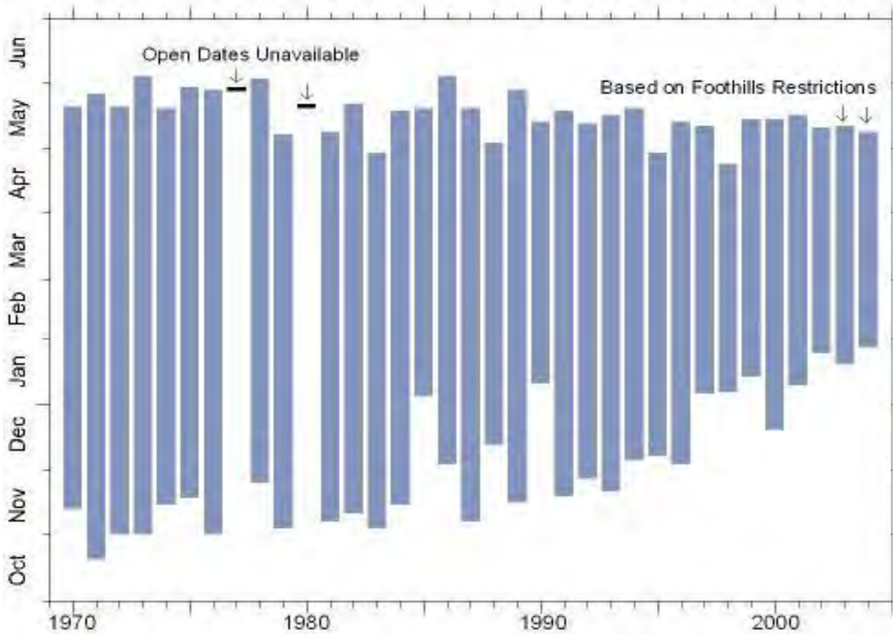

Figure 9-6. Alaska tundra travel season 1970–2004
Source: NOAA 2014

In addition to a shorter season, the area of tundra that is expected to be sufficiently frozen to support ice roads is projected to fall. The Intergovernmental Panel on Climate Change (IPCC) projects that, by mid-century, the average land area accessible by winter season ice roads in Alaska will fall by 29% compared to today (2045–2059 compared to 2000–2014) (IPCC 2014a).

Oil and Gas Exploration and Production

Resilience Solutions

Reductions in permafrost load-bearing capacity can be addressed by engineering structures with appropriate design criteria for the life of the foundation. Additionally, measures to insulate or ventilate underlying permafrost, such as construction of a gravel pad of appropriate depth or the use of thermal piles, can help maintain the permafrost temperature and protect foundations from thawing (Seifert 2011).

As understanding of tundra damage and regulations regarding tundra travel evolve, new technologies and approaches to protecting the tundra are emerging. For example, pre-packing of tundra snow prior to road opening may allow more rapid freezing of active layer soils and earlier opening of tundra travel (Byrne and Shultz 2015).

Hydropower

Subsector Vulnerabilities

Hydropower systems in Alaska constitute an important share of electricity generation, providing about one quarter of all electricity in the state (EIA 2013a). Reliance on hydropower for electricity is distinctly regional, with the great majority of hydropower capacity located in the Railbelt region and southeast parts of the state. In the southeast, hydropower constitutes about one-half of installed capacity (AEA 2013a). However, apart from small hydropower facilities near Bristol Bay and in the Aleutian Islands, there is no installed hydroelectric capacity in the northern or western portions of the state (Table 9-2) (AEA 2013a).

Hydropower projects in Alaska's remote regions are typically run-of-the-river plants, which divert a portion of the flow of the river through turbines to generate power. These projects tend to be smaller operations such as the 105 kW Town Creek Project in the City of Akutan (McMillen 2011). Alaska also uses several lake-tap hydropower projects, such as the 31 MW Crater Lake Project (part of the Snettisham Project that powers Juneau), as well as traditional dams such as the 120 MW Bradley Lake Hydroelectric Project (AEA 2011, AEA 2014b). Alaska's larger dams are found in the southeastern and Railbelt regions of the state.

Table 9-2. Hydroelectric capacity in Alaska, 2011

Region	Hydroelectric Capacity (MW)	% of Total Capacity in Region
Southeast	210.1	51%
Copper River/Chugach	19.2	33%
Railbelt	184.4	13%
Kodiak	22.9	37%
Bristol Bay	0.8	3%
Aleutians	0.8	2%
Rest of Alaska	0	–

Source: Adapted from AEA 2013a

Climate change is projected to have the following impacts on hydropower in Alaska:

- More precipitation as rain rather than snow and increasing temperatures, particularly in winter, may result in earlier spring thaw, which could increase water availability for hydropower generation in the spring and reduce water availability in the summer (ACIA 2005, DOE 2013).
- Accelerating glacial melt may increase water availability for hydropower generation on glacier-fed waterways in the short term but is expected to threaten these resources in the longer term by reducing river discharge and hydropower generation (DOE 2013, USGCRP 2014). Near-term increases in streamflow may also affect sediment loading, potentially reducing reservoir capacity and hydropower capacity (Cherry et al. 2010a).
- Thawing permafrost may affect the design of potential new dams making use of Alaska's untapped hydropower resources (ACIA 2005, Sayles 1987).

Declining snowpack and earlier snowmelt may shift peak streamflow timing and reduce water availability and hydropower generation in the summer at facilities that rely on snowmelt-fed rivers. This effect may be particularly acute at run-of-the-river facilities, which are directly dependent on river discharge (ACIA 2005, Blackshear et al. 2011, IRENA 2012, DOE 2013). The average winter temperature minimum in southeastern Alaska has been increasing at an accelerating rate since 1940, and by the end of the century, average winter temperatures are projected to stay above freezing (Cherry et al. 2010b, NOAA 2013). Increases in winter temperatures will increase the amount of precipitation that falls as rain rather than snow (Cherry et al. 2010b). For watersheds that typically store water in mountain snowpack from fall through spring, these effects could reduce the total water available from snowpack.

In the southern portion of Alaska, precipitation is projected to increase, but the impact of these changes on hydropower generation is uncertain. Higher air temperatures are expected to increase evaporation, and longer growing seasons for vegetation in Alaska may ultimately reduce water availability for hydropower despite increased precipitation (USGCRP 2014). Vegetation changes associated with a warming climate may withdraw water from watersheds and reduce streamflow available for hydropower (ADNR 2014). Furthermore, the seasonality of storage reservoirs means that not all precipitation can be used for hydropower production. For example, projected increases in autumn precipitation may not contribute to hydropower production if warming temperatures mean additional precipitation falls as rain rather than snow. Since reservoirs are already at capacity by the fall, additional rain will likely be spilled over at traditional and lake-tap facilities (Cherry et al. 2010b).

Accelerating glacial melt is expected to generally increase streamflow and hydropower potential in Alaska on glacier-fed streams in the near term. But as glaciers are expected to continue to shrink, hydropower production will likely eventually decline as less water is available (ADNR 2014, DOE 2013, USGCRP 2014). Currently, approximately half of Alaska's total runoff begins as glacier meltwater (ADNR 2014). From the mid-1990s to 2000, the rate of glacial melt in North America tripled relative to the melt rate from the mid-1950s to the mid-1990s, and Alaska's glaciers currently exhibit the highest rates of decline anywhere on earth (ADNR 2014, Zemp and Haberli 2007). While the timing of each glacier's decline and potential disappearance depends on a number of factors, determining when a glacier's runoff is likely to peak and begin to fall is critical for water and hydropower resource planning (ADNR 2014).

Depending on the hydrology and geology of each basin, increases in streamflow may increase the amount of sediment carried in a river (Cherry 2009). Sediment can affect hydropower facilities by collecting behind a dam, slowly reducing the storage capacity of a reservoir (Cherry et al. 2010a). Additionally, sediments present in water that passes through a turbine can wear down the turbine blades, reducing the efficiency and total capacity of a hydropower plant (Cherry et al. 2010a). Additional research is still needed to understand the role that climate change plays in affecting sediment loading in Alaska's rivers and basins, including those currently and potentially useful for hydropower production (ADNR 2014, Cherry 2009).

Although dams built on permafrost foundations are rare, some do exist in Alaska (ACIA 2005, Sayles 1987). The largest of these, a containment structure for a mining operation outside of Levelock, failed in 1962 after falling into disuse. Thermal degradation of underlying permafrost led to seepage and erosion through the dam and embankments, and the dam was breeched during spring flooding (Sayles 1987). Although none of Alaska's permafrost-founded dams houses hydropower facilities, thawing permafrost would likely affect the design of potential new dams making use of Alaska's untapped hydropower resources, as these dams would need to be much higher than existing permafrost dams and ensure that the underlying permafrost would not thaw, settle, or shift (ACIA 2005, EIA 2014b). For example, construction of new frozen core dams would need to take future warming into account when planning cooling systems (Miller et al. 2013).

Hydropower

Resilience Solutions

Hydropower operators can increase the resilience of their facilities by increasing monitoring of snow water resources, allowing operators to better anticipate changes to riverflow (Cherry et al. 2010b). In general, increased transmission capacity can allow water planners and hydropower operators to take advantage of spatial variability in water availability as well as better utilize all generation resources. For example, energy managers in Sitka are planning to reduce their dependence on local hydropower by building additional interties to nearby communities (Cherry et al. 2010b).

Another resilience measure suitable for some hydropower operators is to maintain higher winter carryover reservoir storage levels and reduce reservoir water releases to adapt to shifting snowpack levels, snowmelt timing, and glacial runoff. For example, the dam at Blue Lake is currently 145 feet high, but managers are raising the height of the dam by 83 feet. This would reduce water releases during high winter flow times and would increase the facility’s generation capacity by 27% (City of Sitka 2015). Run-of-the-river hydropower operators may increase resilience to changing seasonal riverflow patterns by increasing pondage (or small-scale storage) at facilities.

Electric Grid

Subsector Vulnerabilities

Alaska's electricity sector can be divided into two types of transmission regions: (1) the interconnected transmission grid in the Railbelt, with diverse generating resources, and (2) local distribution grids serving rural communities operating small generation facilities. Utilities in the Railbelt are interconnected by long-distance power lines that operate at higher transmission voltages (Figure 9-7). Outside of the Railbelt, communities rely on locally produced energy, such as diesel generators, or on nearby resources such as wind turbines and hydropower facilities. Some rural communities operate interties that connect the distribution grids of two or three communities but operate at lower distribution voltages.

The Railbelt-area transmission grid connects the Kenai Peninsula and Anchorage to communities in the interior around Fairbanks. This region includes over 80% of Alaska's electricity generation and consumption and six utilities: Anchorage Municipal Light & Power, Chugach Electric Association, Golden Valley Electric Association, Homer Electric Association, Matanuska Electric Association, and Seward Electric System (ARCTEC 2013, EIA 2013a, EIA 2013b). Although the grid is Alaska's largest, the Railbelt relies on relatively low-voltage transmission lines compared to the lower 48 states—mostly 115 kV lines but also 230 kV, 138 kV, and 69 kV lines (AEA 2014a, ARCTEC 2013). The transmission grid helps connected utilities share reserve capacity, but the grid suffers from significant capacity constraints that can limit the operation of generators such as the Bradley Hydroelectric Project (AEA 2013b, Brehmer 2014). Several plans have been developed by utilities in the region and the Alaska Energy Authority (AEA) to expand transmission capacity and range. The 2013 Railbelt Transmission Plan proposes upgrading several lines to 230 kV, adding new redundancy, and incorporating other grid improvements including grid-scale storage systems (AEA 2013b).

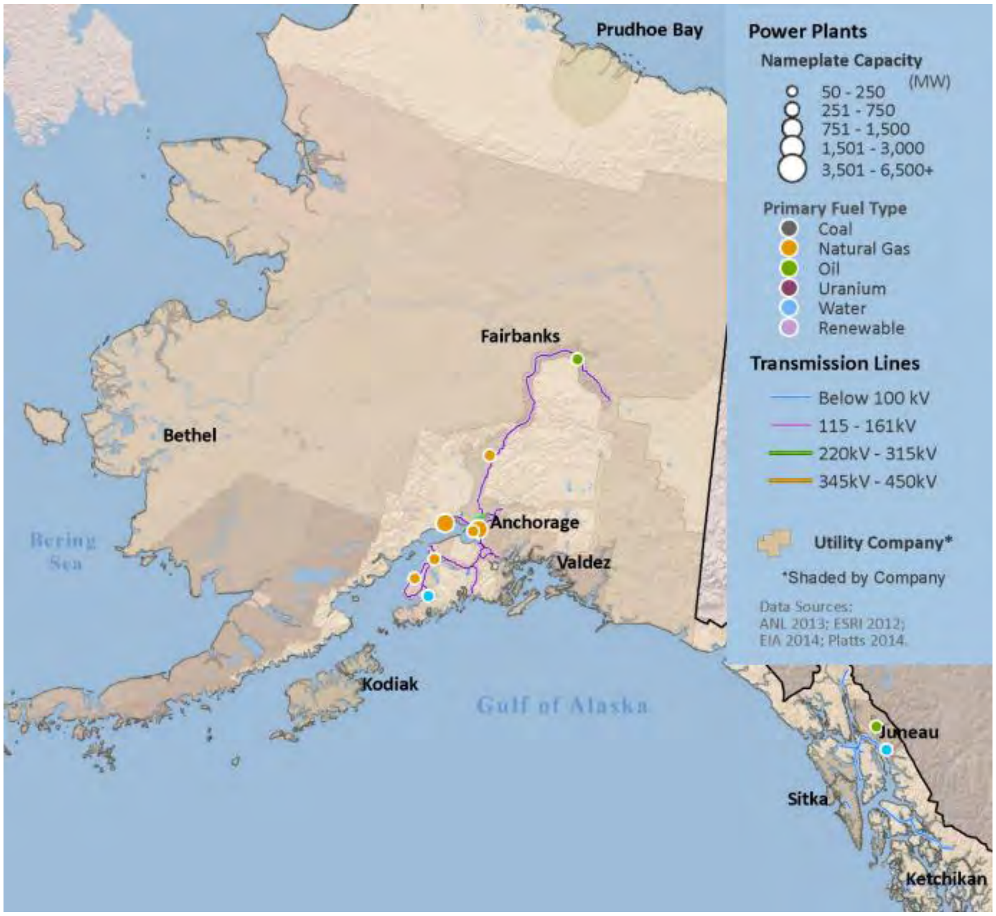

Figure 9-7. Alaska electricity infrastructure
Source: DOE 2015

For many of Alaska's small rural villages, electrical loads are met by a single central diesel generator and served by local distribution grids. Historically, these communities have been considered too far apart and serving loads too small to justify the cost of long-distance transmission lines (AEA 2009, NANA Pacific 2008). However, for some rural communities, short-distance low-voltage distribution interties can prove economic by helping achieve greater efficiency, including by reducing costs associated with fuel delivery (AVEC 2013). Additionally, communities with access to renewable resources rely on short-distance transmission lines to deliver power. For example, much of Juneau's electricity is generated at the Snettisham Hydroelectric Project, which relies on a 44-mile high-voltage transmission line to reach the city (AIDEA 2014).

Climate change is projected to have the following impacts on the electric grid in Alaska:

- More frequent and extensive forest fires may increase the risk of damage to transmission lines in the Railbelt, as well as in rural communities (LTER 2006, USGCRP 2014).
- Thawing permafrost can compromise the foundation of power line towers and may affect towers in large parts of northern and interior Alaska (ACIA 2005, USARC 2003, USGCRP 2014).
- Coastal flooding and erosion resulting from permafrost thaw and declining sea ice cover may increase the risk of damage to distribution systems in rural villages (GAO 2003, USGCRP 2014).
- Higher temperatures and changes to precipitation may increase the frequency of avalanches, which, in some locations, can threaten transmission lines and other infrastructure (ACIA 2005).
- Increased precipitation, higher rates of glacier melting, and greater risk of glacier outbursts may increase the likelihood of conditions favorable to flooding, which could damage electrical transmission and distribution lines (IPCC 2014b, NOAA 2013, USGCRP 2014).

Alaska's warming climate is driving an increase in the likelihood, length of wildfire season, and range of wildfires across much of the state's southern coast and interior regions (USGCRP 2014). Increased fire activity may threaten transmission and distribution power lines, as well as substations and other support equipment and structures. Warming temperatures have led to a longer growing season and expanded northward the range of spruce forests and other vegetation, as well as leading to drier conditions in interior Alaska (USGCRP 2014). Additionally, higher precipitation and temperatures have increased growing rates, accelerating the pace at which rights-of-way can become overgrown (USGCRP 2014). In the last decade, more large fires burned across Alaska than in any decade since recordkeeping began in the 1940s (USGCRP 2014).

Wildfires causing damage to power lines resulting in lengthy outages

In May 2014, the Funny River fire burned through parts of the Kenai Peninsula (in the Railbelt region), leading the Homer Electric Association (HEA) to shut down a nearby transmission line, causing a widespread outage, and interrupting power to the incident command center responding to the fire (Kelly 2014). In 2007, another fire in the area caused HEA to shut down the transmission line connecting to the Bradley Lake Hydroelectric Plant (HEA 2007).

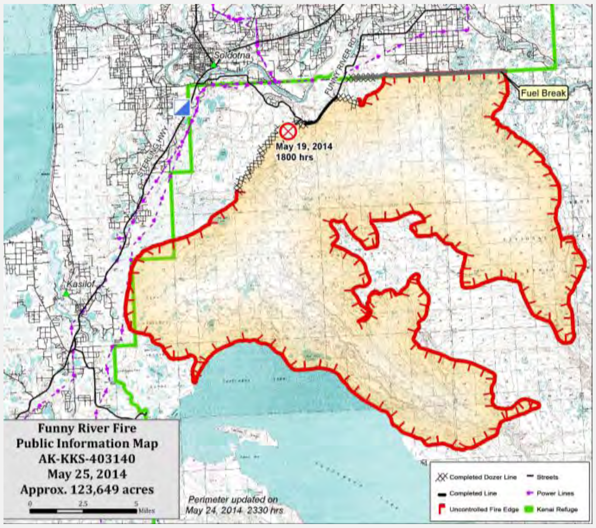

Figure 9-8. Funny River fire threatening the Soldotna-Homer transmission line (in purple) on the Kenai Peninsula in 2014
Source: Adapted from AFS 2014c

Fires can burn wooden power poles and destroy substations and transformers, and heat and smoke can degrade the capacity of a line, as well as increase the risk of arcing between lines or to ground (DOE 2013). Fire retardants used to combat fires can also foul transmission lines and reduce capacity. All of these impacts can lead to extended outages, especially if fires affect lines without redundant capacity or if backup generation is not available. Vegetation overgrowth can also increase the risk of fires caused by power line tree strikes. For example, in 2014, a Golden Valley Electric Association transmission line was struck by a falling tree, causing a fire that burned an acre around the power line (AFS 2014a). The following day, an additional 15 fires started in the Fairbanks area, many caused by trees being blown over onto power lines (AFS 2014b).

Much of the interior Railbelt, including Fairbanks and the surrounding area, is underlain by discontinuous "warm" permafrost, which is the most likely to thaw in the coming decades. For example, the Alaska Intertie, a 138 kV transmission line connecting Fairbanks to the rest of the Railbelt region south of Healy, Alaska, is built across 170 miles of warm permafrost (AEA 2014a, Wyman 2009). The line has suffered significant loss of permafrost along its right-of-way, resulting in frost heave (vertical lifting of piles due to freezing of water in the active layer soils) lifting pole foundations 3–6 feet and necessitating expensive repairs (Wyman 2009).

Permafrost thaw, uneven settlement, and the risk of frost heave also affect rural distribution lines and interties. For example, AVEC is planning an intertie line for the communities of St. Mary, Pilot Station, and Mountain Village, located in areas of warm, discontinuous permafrost along approximately 30 miles of the Yukon River in western Alaska. To reduce the risk of frost heave, minimum pile depths of 40 feet are recommended (Duane Miller Associates 2009). In Atmautluak, poles supporting the Village's distribution lines began to show signs of frost jacking and tipping due to permafrost thaw (Figure 9-9) (Atmautluak Traditional Council 2010).

Figure 9-9. Overhead distribution lines in Atmautluak, Alaska
Source: ADEC 2015

In some rural communities threatened by erosion and coastal flooding, electrical distribution systems may also be vulnerable to these impacts. The combined effects of permafrost thaw and declining sea ice can increase wave height and storm surge during storms, and permafrost thaw can soften the soil, increasing erosion rates (Alaska AAG 2010, USGCRP 2014). For example, beach erosion and flooding enabled by a decrease in sea ice threatens over one mile of Barrow's subterranean utility corridor, which carries power distribution lines (as well as water, wastewater, and television, telephone, and internet utility lines) throughout the community (BUECI 2015, GAO 2003).

The frequency of avalanches is projected to increase throughout mountainous regions of Alaska as temperatures and precipitation increase (ACIA 2005, USFS 2010). Although power lines and other infrastructure are typically sited to avoid such hazards, a series of avalanches in April 2008 near Juneau destroyed a mile-and-a-half section of the transmission line connecting the Snettisham Hydroelectric Project to the city (ACIA 2005, DOE 2008). Although diesel generators located in the city were able to provide sufficient back-up power, repairs to the line took over a month and a half. During that time, the emergency electricity rates were almost 500% higher than normal (DOE 2008).

While the influence of climate on flooding is complex and the specific effects of climate change on Alaska's rivers will vary across different regions and basins, a combination of projected changes to Alaska's hydrological systems may increase conditions favorable to flooding (ACIA 2005, USGCRP 2014). Projected increases in precipitation and glacial melt are likely to increase streamflows in Alaska's rivers (ADNR 2014, NOAA 2013, USGCRP 2014). Furthermore, accelerating glacial melt is associated with increased incidence of glacial outbursts, which may increase the risk of flooding, erosion and landslides, and associated damage downstream (IPCC 2014b). As glaciers retreat, frontal moraines can cause unstable glacial lakes to form in front of the glaciers, leading to increased risk of glacial lake outburst floods. Combined with increasing rainfall, the potential for destructive flooding may increase.

Flooding can knock out power in Alaska's population centers

In 2006, following several days of intense precipitation, flooding on the Susitna River north of Anchorage washed out several 230 kV transmission towers connecting to the Beluga generating station. A week earlier, a tower on a parallel line also fell into the river, causing extended power outages (Chugach 2006).

A sudden outburst of a glacial lake forming behind the front of the Mendenhall glacier in 2011 caused power outages and property damage in Juneau. By the summer of 2014, water had once again built up behind the front, leaving residents at risk (Forgey 2014).

Electric Grid

Resilience Solutions

Measures to improve the resilience of new and existing electric transmission infrastructure include engineering structures to better withstand hazards—increased forest fire activity, thawing permafrost, and coastal erosion where relevant—as well as management practices to protect infrastructure from these hazards, and planning to improve resilience to grid outages. In many places, Alaska's electric grid is currently vulnerable to disruption, as many of Alaska's long-distance transmission lines and distribution interties operate without redundancy (AEA 2013b, AVEC 2013). The AEA and many of Alaska's utilities are currently considering several plans to increase transmission redundancy (AEA 2013b, AVEC 2013, Lincoln 2014). Transmission expansion plans in the Railbelt region would increase the region's resilience to climate change impacts and other potential disruptions; however, reliability concerns must be balanced against the high cost of transmission infrastructure. For example, one study estimates that 230 kV lines cost \$0.5–\$1.5 million per mile, depending on conditions (NANA Pacific 2008). In rural regions, AVEC estimates a cost of \$0.25–\$0.45 million per mile for distribution interties (AVEC 2013).

Practices to reduce transmission line vulnerability to wildfire include proactive vegetation management, especially in areas where ecosystems are transitioning to greater vegetation and wildfire risk (USGCRP 2014). By maintaining rights-of-way and trimming back encroaching trees and underbrush, utilities can minimize not only wildfire impacts on lines but also the likelihood of fires started by line strikes (DOE 2013). Since access to rights-of-way can pose a problem to regular maintenance, expanded use of aerial trimming may also improve performance (Sheppard 2012, Wyman 2009).

Uneven permafrost thaw, loss of soil support, and exposure to frost heave can be accounted for when designing new transmission line towers. The use of tower designs—such as the X-tower (Figure 9-10)—that can tolerate greater lateral movement of foundations can reduce the impact of differential settlement (Wyman 2009). Frost heave of power line poles and towers can be mitigated by designing future transmission lines with pile foundations that are sufficiently deep to counter frost heave forces (Wyman 2009). While this increases the initial cost and may require a change in typical construction practices, this would avoid costly maintenance and repair of lines that would otherwise be necessary with shifting tower foundations (Wyman 2009). Existing towers experiencing frost heave should be monitored, and when necessary, wood piles can be replaced with steel pipe or H-piles, which reduces heave forces (Atmautluak Traditional Council 2010, Polarconsult Alaska 2009). Additionally, for guyed towers, installation of breakable links can reduce the risk of compressive tower failure when towers undergo heave (Polarconsult Alaska 2009).

For utility corridors, distribution lines, and other grid equipment threatened by erosion, resilience solutions can include installing protective barriers to slow the rate of erosion or relocate infrastructure. In Barrow, efforts to protect shoreline infrastructure and buildings have included beach nourishment, construction of berms, and the use of gabions and geotextile mats to harden the shoreline (USACE 2007). Such measures can be costly; in Barrow, beach nourishment alone cost $28 million over a 10-year period (USACE 2007). In recent years, some of Barrow's vulnerable structures have been relocated due to the high cost of shoreline maintenance (USACE 2007).

Construction plans for the Northern Intertie include resistance to permafrost thaw

The Northern Intertie is a new long-distance transmission project that will increase capacity and resilience between the Fairbanks and Anchorage/Kenai regions by providing a second transmission corridor (AEA 2013b). The line runs 170 miles across extensive warm, discontinuous permafrost roughly parallel to the Alaska Intertie (AEA 2013b). By studying the existing Alaska Intertie's foundations, designers determined that permafrost thaw was likely and that the resulting exposure to annual freeze-thaw cycles would threaten the new project's foundations. The resulting design addressed these vulnerabilities by deploying flexible X-tower supports and driving the pile foundations much deeper than traditional design requirements; piles were driven a minimum of 36 feet and, in some cases, up to 90 feet deep (Wyman 2009).

Figure 9-10. The X-tower transmission line support, which allows greater lateral movement of tower foundations
Source: AEA 2013c

For localities in the Railbelt that are connected to the region's transmission grid and that rely on large, centralized power plants, the development of decentralized generation resources may also improve those communities' ability to weather electric grid disruptions. Such resources can include traditional fossil-fired generators, as well as renewable resources that do not rely on fuel imports, including wind power, ocean energy, and locally sourced biofuel resources.

Distribution intertie lines can diversify power supplies and improve resilience in rural communities

The communities of Tununak, Nightmute, and Toksook Bay on Nelson Island on the Bering Sea are connected by 23 miles of low-voltage intertie lines serving a population of about 1,200 people (AVEC 2013, REAP 2010). These intertie projects allow the Alaska Village Electric Cooperative to interconnect generation resources and reduce costs (AVEC 2013, REAP 2010). Opportunities for additional interties may exist; of Alaska's 183 villages participating in the AEA's Power Cost Equalization program (which subsidizes rural electricity), only 27 operate electrical connections to another village (AVEC 2013).

Regional Climate Change Observations and Projections in Detail

Higher Temperatures

Historical observations

- **Average temperatures have increased 3°F since 1949:** Although warming has occurred across Alaska and in all seasons, historical increases in temperature have been dominated by warming in the winter and spring seasons and have primarily occurred in Alaska's interior (NOAA 2013, USGCRP 2014).
- **The growing season has lengthened by 45% in interior Alaska:** Over the course of the last century, the growing season (average annual number of days between first and last freezing temperatures) in the interior of Alaska has grown longer, with most of the growth in the last 25 years; in Fairbanks, the frost-free season has grown 2–3 weeks since 1950 (NOAA 2013, USGCRP 2014).
- **Extremely cold temperatures have occurred less often, and extremely warm temperatures have occurred more often:** Over the period 1950–2008, all observed weather stations in all regions of Alaska except the Southeast have showed increasing occurrence of the hottest 1% of days and a decreasing occurrence of the coldest 1% of days (NOAA 2013).

Future projections

- **Average temperatures are projected to increase at a faster rate than elsewhere in the United States:** By the end of this century (2070–2099) under a higher emissions scenario (A2), temperatures across Alaska are expected to increase 7.5°–13.5°F compared to 1971–1999 levels, with the largest projected increases in the north and the smallest in the south (USGCRP 2014).
- **The growing season is projected to continue to expand:** Across large parts of southwestern and interior Alaska, increases of 15–25 days are projected by 2060–2069 (compared to 2010–2019), and in a large part of southwestern Alaska, the growing season lengthens to more than 200 days (NOAA 2013).
- **Spring thaw is projected to arrive earlier, and fall freezes are projected to occur later:** Spring thaw over much of Alaska is projected to advance by 2–3 weeks by 2090–2099, relative to 1961–1990. Along the western and northern shorelines, autumn freeze is delayed 40–60 days as a consequence of sea ice loss (NOAA 2013).

Increasing Precipitation and Changing Water Patterns

Historical observations

- **Average annual precipitation has increased:** Across the state, average annual precipitation has increased about 10% over the period 1949–2005 (NOAA 2013).
- **Glaciers have retreated substantially across Alaska:** Current rates of glacial mass loss from Alaska and British Columbia total 40–70 gigatons per year (USGCRP 2014).

Future projections

- **Total annual precipitation is projected to increase across the state:** In a higher emissions scenario, increases of 15%–35% are projected by 2070–2099 (compared to 1971–1999), with larger increases in the north and interior, and smaller increases in the (already wet) south; under a lower emissions scenario, increases may range from 5% to 20% (NOAA 2013).
- **Seasonal changes are projected to be fairly consistent:** Across the state, increases are projected in all seasons, with the largest increases in winter, and smaller but positive changes in all other seasons. Winter average annual precipitation is projected to increase an average of 30% under a higher emissions scenario, with spring, summer, and fall increases of 22%, 21%, and 24%, respectively (NOAA 2013).
- **Glaciers are expected to continue shrinking:** Increasing temperatures are expected to drive continued glacial retreat, with glaciers that empty into the ocean at the highest risk (ACIA 2005, USGCRP 2014).

Extreme Precipitation, Wildfires, and Sea Level Rise

Historical observations

- **Wildfires have burned more acres:** During the 2000s, an average of 1.9 million acres were burned by wildfires each year, an amount 50% higher than any previous decade since the 1940s (NOAA 2013).

Future projections

- **Increasing fire activity is expected to continue in the future:** Drying landscapes, as well as increases in vegetation, are expected to increase the risk of fire in the future (USGCRP 2014).
- **Permafrost temperatures are projected to increase, and permafrost thickness is expected to decline across the state:** In zones of discontinuous and sporadic permafrost where temperatures are near freezing, increasing temperatures are expected to lead to loss of permafrost; in areas of continuous permafrost, warming temperatures are expected to lead to declines in permafrost layer thickness and increases in active soil layer thickness (ACIA 2005, USGCRP 2014).
- **The extent of sea ice is expected to decline substantially:** By the end of the century, the extent of winter sea ice is expected to decline substantially, leaving much of Alaska's southwestern coastline on the Bering Sea ice-free. Summer sea ice may disappear completely before mid-century (ACIA 2005, USGCRP 2014).
- **Relative sea level rise is not as severe in the region as elsewhere in the United States:** Uplift across most of the Alaskan coastline and rebound from melting glaciers are countering the effects of sea level rise, meaning local sea levels are falling relative to land, although more research is needed for much of Alaska's coastline (Freymuller 2010).

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Chapter 9 Endnotes

[a] Sources: NOAA 2013, USARC 2003, USGCRP 2014
[b] Sources: USARC 2003, USGCRP 2014
[c] Sources: ACIA 2005, USGCRP 2014
[d] Sources: USARC 2003, USGCRP 2014
[e] Source: USGCRP 2014
[f] Sources: DOE 2013, LTER 2006, USGCRP 2014
[g] Sources: ACIA 2005, NOAA 2013, USGCRP 2014
[h] Sources: Cherry 2009, Cherry et al. 2010a, NOAA 2013, USGCRP 2014
[i] Sources: ACIA 2005, DOE 2013, USARC 2003, USGCRP 2014
[j] Source: Newtok Planning Group 2014
[k] Sources: ANTHC 2014, USARC 2013
[l] Sources: ACIA 2005, DOE 2013, USGCRP 2014
[m] Sources: ACIA 2005, Cherry 2009, Cherry et al. 2010a, DOE 2013
[n] Sources: Cherry et al. 2010, USGCRP 2014
[o] Source: USGCRP 2014
[p] Source: Cherry et al. 2010b

Chapter 10: Hawaii and Puerto Rico

Climate Change and the Energy Sector

Overview

Hawaii and Puerto Rico are the largest U.S. islands in population, size, and energy consumption.[1] These islands are isolated from larger mainland energy supply networks, including pipelines, railroads, and transmission grids. Both are located in tropical climates—Hawaii in the Pacific Ocean and Puerto Rico in the Caribbean—and since they are critically reliant on coastal infrastructure, they are vulnerable to similar climate change impacts such as large storms and sea level rise. Key climate trends affecting the energy sector in the region include the following:

- **Atlantic hurricanes are projected to increase in intensity, and the most intense hurricanes are projected to occur more frequently. Pacific hurricane storm tracks are projected to shift toward Hawaii.**[a] Increasing hurricane intensity and frequency increases the risk of damage to energy infrastructure, disruptions to fuel shipments caused by coastal and inland flooding and erosion, wind and wave damage, and landslides.[b]
- **Average sea levels are projected to rise.**[c] Rising sea levels increase storm surge flood stages and storm-driven waves, pushing coastal impacts further inland. Increasing sea levels also decrease the depth of freshwater lenses underlying islands, reducing an important source of cooling water for some thermoelectric generators.[d]
- **Average temperatures are projected to increase over the course of the next century.**[e] Higher temperatures can reduce the efficiency of thermoelectric power plants and the capacity of transmission lines—especially on the hottest days—and cause damage to roads and power transformers, shortening the lifetime of critical energy infrastructure. Higher temperatures are also likely to increase demand for cooling energy.[f]

QUICK FACTS

		Hawaii	Puerto Rico
Population (2013)		1,400,000	3,500,000
Area (square miles)		10,932	5,325
Annual energy expenditures		$7.8 billion	N/A*
ENERGY SUPPLY AND DEMAND*		**Hawaii**	**Puerto Rico**
Electric power	*TWh*	10.5	20.0
Fuel Consumption			
Petroleum	*million bbl*	42	65
Coal	*million tons*	0.8	1.7
Natural gas	*bcf*	2.7	48

**Electricity production and consumption are identical. No fuel is produced.*

ELECTRIC POWER	Annual Production (GWh)	*% of Total*	Capacity (MW)
Hawaii			
Petroleum	7,483	*71%*	2,181
Coal	1,537	*15%*	203
Renewables	1,039	*10%*	517
Other	410	*4%*	81
Puerto Rico			
Petroleum	13,000	*65%*	4,778
Natural gas	3,600	*18%*	540
Coal	3,200	*16%*	454
Renewables	200	*1%*	224

CRITICAL INFRASTRUCTURE	Hawaii	Puerto Rico
Oil refineries:	2	0
Petroleum ports (>200 tons/yr):	6	3
Major power plants (> 1 MW):	43	15**

*Annual energy expenditure for Puerto Rico is not available.
** Includes only commercial plants.
Notes: Energy data for Hawaii is from 2012. Energy data for Puerto Rico is from 2013, except total generation data, which is from 2011. Electricity production by fuel is calculated based on both 2011 and 2013 data.
Sources: EIA 2015a, EIA 2013b, EIA 2013c, PREPA 2013, US Census Bureau 2014a, US Census Bureau 2014b

Table 10-1: Examples of important energy sector vulnerabilities and climate resilience solutions in Hawaii and Puerto Rico

Subsector	Vulnerability	Magnitude	Illustrative Resilience Solutions
Fuel Transport and Storage	Coastal flooding and erosion; wave and wind damage to ports, ships, terminals, refineries and storage, bridges and roads; landslide and heat damage to roads[g]	Hurricane Georges in 1998 destroyed three bridges and damaged roads costing $20 million; Hawaii's Barbers Point Harbor, the primary interisland distribution fuel hub, vulnerable to amplified tides and waves [h]	Building seawalls or natural buffer zones, hardening infrastructure to resist inundation, replacing equipment with submersible or floating infrastructure, relocating roads
Electricity Generation	Coastal plants vulnerable to flooding and structural damage from storms, sea level rise, and erosion[i]	Majority of power plants vulnerable to sea level rise-enabled coastal flooding[j]	Coastal hardening; increased, diversified, and distributed capacity
Electric Grid	Flooding, erosion, wave, and wind damage to towers and substations[k]	Outages caused by Hurricane Georges for 96% of Puerto Rico's electricity customers in 1998[l]	Strengthened tower and substation designs, selective undergrounding of transmission and distribution lines
Electricity Demand	Increased average and peak demand for cooling energy[m]	Projected rise in average temperatures by 2.0°F–5.0°F in Hawaii[n] and by 3.6°F–9°F in Puerto Rico by 2100[o]	Increased capacity, energy efficiency and load management measures

[1] Other U.S. islands located in the Pacific, including Guam, American Samoa, and Northern Marianas, are not examined in this report but are likely to have climate trends, energy sector vulnerabilities, and resilience solutions similar to those in Hawaii. Likewise, the U.S. Virgin Islands, located in the Caribbean, is not separately examined but is likely to have impacts and solutions similar to those in Puerto Rico.

Regional Energy Sector Vulnerabilities and Resilience Solutions

Key energy subsectors and illustrative examples of resilience solutions in Hawaii and Puerto Rico are discussed below. System components that are most vulnerable to climate change are described first.

Fuel Transport and Storage

Subsector Vulnerabilities

In both Hawaii and Puerto Rico, separation from the mainland's ground transportation networks—including roads and railroads, electric grids, and pipelines—necessitates that imported energy resources come via marine vessel. Imports of petroleum products include chiefly diesel, gasoline, and distillates, as they are the primary fuel types for electricity generation and transportation on the islands; but imports also include coal from barges and liquefied natural gas (LNG) both from tankers and in containerized form (EIA 2015a).

Petroleum is the primary energy source for Hawaii and Puerto Rico (EIA 2015a). Both Hawaii and Puerto Rico receive large quantities of petroleum products at different types of ports, barge landings, and docks. At some sites, such as offloading docks for electricity generating stations, fuels are stored and consumed on location and require no secondary transportation once on the island. For example, Puerto Rico Electric Power Authority's (PREPA's) largest power plant (Aguierre, located on Puerto Rico's southwestern coastline) receives both No. 2 and No. 6 fuel oils from barges via dedicated discharging docks and stores fuel on site for use in its boilers and turbines (PREQB 2008). Since the closing of the Cataño Refinery in 2009, Puerto Rico has no refining capacity and must import finished petroleum products.

In Hawaii, unrefined crude oil is the primary petroleum import and is delivered to two refineries on Oahu. The refineries use offshore moorings to receive crude oil. Refined products that are used for transportation, heating, and electricity generation are transported from these refineries to downtown Honolulu via a 10-mile underground pipeline (OMPO 2011). Petroleum products are also loaded onto barges for transport to other fuel ports across the state (OMPO 2011). Hawaii's refineries supply feedstocks for the state's synthetic natural gas processing plant that converts naphtha to methane, and the facilities distribute this natural gas to commercial and residential customers via a pipeline distribution system (EIA 2015a). This system is also being supplemented by small imports of containerized LNG (EIA 2015a).

Relatively little natural gas is used in Puerto Rico and Hawaii. Puerto Rico imports natural gas for electricity production via LNG tankers at EcoEléctrica's Peñuelas LNG terminal and regasification facility located on Guayanilla Bay on the island's southern coast. Because of the historically high cost of petroleum relative to other fuels, PREPA is planning to convert several of its oil-fired turbines to use natural gas, requiring an expansion of the island's LNG import capacity (EIA 2015a). PREPA is planning a new LNG import terminal to serve its 1,500 MW Aguierre power plant on the island's southeastern coast, and the power company is considering using either pipelines or a second LNG import terminal to access its power plants on the northern coast (EIA 2015a). Containerized LNG is also imported for small industrial purposes (Crowley 2014, EIA 2015a).

After fuel is shipped to the islands, it is primarily transported via roads, as railroads are not commonly used in Hawaii or Puerto Rico. Other less common forms of non-road energy transport include conveyors and pipelines. For example, on Oahu, coal offloaded for the AES-Barbers Point power plant is carried via a 1.6-mile elevated, enclosed conveyor belt (OMPO 2011).

Climate change is projected to have the following impacts on fuel transport and storage in Hawaii and Puerto Rico:

- Rising sea levels, combined with increasing frequency of the most intense hurricanes in the Atlantic (and a possible increase in the number of Pacific hurricanes affecting Hawaii), increase the risk of flooding-, erosion-, wave-, and wind-related damage to coastal fuel transport and storage infrastructure such as roads, ports, landings and docks, and storage tanks (API 2014, DOE 2013, Murakami et al. 2013, PRCCC 2013b, USGCRP 2014).
- Increasing frequency of intense North Atlantic hurricanes and a shift in the track of Pacific hurricanes toward the Hawaiian Islands increases the risk of disruption to shipping from storms impacting navigation (Murakami et al. 2013, USGCRP 2014).
- Increasing occurrence of extreme precipitation, Pacific hurricanes, and increasing rainfall from Atlantic hurricanes may contribute to more frequent inland flooding and landslides (especially in the spring), potentially damaging roads, bridges, and energy infrastructure (Murakami et al. 2013, PRCCC 2013a, PRCCC 2013b).
- Increasing temperatures, including more intense and longer-lasting heat waves, soften asphalt and may contribute to additional damage to island roads important for fuel transport (PRCCC 2013a, PRCCC 2013b).

Coastal flooding poses a major challenge to the energy infrastructure of island communities. In Puerto Rico, major coastal flooding is typically associated with storm surge and high wave action brought by hurricanes, but can also be caused by other storms. In Hawaii, tropical cyclones are also dangerous causes of coastal flooding, and evidence suggests that a northward shift in Pacific cyclone tracks could expose Hawaii to more frequent hurricane impacts (Murakami et al. 2013). In the Atlantic, research suggests a roughly two-fold increase in the occurrence of Category 4 and 5 hurricanes by the end of the century (Bender et al. 2010). Additionally, rising sea levels can magnify the effects of storm surge flooding by creating a higher baseline for flood stages (USGCRP 2014). For both Hawaii and Puerto Rico, coastal flooding threatens to disrupt and damage important coastal infrastructure, including roads, bridges, ports, docks, and storage tanks (OMPO 2011, PRCCC 2013b). Flooding can shut down port operations and cause structural damage to docks, buildings, and heavy machinery necessary for loading and unloading fuels (OMPO 2011, PRCCC 2013b). For example, the seaport in Arecibo, Puerto Rico, currently experiences regular problems with flooding because of its exposure to high-energy waves (PRCCC 2013b). Rising sea levels will likely intensify flooding, pushing storm surge and storm waves farther inland (USGCRP 2014). Similarly, Barbers Point Harbor in Kalaeloa, Hawaii, is vulnerable to amplified tides and waves due to seiches (OMPO 2011). This harbor is used for offloading coal for AES-Barbers Point, as well as loading petroleum products from the Barbers Point refineries (OMPO 2011). Because of its importance to the island's energy supply, disruptions to the harbor's ability to load and offload fuels could disrupt energy systems and have severe implications for the state's economy (OMPO 2011).

As with fuel transfer facilities at ports, the loading and unloading docks used by island power plants and refineries are vulnerable to damage and disruption from coastal flooding. All of Puerto Rico's major power plants use on-site docks to bring fuel to their facilities. Studies have identified six of the territory's power plants as vulnerable to flooding, with the 602 MW oil-fired Palo Seco and the 220 MW dual-fuel Mayagüez power plants being most vulnerable (Figure 10-1) (PRCCC 2013b, PREPA 2013).

Figure 10-1. PREPA's Palo Seco Power Plant on Puerto Rico's northern coast
Source: EPA 2012

Coastal flooding can also disrupt and damage roads and bridges, which are key transportation links in island energy systems. Flooding can inundate roads, blocking access to fuel ports and preventing fuel deliveries to power plants. Erosion caused by heightened wave activity can damage bridges and may require that existing bridges be raised. Of the 240 bridges in Puerto Rico's coastal zones, 30 are potentially vulnerable to coastal flooding (PRCCC 2013b). In 1998, flooding from Hurricane Georges did a total of $21 million in damages to roadways in Puerto Rico and led to the destruction of three bridges (PRCCC 2013b). In Honolulu Harbor, Hawaii, sea level rise and increased storm surge projected for 2100 could have combined impacts that expose harbor access roads and bridges to inundation and erosion, potentially disrupting fuel supplies (OMPO 2011).

Coastal flooding can damage and disrupt the operation of refineries and fuel storage tanks (PRCCC 2013b). Refinery buildings, structures, and storage tanks can be damaged by waves and salt water inundation; and storage tanks can be lifted if their containment berms are breached (DOE 2010). Analysis of flood impacts at the Chevron refinery on Barbers Point in Oahu found that three feet of sea level rise would expose the refinery to significant flooding vulnerabilities; this is within the 1–4 foot range projected by the end of the century (OMPO 2011, USGCRP 2014). While Puerto Rico has no refining facilities, fuel tanks at several airports, including the Luis Muñoz Marín International Airport and the Isla Grande Airport, are at risk from sea level rise (PRCCC 2013b). Additionally, coastal flooding can damage underground fuel storage tanks in low-lying areas such as those used by gas stations (PRCCC 2013b).

Roads as critical energy corridors

The Farrington Highway on Hawaii's most populous island, Oahu, is the only road connecting the 45,000 residents of the Waianae Coast to the rest of the island's communities and infrastructure (OMPO 2011). The 18-mile two-lane highway runs along the coast and has historically seen closures due to both coastal and inland flooding, downed utility poles, and other emergencies. Furthermore, some segments of the highway are being undercut by erosion. Projected increases to sea level and storm surges will exacerbate these problems, and the highway is classified as “high vulnerability” by the Oahu Metropolitan Planning Organization (OMPO 2011). Collapse or other damage to the Farrington Highway could cut off entire communities from fuels and other critical supplies (OMPO 2011).

Hurricanes can disrupt shipping by preventing navigation for several days at a time. The increased intensity and frequency of the most intense hurricanes in the Atlantic, and the possibly of more hurricanes affecting Hawaii, may threaten the ability of fuel barges to make critical deliveries. While large power plants typically have stockpiles of fuel, shipping disruptions combined with damage to port facilities may compound the risks to fuel transport posed by severe weather events. For example, Puerto Rico's largest generating station, the oil-fired Aguierre Power Plant, typically receives fuel deliveries once every three days, but it does have on-site capacity to store approximately 36 days of fuel for typical operations[2] (PREPA 2013).

Wind impacts resulting from hurricanes can affect a variety of transportation and storage infrastructure, including large storage tanks and elevated facilities (API 2014, OMPO 2011, PRCCC 2013b). The elevated, enclosed conveyor belt used to transport coal inland to the AES-Barbers Point coal plant may be susceptible to wind damage, as may container port cranes necessary for the loading and offloading of fuel products (OMPO 2011).

Inland flooding and landslides may pose a risk to Puerto Rico's roads, bridges, and ports, as some climate models project significant increases in the intensity of hurricane-related extreme precipitation events in the springtime (PRCCC 2013a). Several ports in Puerto Rico already experience regular river flooding, including the Pan American dock in San Juan and the Port of Ponce (PRCCC 2013b). Landslides occur when bursts of heavy rainfall destabilize the soil on sloped terrain, and in Puerto Rico, they are a significant source of damage to property, including roads (Figure 10-2) (PRCCC 2013b). For example, heavy storms in May and June of 2011 led to landslides and extensive road and bridge damage in parts of Puerto Rico. A state of emergency was declared, and almost $6 million was requested to repair damage to roads and bridges (FEMA 2011).

Figure 10-2. Severe storms and flooding swept away roads and bridges in Barranquitas, Puerto Rico
Source: FEMA 2010

[2] These shipments deliver 780,000 barrels of residual fuel oil, and consumption is around 21,700 barrels per day (PREPA 2013).

Over a long period of time, warmer temperatures may also affect roads. Higher temperatures weaken asphalt, and continuous use at elevated temperatures can reduce roadway lifetimes. On the islands, where roads are crucial fuel transport links, the reliability of road infrastructure is essential. Use of roadways during periods of elevated temperatures—especially during prolonged heat waves—may lead to cracking and rutting, requiring more frequent and costly maintenance and eventually earlier replacement of road surfaces (PRCCC 2013b).

Fuel Transport and Storage

Resilience Solutions

Enhancing resilience to coastal flooding and erosion requires either relocation or hardening of existing assets, as well as planning to ensure that future investments are designed in anticipation of the range of possible future impacts (DOE 2013). Hardening of assets can involve constructing seawalls to reduce erosion, enclosing equipment in submersible cases, replacement with submersible equipment, or raising infrastructure above projected flood stages (DOE 2013). Relocation of assets inland or to higher elevation coastlines can increase resilience to flooding and erosion, but the practice is contingent on local geography and may not be a feasible or cost-effective option for large facilities with significant dedicated infrastructure.

Harbor facilities such as docks, access roads, storage areas, and tanks may be raised in anticipation of higher flood stages, and vegetative buffer zones may be used to reduce flooding and erosion. For example, an open vegetative area on the southern (ocean-facing) shore of Sand Island in Honolulu Harbor may act as a buffer zone for both erosion and flooding of infrastructure in Hawaii's largest port (OMPO 2011). In cases in which infrastructure is destroyed and must be rebuilt, replacement facilities can incorporate hardening measures into new designs. Following Hurricane Georges in 1998, the damaged Río Tallaboa Bridge was heightened to avoid future damage from coastal flooding (PRCCC 2013b). Sea walls are a likely hardening option for large facilities that may not be economically raised or relocated. Sea walls can stabilize or stop erosion and can provide protection from storm surge flooding (O'Connell 2009). However, sea walls may also carry negative side effects: hardening of Hawaii's shorelines have contributed to the loss or narrowing of 24% of Oahu's natural sandy beaches—a crucial economic asset for the state (O'Connell 2009).

For many climate impacts, including damage to roads from increased heat, landslides, and wind, improved planning and designs may be the most effective means of reducing vulnerabilities. As roads damaged by flooding are replaced, new routes, designs, and innovative materials may be considered.

Thermoelectric Power Generation

Subsector Vulnerabilities

Hawaii and Puerto Rico share several commonalities between their respective fleets of power plants. As the islands have no domestic fossil fuel production, they must rely on imports of fuels to operate their baseload thermoelectric power generation. Most of the power plants use ocean water for cooling, while the remainder typically use recirculating cooling systems to reduce their reliance on freshwater, as the availability is limited (UCS 2012).

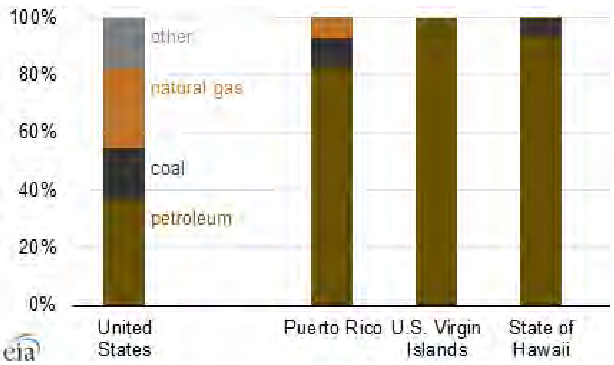

Figure 10-3. Share of energy consumption by fuel (2012)
Source: EIA 2014

Historically, U.S. islands have relied on petroleum as their primary energy source, including as a fuel for electricity generation (Figure 10-3) (EIA 2014). Petroleum-fired power plants include both traditional steam boilers burning residual fuel oil and combustion turbines/combined-cycle plants burning distillates (EIA 2013c). Hawaii and Puerto Rico each have one coal-fired power plant: AES-Barbers point, on the Hawaiian island of Oahu, and AES-Puerto Rico in Guayama (Hawaiian Electric 2013, PREPA 2013). Puerto Rico also hosts a 540 MW natural gas-fired combined-cycle power plant, EcoEléctrica, which is fueled by an on-site LNG receiving terminal (PREPA 2013). PREPA purchases power from EcoEléctrica, and in 2013, PREPA converted two units of its nearby Costa Sur generating station to dual-fuel firing, capable of burning oil or natural gas purchased from EcoEléctrica's terminal (PREPA 2013). PREPA is planning to convert additional petroleum-fired power plants to dual-fuel capability, starting with the 1,500 MW Aguierre power plant, following construction of additional LNG import capacity (EIA 2015a, PREPA 2013). In Hawaii, Hawaiian Electric Company and its subsidiaries ("Hawaiian Electric," the state's primary utility, which serves approximately 95% of Hawaii's residents) are also considering a future energy plan that would convert many petroleum-fired power plants to also use natural gas (Hawaiian Electric 2013, Hawaiian Electric 2014, Hawaiian Electric 2015a). Hawaiian Electric's preferred energy plan would see petroleum use fall dramatically by 2017, and the AES-Barbers Point coal plant would switch to 50% biomass co-firing (Hawaiian Electric 2014).

Use of renewables is increasing in Hawaii. In 2012, wind, geothermal, biomass, and some hydroelectric and solar produced approximately 10% of Hawaii's electricity (EIA 2013a). Puerto Rico uses relatively few renewable generators, with 224 MW of installed renewable capacity producing approximately one percent of the island's total power (PREPA 2013, EIA 2015a).

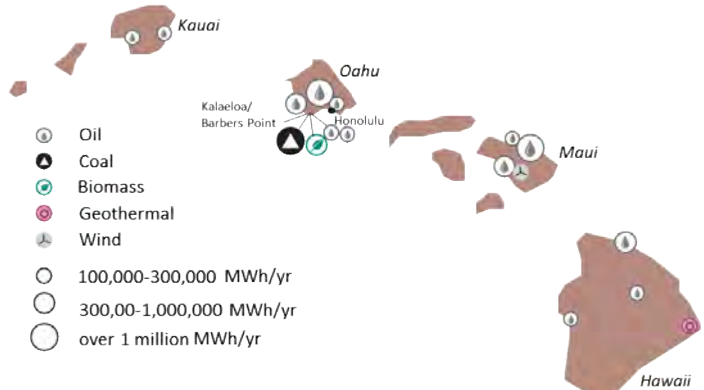

Figure 10-4. Locations of large electricity generation facilities in Hawaii (2005)
Data source: UCS 2012

The bulk of Hawaii's and Puerto Rico's electric power generation infrastructure is concentrated in low-lying, coastal areas (Figure 10-4 and Figure 10-5) (EIA 2015a, PRCCC 2013b). On the island of Oahu (with Hawaii's largest population), the Kalaeloa/Barbers Point area hosts nine power plants, including the island's largest, alongside two refineries. The Kalaeloa coastal plain is 9–12 feet above mean sea level (OMPO 2011). In Puerto Rico, several generating stations are located near the coast, including the AES-PR and PREPA Aguierre power plants in the southeast and the PREPA Costa Sur and Ecoeléctrica plants outside Ponce (PREPA 2013).

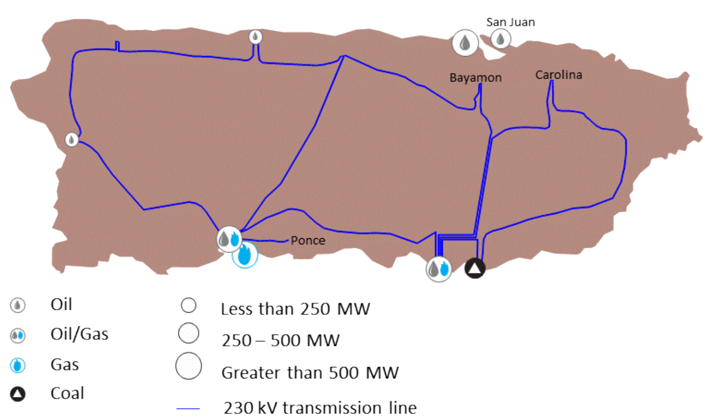

Figure 10-5. Locations of large electricity generation facilities and major transmission lines in Puerto Rico (2012)
Data source: PREPA 2013

Climate change is projected to have the following impacts on electric power generation in Hawaii and Puerto Rico:

- Increasing hurricane intensity and frequency of the most intense hurricanes in the Atlantic, as well as a possible increase in the frequency of hurricanes affecting Hawaii, may increase the vulnerability of coastal power plants to damage and disruption from sea level rise-enhanced storm surge flooding, heightened wave action, and wind damage (DOE 2013, Murakami et al. 2013, OMPO 2011, PRCCC 2013b, USGCRP 2014).
- Salt water intrusion caused by sea level rise, increases in evaporation rates, and changes in precipitation (in Puerto Rico) may decrease the availability of fresh water for cooling of thermoelectric power plants in Hawaii and Puerto Rico (DOE 2013, IPCC 2014, PRCCC 2013b, USGCRP 2014).
- Higher temperatures may reduce the efficiency of thermoelectric power plants and diminish the peak capacity of island electricity systems (DOE 2013).

Hurricanes pose a considerable threat to island energy infrastructure, including power plants. Associated heavy rainfall and storm surge can cause coastal flooding that forces shutdowns, disrupts generation, and damages and destroys electrical equipment by inundating it with saltwater. Wind, wave action, and erosion can also cause structural damage (DOE 2013). Because many power plants in Hawaii and Puerto Rico are located close to the ocean, coastal flooding can threaten a significant share of an island's electric generating capacity in a single event. For example, on Hawaii's populous island of Oahu, hurricanes are historically the most damaging natural events (City and County of Honolulu 2012). The large concentration of energy infrastructure along the coast increases Oahu's vulnerability to winds, flooding, erosion, and wave damage from tropical cyclones (Figure 10-6). For example, nine power plants clustered in the low-lying area around Kalaeloa/Barbers Point represent almost 70% of the island's generating capacity (OMPO 2011). Similarly, models simulating 643 historical storm tracks in the vicinity of Oahu and Kauai (including Category 2, 3, and 4 storms) have shown that in the worst-case scenario (direct impact of a Category 4 hurricane), much of Honolulu would be inundated by a combination of storm surge and wave force (Kennedy et al. 2012). A total of 61% of the electric power generation facilities in Oahu are located within the inundation zone of a Category 4 hurricane (FEMA 2009).

The electric power sector and the fuel transport infrastructure are often interdependent systems (DOE 2013). In Hawaii and Puerto Rico, several important fuel supply facilities and power plants are co-located in coastal industrial areas (OMPO 2011, DISUR 2012). Because these assets often have low levels of redundancy (OMPO 2011), the direct impact of a hurricane has high potential for affecting these assets simultaneously, further elevating the risk that damage or disruption to one of the energy subsectors will cascade into the other.

Figure 10-6. Hawaiian Electric Company power plant at Kahe Point in West Oahu
Source: Zamuda 2015

Climate change is projected to contribute to the increasing scarcity of freshwater on islands. Local freshwater scarcity for power plants can be caused by intrusion of salt water into fresh water reservoirs, increased evaporation of surface water due to higher temperatures and, in Puerto Rico, projected declines in future precipitation (PRCCC 2013a, USGCRP 2014).[3] Disruptive changes in water availability can impact power plants; if reduced surface water availability affects power plant intakes, or if saltwater intrusion fouls power plant wells, finding a new source of water could prove expensive.

Almost 30% of Hawaii's electricity generating capacity relies on freshwater for cooling (UCS 2012). These power plants employ recirculating cooling systems, and the U.S. Geological Survey (USGS) estimates freshwater withdrawals for thermoelectric power production to be approximately 3% of total withdrawals (USGS 2005). The rest of the state's power plants use either ocean water or dry cooling systems (UCS 2012). In Puerto Rico, all six of PREPA's baseload power plants use some freshwater for cooling; however, the USGS estimates that freshwater withdrawals in Puerto Rico for thermoelectric power production represent less than 1% of total water withdrawals (USGS 2005).

Projected increases in temperature for the island regions are relatively mild compared to other places in the United States; however, even incremental increases in temperature reduce the efficiency of combustion turbine

[3] Precipitation models for the Caribbean are uncertain compared to other regions, but indicate decreasing precipitation over the course of this century (PRCCC 2013c, USGCRP 2014).

power plants (DOE 2013, NOAA 2013, PRCCC 2013a). While the changes in power output are small (less than a 1% reduction for every 2°F increase in temperature), they could have significant impacts on the electricity supply system, particularly during heat waves, if losses in capacity are not offset by greater supplies elsewhere or by reduced demand (DOE 2013). Because capacity reductions due to efficiency reductions are largest when temperatures are highest, increasing peak temperatures reduce a power plant's effective peaking capacity at the same time that demand for cooling energy peaks (see Energy Demand section).

Thermoelectric Power Generation

Resilience Solutions

Because of the dependence of both Hawaii and Puerto Rico on coastal power plants, resilience to damage and destruction from hurricanes may be improved through an array of strategies that involve protecting against high winds, storm surge, coastal erosion, and flooding. These include engineering improvements to structures, installing or enhancing sea walls and other barriers, and relocating or elevating facilities such as fuel storage tanks and unloading docks. Additionally, site selection and design of new power plants and support facilities (including future LNG import terminals and gasification facilities) can incorporate projected rather than historic coastal flooding heights, wind speeds, and wave energy projections. For example, a new 27 MW utility-scale solar photovoltaic (PV) project in Loiza, Puerto Rico, was completed in 2013. Located in a hurricane-prone area, the elevated solar array was designed to resist damage from both flooding and high winds (TSK Group 2013).

Electricity system resilience can also increase through diversification of the generation fuel mix to include local renewable resources, such as biomass, solar PV, or onshore wind turbines that are located inland and do not rely on fuel transportation infrastructure. Because electricity generation in Puerto Rico and Hawaii relies primarily on imported petroleum, electricity prices are much higher than in the continental United States (Figure 10-7). In recent years, high oil prices and low natural gas prices have provided a strong economic incentive for islands to diversify fuel sources for electric power generation. An increasingly diverse fuel mix that includes renewables (such as locally-sourced biomass) will provide islands with improved resilience to climate change-related disruptions in petroleum supply. Furthermore, due to the high price of electricity on the islands, renewable technologies are much more likely to be cost competitive with incumbent generators. Both the Hawaiian and Puerto Rican governments have policies intended to help transition their respective fuel mixes to include larger shares of renewables. Hawaii has Renewable Portfolio Standards with a 40% target by 2030 and a 100% target by 2045, and Puerto Rico has a 20% goal for 2035 (EIA 2015b, Hawaiian Electric 2015b, PRGEF 2015).

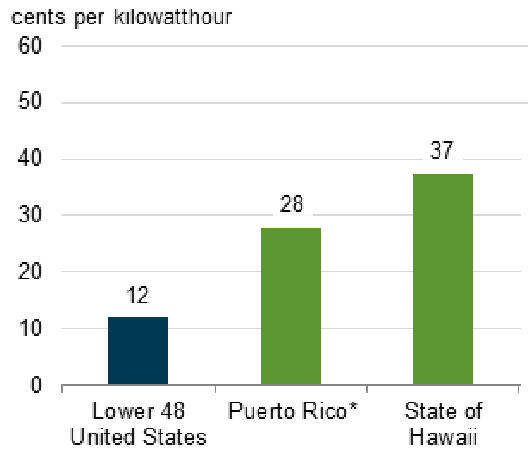

Figure 10-7. Average residential electricity prices (2012)
(*Puerto Rico data is from 2011)
Data source: Adapted from EIA 2014

Puerto Rico is focusing on wind, solar, and waste-to-energy projects to meet its renewable portfolio standard. More than 400 MW of solar PV and 250 MW of wind are in development (EIA 2015a). Studies so far show Puerto Rico has limited potential for large-scale wind projects, but has taken advantage of the tropical sun and become a leader in distributed solar applications, including solar hot water heaters and PV (Figure 10-8). No municipal solid waste or other waste-to-energy facilities have yet been built, but PREPA has signed more than a dozen power purchase agreements with developers. Puerto Rico is exploring the use of biofuels, primarily those derived from agricultural wastes, and investigating ocean energy technologies. However, PREPA faces financial barriers to making large investments in new resilience measures, as existing debts may constrain its financing.

Figure 10-8. A 286 kW solar PV installation at an industrial site in Puerto Rico sells excess power to the grid
Source: USDA 2012

Because most island power plants already use saline sources for cooling water or employ recirculating systems, the power generation sectors in Hawaii and Puerto Rico may be more resilient to potential water scarcity in the future than U.S. mainland power plants. However, implementation of advanced hybrid/dry cooling systems that can operate with minimum cooling water could be considered for future thermoelectric capacity to avoid freshwater availability concerns.

Reductions in peaking capacity caused by higher temperatures can be addressed through the addition of new capacity (discussed above) and through demand reduction measures (See Electricity Demand section).

Electric Grid

Subsector Vulnerabilities

The electric transmission and distribution systems of Hawaii and Puerto Rico are isolated from wider electricity grids, and the use of submarine interconnections between islands is limited. The majority of transmission and distribution lines on the islands are aboveground with limited undergrounding of lines.

Puerto Rico's electric grid is operated by PREPA, a government-owned corporation, and consists of approximately 1,100 miles of 230 kV and 115 kV lines and 45 transmission substations that provide the grid's backbone and sectionalize the island into three main loops. In the San Juan area, 35 miles of 115 kV lines have been undergrounded (PREPA 2013). PREPA operates a 38 kV subtransmission network, primarily in and around load centers but also to serve remote communities in the island's interior. The 38 kV grid also includes 55 miles of submarine transmission cables connecting the main island's grid with the islands of Vieques and Culebra (PREPA 2013). PREPA's distribution grid comprises 333 distribution substations and approximately 31,500 miles of distribution lines, including approximately 1,900 miles of underground distribution lines, primarily in urban areas (PREPA 2013).

In Hawaii, none of Hawaiian Electric's five island grids are interconnected; each island operates an independent grid connecting local generation to load (Hawaiian Electric 2013). As part of its integrated resource planning process, Hawaiian Electric has considered interconnections between Oahu, Maui, and Hawaii as a solution to reduce long-run costs; however, no submarine lines are currently used in the state (Hawaiian Electric 2013).

Climate change may increase the vulnerability of the electric grid in Hawaii and Puerto Rico in the following ways:

- Increasing hurricane intensity and frequency of the most intense hurricanes in the North Atlantic, and a possible shift in Pacific hurricane tracks toward Hawaii, will put electric transmission and distribution infrastructure at increased risk of damage and disruption from coastal flooding and erosion, wave, and wind damage (DOE 2013, Murakami et al. 2013, PRCCC 2013b, USGCRP 2014).
- Rising sea levels will magnify the impacts of storm surge and wave action and increase risk of inundation of low-lying coastal infrastructure such as switchyards and transmission and distribution substations (OMPO 2011, PRCCC 2013b, PREPA 2013, USGCRP 2014).
- Increasing temperatures reduce grid capacity and may shorten the expected lifetime of transformers (Bérubé et al. 2007, DOE 2013, USBR 2000).

Hawaiian Electric supplies power to about 95% of Hawaii's population and owns about 3,000 miles of transmission and distribution lines, of which about 60% are aboveground (Hawaiian Electric 2015a). Almost all of the transmission and distribution circuit mileage in Puerto Rico's electricity system is aboveground (PREPA 2013). Historically, tropical storms have caused major damage and disruption to the Hawaiian and Puerto Rican electric grids (see sidebar: Hurricanes in Hawaii and Puerto Rico). Wind and torrential downpours threaten overhead transmission lines by causing direct structural damage to poles and transmission towers, damaging or breaking conductors, and increasing the risk of lines being downed by fallen trees and vegetation (DOE 2013). Inland flooding associated with extreme precipitation events can erode riverbanks and uproot power poles. Coastal flooding, amplified by sea level rise, can inundate substations, transmission centers, and switching yards (DOE 2013, PREPA 2013). Destructive waves from storms, heightened by sea level rise, can also erode protective shorelines and cause structural damage to grid infrastructure located along the coast. Furthermore, the risks presented by climate change to Puerto Rico's grid could complicate ongoing efforts to address existing challenges in the island's electric power system, including reliability issues, system security margins, voltage stability, and transmission losses (DISUR 2012).

Hurricanes and the electric grid

- Hawaii: In 1992, Hurricane Iniki knocked out power to 80% of Kauai residents for four weeks. Iniki destroyed a quarter of the island's electric transmission poles and a third of its distribution poles (Sommer 2002).
- Puerto Rico: Recent hurricanes have caused a combined $336 million in damages to the Puerto Rican electric power system, including $36 million in 1996 (Hortense), $240 million in 1998 (Georges), and $60 million in 2004 (Jeanne) (PREPA 2013). Hurricane Georges resulted in power loss for 96% of Puerto Rico's customers and at least half of the island's electrical poles and cables were damaged (PRCCC 2013b).

Increases in average and peak temperatures can also affect the capacity and lifetime of transmission and distribution components (Bérubé et al. 2007, DOE 2013). At higher temperatures, transmission wires sag, increasing the risk of arcing between conductors, or to other objects such as trees. In order to reduce the risk of line outages, operators reduce the current carrying capacity of transmission lines on very hot days, typically when peak capacity is most needed (DOE 2013). Traditional power transformers can also be damaged by operating at elevated temperatures, requiring earlier replacement and higher costs (Bérubé et al. 2007, USBR 2000). Although projected temperature increases in Hawaii and Puerto Rico are moderate compared to other regions, current temperatures in these island regions are already elevated relative to most U.S. mainland locations, so even small increases in ambient temperatures could have significant impacts on transformer lifetime (Bérubé et al. 2007, Hashmi et al. 2013, NOAA 2013, PRCCC 2013a).

Electric Grid

Resilience Solutions

The resilience of island electric grids can be improved by building redundant and sectionalized circuits for rural areas to prevent widespread outages on backbone lines; by hardening structures including towers, conductors, and transformers; by undergrounding critical grid corridors; and by exploring the use of distributed generation capacity where feasible.

Installing transmission and distribution lines underground can protect them from wind impacts. Although the cost of undergrounding lines is high, selective undergrounding can help protect critical corridors to maintain system stability in an emergency. For example, following the devastation of Hurricane Georges in 1998, PREPA undergrounded 28 miles of San Juan’s 115 kV transmission lines, as well as a significant number of distribution lines, to improve the resilience of the city’s transmission and distribution grid to future hurricanes, tropical storms, and other disruptions (Figure 10-9) (PREPA 2013). These undergrounded lines are designed to maintain service to the city's central business district in the event that overhead lines are lost (PREPA 2013).

Hawaiian Electric is already deploying many projects that will improve Hawaii’s grid resilience. Hawaii's utilities are acting on a strategy to further lower electricity prices, increase integration of the state's renewable resources, harden infrastructure against tsunamis or hurricanes, and increase the flexibility and redundancy of grid operations under emergency conditions (Hawaiian Electric 2013). For example, to protect its grid operations from the impacts of a tsunami, Maui Electric (a subsidiary utility of Hawaiian Electric) is planning to move its central dispatch center to higher ground outside of the anticipated inundation zone (Hawaiian Electric 2013). This step will have the added benefit of avoiding the potential coastal flooding associated with a hurricane. The City of Honolulu is proposing an array of projects to improve resilience to impacts of future hurricanes: hardening above-ground utility assets, increasing electric power generation capacity, and integrating new topographic wind speed maps into electricity distribution infrastructure planning (City and County of Honolulu 2012).

Figure 10-9. PREPA's underground 115 kV transmission system for San Juan, Puerto Rico

Source: PREPA 2013

Connecting island grids to larger networks may also improve grid resilience by providing operators with greater flexibility if generation assets are lost or if portions of the grid must be sectionalized. In Puerto Rico, proposals to connect the island's grid to other Caribbean islands have been suggested (VIWAPA 2011). Similarly, Hawaiian Electric has considered a number of scenarios using interisland grid interconnections to increase resilience and decrease long-run system costs (Hawaiian Electric 2013).

Electricity Demand

Subsector Vulnerabilities

Electricity demand in Hawaii is driven by economic and population growth, both of which have outpaced the mainland (US Census Bureau 2014a, Hawaiian Electric 2013). In Puerto Rico, the population is shrinking, and the economy has struggled to return to pre-recession growth; however PREPA projects that growth in electricity demand will outpace the national average by 2017 (EIA 2015a, PREPA 2013).

Climate change is projected to affect electricity demand in the following way:

- Increasing temperatures are likely to increase power demand for air conditioning, which could have implications for electricity reliability if such increases in demand are not compensated by increased supplies or reduced demand elsewhere in the system (DOE 2013).

Both Hawaii and Puerto Rico have tropical climates moderated by influences from the ocean, with fewer extremes in seasonal temperatures than most other regions of the United States. For example, the warmest month in Hawaii is August, with an average temperature of 78°F; the coolest month is February, with an average temperature of 72°F (NOAA 2013). Average temperatures in Hawaii and Puerto Rico are projected to increase as a result of climate change: 2°F–5°F by the end of the century in Hawaii and 3.6°F–9°F in Puerto Rico (NOAA 2013, PRCCC 2013c). Higher temperatures are likely to increase electricity system loads, which may cause both Hawaii and Puerto Rico to face electricity supply constraints.

Most homes in Hawaii and Puerto Rico use air conditioning, so an increase in air temperature will likely drive an increase in the energy use of existing air conditioners, an increase in the hours of operation, or both (Champagne et al. 2010, PNNL 2008). In Puerto Rico, for example, most air conditioners are in operation between 7 and 12 hours a day (Champagne et al. 2010). Without demand management, improvements in air conditioner energy efficiency, or new generation capacity, increasing use of air conditioning may increase power sector vulnerability to service disruptions.

Population growth is also a significant factor in total energy demand, amplifying the impacts on electricity demand attributed to increasing temperatures alone. Hawaii's population is projected to expand 25% between 2010 and 2040 (DBEDT 2012). Conversely, Puerto Rico's declining population (a projected 14% reduction between 2010 and 2040) may offset increases in demand caused by higher temperatures in the long-run (Pew 2014).

Increasing electricity demand could compound vulnerabilities of the broader electricity supply on the islands, as higher temperatures coincide with reduced power plant and transmission line efficiency and capacity.

Electricity Demand

Resilience Solutions

Both Hawaii and Puerto Rico have programs and incentives designed to improve energy efficiency and reduce demand—measures that will improve the energy sector's resilience to higher temperatures.

Hawaii has established a state energy efficiency portfolio standard that requires the state to achieve a 4,300 GWh savings in energy demand through efficiency by 2030, a reduction equivalent to 38% of total generation in 2008 (EIA 2013a, HPUC 2013). The state has also decoupled the profits of investor-owned electric companies from total electricity sales, enabling companies to encourage efficiency (ACEEE 2014, HSEO 2015a). Hawaii has had a recent increase in the number of energy efficiency programs available to utility customers, such as the Hawaii Residential Direct Load Control Program, which allows customers to participate in demand response by installing "EnergyScout" load control receivers that can control hot water heaters and air conditioners during critical periods. The program has approximately 36,000 customers controlling 17 MW of load (ACEEE 2014, Hawaiian Electric 2013). Similarly, PREPA offers commercial and industrial customers time-of-use rates that encourage large users to shift demand to off-peak times (PREPA 2013).

Both Hawaii and Puerto Rico have made progress in replacing electric water heaters with solar water heaters, reducing a significant source of residential electricity demand from the grid. Both governments have also recently enacted building code standards that mandate the use of solar hot water heaters in newly constructed single-family homes (HSL 2014a, PRPRA 2010). Hawaii residents may receive up to $2,250 in tax credits for installing solar water heaters, and approximately 85,000 solar water heaters, or one in four households, are already in operation (Hawaii Electric 2015b, HSL 2014b). In Puerto Rico, incentives and programs to deploy solar water heaters, combined with incentives for small-scale PV, have removed 40 MW of load from the electric grid (EIA 2015a).

Finally, new power generation capacity can help electric grid operators meet increasing demand. Hawaii and Puerto Rico are endowed with abundant solar resources, and adding more solar PV to the generation mix can help meet daytime increases in air conditioning demand. To accommodate the increasing share of intermittent renewables in the state's electricity mix, both demand response and energy storage are expected to play increasingly important roles in the Hawaiian electric power market. PREPA is using a strategy of purchasing power from independently-owned renewable energy projects to increase its reserve margins (Hawaiian Electric 2013, PREPA 2012). In recent years, Hawaii has also seen an increase in the number of distributed renewable energy systems.

Regional Climate Change Observations and Projections in Detail (Hawaii)

Higher Temperatures

Historical observations

- **Over the last century, average temperatures have increased 0.07°F per decade, equal to an increase of 0.6°F** between 1919 and 2006. The rate of warming has accelerated in the last four decades and has increased faster at higher elevations (NOAA 2013).
- **Since 1975, temperature patterns have become increasingly decoupled from historical drivers of regional climate.** Before 1975, temperature was tightly coupled to the Pacific Decadal Oscillation. Global warming may be responsible for the subsequent decoupling (NOAA 2013).
- **Between 1958 and 2009, the number of below-freezing days at high elevations decreased** (NOAA 2013).

Future projections

- **Average temperatures are projected to increase:** Increases of 2.0°F–5.0°F are projected by 2070–2099 compared to 1971–1999 levels, depending on the region and greenhouse gas emissions (NOAA 2013).

Precipitation

Historical observations

- **A general downward trend in precipitation has occurred.** Although there is high variation among leeward and windward areas, the overall decline in rainfall is consistent with an increase in frequency of the Trade Wind Inversion, a decline in trade wind occurrence, and associated warming at higher elevations (NOAA 2013).
- **Hawaii has experienced increasing drought during the winter rainy season.** From 1980–2011, all of the major Hawaiian Islands have experienced longer periods of consecutive dry days compared to the period 1950–1979 (NOAA 2013).
- **Extreme precipitation events have declined.** A significant decrease in the frequency of high-intensity or moderate-intensity precipitation events occurred in the period 1980–2011 compared to 1950–1979 (NOAA 2013).

Future projections

- **Projected changes in average precipitation are small and not statistically significant.** By the end of the century (2070–2099), precipitation is projected to change by -1% to more than 3% compared to the period 1971–1999 under an A2 emissions scenario (NOAA 2013a). Under a B1 emissions scenario, precipitation is projected to decrease by more than 2% in the Northern islands while increasing by about 2% in the Southern islands (NOAA 2013).

Hurricanes and Sea Level Rise

Historical observations

- **Pacific hurricanes are less frequent but more severe.** Over the past 20 years, fewer hurricanes have occurred across the Pacific, but the number of major hurricanes (Category 4 and 5) has increased (NOAA 2013).
- **Sea level has increased by 8 inches since 1900.** Global mean sea level has accelerated in the past two decades, rising 1.3 inches per decade. Higher rates of sea level rise in Hawaii compared to global sea level are partly attributed to changes in prevailing wind patterns associated with El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) (USGCRP 2014).

Future projections

- **The frequency of hurricanes near Hawaii is projected to increase.** By 2075–2099, a Northwestern shift in the track of hurricanes in the Pacific Ocean may increase the frequency of hurricanes affecting Hawaii (Murakami et al 2013).
- **Global mean sea level is projected to rise by 1 to 4 feet by the end of the 21st century** (USGCRP 2014).

Regional Climate Change Observations and Projections in Detail (Puerto Rico)

Higher Temperatures

Historical observations

- **Since 1900, average temperatures in Puerto Rico have increased by more than 2°F.** The rate of measured temperature change has been between 0.022°F and 0.25°F per year (PRCCC 2013a).
- **The Caribbean has seen an increase in very warm days and nights.** Since the 1950s, the region has experienced an increase in the number of days above 90°F and nights above 75°F (USGCRP 2014).

Future projections

- **Average temperatures are projected to increase.** Projected temperatures for Puerto Rico show an increase of at least 1.4°F by mid-century and as much as 3.6°F–9°F by the year 2100 (PRCCC 2013a).
- **Temperature increases in Puerto Rico are expected to be higher than the tropical average** (PRCCC 2013a).

Precipitation

Historical observations

- **Precipitation trends in the Caribbean are unclear.** Some regions have experienced more precipitation than the historical average, and others less (USGCRP 2014).

Future projections

- **Projected changes in average precipitation are uncertain.** Models are not consistent, but the majority show future decreases in precipitation (USGCRP 2014).

Severe Weather and Sea Level Rise

Historical observations

- **In the past several decades, intense hurricanes in the North Atlantic have increased in frequency.** The number of Category 4 and 5 hurricanes has increased substantially since the early 1980s compared to the historical record starting in the mid-1880s (USGCRP 2014).
- **Sea level rise has contributed to coastline loss**. The coastline of Rincón, Puerto Rico, has eroded at 3.3 feet per year because of sea level rise (USGCRP 2014).
- **Sea level has increased by 8 inches since 1900.** Global mean sea level has accelerated in the past two decades, rising 1.3 inches per decade (USGCRP 2014).

Future projections

- **The frequency of the strongest (Category 4 and 5) hurricanes is projected to increase in the North Atlantic** (USGCRP 2014).
- **Hurricane-associated storm intensity and rainfall rates are projected to increase:** Rainfall rates within 100 km of tropical storm centers are projected to increase by 20% by 2100 (USGCRP 2014)
- **Global mean sea level is projected to rise by 1 to 4 feet by the end of the 21st century** (USGCRP 2014).

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Chapter 10 Endnotes

[a] Sources: Murakami et al. 2013, USGCRP 2014
[b] Sources: DOE 2013, PRCCC 2013b, USGCRP 2014
[c] Source: USGCRP 2014
[d] Sources: DOE 2013, IPCC 2014, PRCCC 2013a, USGCRP 2014
[e] Sources: NOAA 2013, PRCCC 2013a
[f] Sources: Bérubé et al. 2007, DOE 2013, NOAA 2013, PRCCC 2013a, PRCCC 2013b
[g] Sources: API 2014, OMPO 2011, NOAA 2013, PRCCC 2013a, PRCCC 2013b, USGCRP 2014
[h] Source: PRCCC 2013b, HDOT 2013
[i] Sources: DOE 2013, IPCC 2014, OMPO 2011, PRCCC 2013a, PRCCC 2013b, USGCRP 2014
[j] Source: PRCCC 2013b, OMPO 2011
[k] Sources: DOE 2013, Hawaiian Electric 2013, PRCCC 2013b, PREPA 2013
[l] Source: PRCCC 2013b
[m] Sources: DOE 2013, NOAA 2013, PRCCC 2013a, USGCRP 2014
[n] Projection of period 2070–2099 compared to 1970–1999 levels, depending on the region and greenhouse gas emissions. Source: NOAA 2013
[o] Source: PRCCC 2013a

11. Discussion and Conclusions

Climate change is already affecting the U.S. energy sector. In recent years, record temperatures, droughts, and floods have damaged energy infrastructure, disrupted energy systems, threatened energy security, and harmed the economies of affected communities and the nation. Climate change projections indicate the potential for more frequent and severe disruptions.

Key conclusions

- Critical energy subsectors are vulnerable to climate change in every region of the nation.
- Efforts to improve climate resilience are underway in every region, but the severe challenges posed by climate change could overwhelm current resilience efforts unless more comprehensive and accelerated approaches are adopted.
- Resilience planning can be improved with better informational resources such as more geographic detail in climate change projections and metrics to help evaluate the value of resilience options.

While climate change impacts will vary by region, all regions will be affected (see Figure 11-1 and text boxes on next page). Region-specific impacts include increasing wildfire mainly in the West. The frequency of the most intense hurricanes are projected to increase in the Atlantic, which threatens the Gulf coast, Atlantic coast, and Puerto Rico. Permafrost thaw is a critical impact in Alaska.

Some vulnerabilities span regional boundaries, particularly where climate change projections and the existing energy infrastructure are similar. Increasing annual temperatures and more intense, frequent, and prolonged heat waves are expected to affect electricity generation, transmission, and demand in nearly every region. Nearly all coastal regions are expected to experience effects of sea level rise on energy infrastructure.

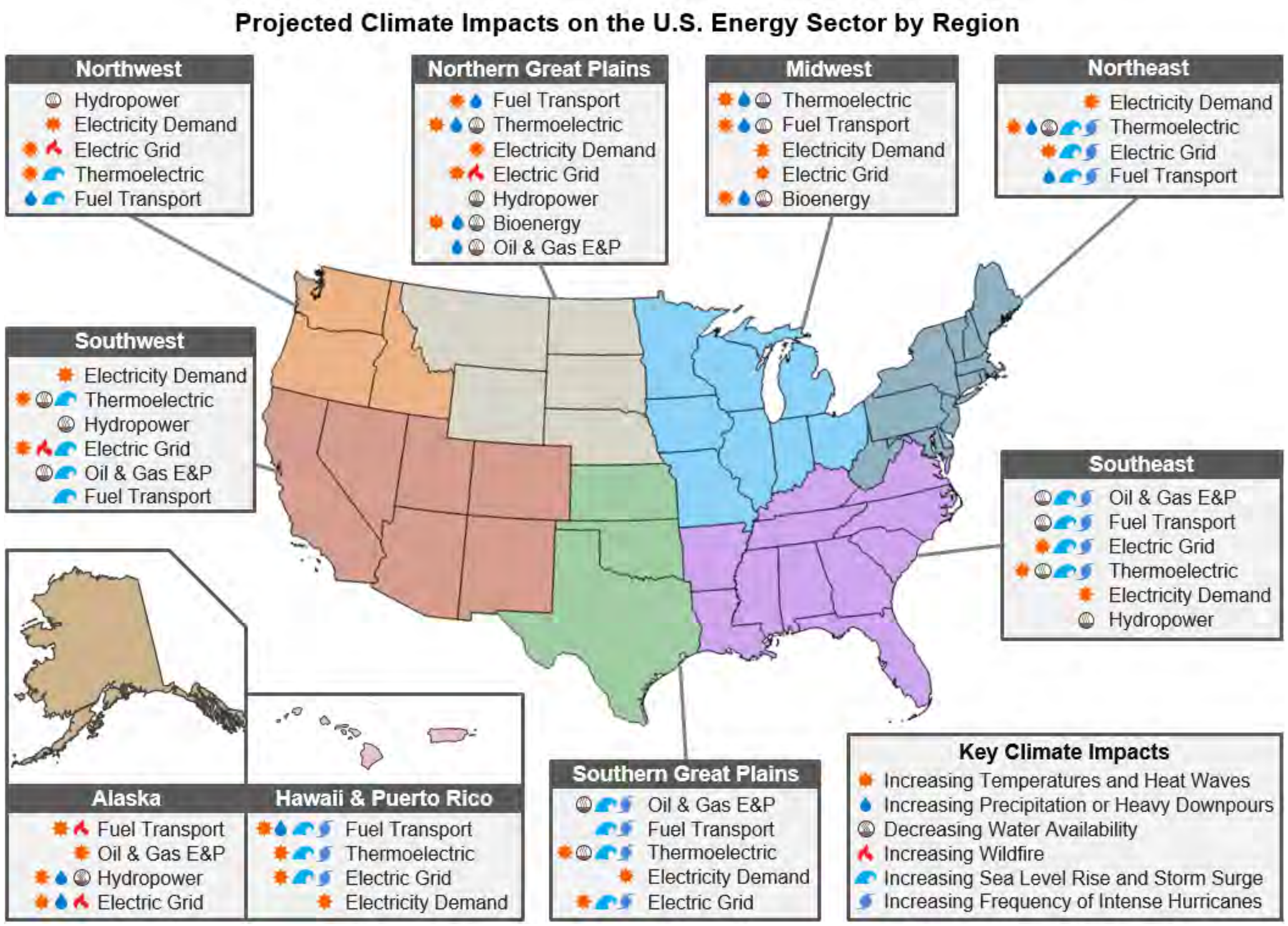

Figure 11-1. Potential climate change impacts on the U.S. energy infrastructure vary by region. Energy subsectors considered most vulnerable to projected climate impacts shown first within each region.

Key climate impacts regional summary

- Increasing temperatures and more frequent and severe heat waves will affect all regions and nearly every energy subsector.
- More frequent heavy rainfall events are a significant threat to infrastructure primarily in northern regions.
- Decreasing water availability is projected to affect energy systems in most regions, particularly in western and southern regions.
- Increasing wildfire impacts are concentrated in western regions.
- Rising sea levels and greater storm surge are increasingly important in nearly all coastal regions, particularly Gulf and Atlantic coastlines.
- Increasing hurricane intensity and frequency of intense hurricanes are a major hazard for regions with Gulf and Atlantic coastlines, including Puerto Rico.
- Thawing of permafrost threatens important energy systems in Alaska.

Major energy systems affected by regional climate impacts

- Oil and gas exploration and production operations are most vulnerable to climate impacts in the Southeast, Southern Great Plains, and Alaska.
- Fuel transport in every region is vulnerable to a variety of climate impacts, such as increasing heavy precipitation, heat waves, droughts, hurricanes, and sea level rise-enhanced storm surge.
- Thermoelectric power generation is vulnerable to increasing temperatures and reduced water availability in most regions, particularly in the Midwest, Great Plains, and southern regions.
- Hydropower is vulnerable to reduced snowpack, earlier melting, and changes to precipitation patterns, mainly in western regions.
- Bioenergy crops in the Midwest and Northern Great Plains may be harmed by higher temperatures and more frequent droughts and floods.
- Electric grid operations and infrastructure are threated in every region by a variety of climate impacts, including increasing temperatures, heavy rainfall events, wildfires, hurricanes, and storm surge.
- Electricity demand is affected by increasing temperatures and is a key vulnerability in nearly every region.

Climate change impacts depend on changes to regional climates and the types of energy systems. At least four critical energy subsectors in each region exhibit important vulnerabilities to changing climate conditions. Climate impacts to the electric grid, thermoelectric power generation, fuel transport, and electricity demand will be manifested in nearly every region. In Figure 11-1, the subsectors in each region that are considered most vulnerable are listed first.[1]

As demonstrated in this report, the large majority of climate change impacts on the energy sector will increase the risk of damage to infrastructure and disruption of systems and services; however, some changes may prove beneficial to existing systems or create new energy opportunities. For example, warmer winter temperatures may significantly reduce energy consumption for heating, especially in northern states, reducing the winter burden on fuel transport systems. Reduced sea ice in the Arctic may open new shipping lanes and offshore oil exploration opportunities. In the Midwest and Northern Great Plains, northern states may see expanded growing seasons that allow the cultivation of new crops.

Across all regions, energy system planners, owners, and operators are taking steps to prepare for climate change by identifying vulnerabilities, investing in more resilient infrastructure, improving operations, and planning for rapid recovery from damages that do occur. In some instances, future climate hazards and probabilities are already being incorporated into risk management systems; however, the magnitude of the challenges posed by climate change on an aging and already stressed national energy system could overwhelm current efforts. The appendix provides an extensive set of resilience actions undertaken or under consideration by planners, owners, and operators.

[1] The order of subsector vulnerabilities is based on judgments by the report authors as well as experts from government agencies, national laboratories, and private sector energy companies. Key factors in assessing relative vulnerability include the extent to which the subsector is expected to be affected by projected climate changes, the prevalence or size of the affected subsector in the region, the implications of damage and disruption to the subsector from projected climate impacts, and the effort required for the subsector to adapt or respond with resilience solutions.

Key challenges

The design and deployment of a 21st-century U.S. energy sector that provides enhanced reliability and climate resilience will encounter a number of key challenges. Figure 11-2 summarizes these challenges, which are grouped into four categories: technological, informational and behavioral, institutional, and policy-related.[2]

Technological challenges include the increased upfront costs that energy asset owners are likely to incur in adopting new technologies that improve resilience, such as costs related to financing, capital, operations and maintenance, and business interruptions. For example, some technologies that can enhance resilience to reduced water availability, such as dry cooling or wet-dry hybrid cooling, may impose higher capital costs upfront while the benefits are distributed over several decades. Innovative technologies may also bring additional uncertainties about performance that complicates financing or insurance. In other situations, proven, cost-effective resilience technologies and systems may be limited in availability or may not exist. In addition, the nation's energy infrastructure is an interconnected, networked system, which may complicate implementation of some resilience solutions that require the effective coordination of many stakeholders.

Informational challenges prevent access to or full understanding of climate projections, vulnerabilities, and resilience solutions. Scientific uncertainty about climate change impacts, including the severity and geographic distribution of certain impacts, can significantly inhibit resilience investments. Planners may lack access to projections of local climate impacts that could support decision making on local resilience solutions, such as facility siting and hardening measures. Informational challenges also arise in translating climate projections into specific actions for energy asset planners, owners, and operators.

Informational shortcomings about both the costs of climate change impacts as well as the benefits of investments in resilience may impede the ability of energy sector owners to make an attractive business case for resilience actions. The lack of metrics, tools, and best practice guidelines increases uncertainty about vulnerabilities and the potential value of resilience solutions. Currently accepted metrics may not always be appropriate to guide companies in planning and defending resilience investments or measuring progress over time. For example, several of the electricity sector's broadly accepted reliability metrics (e.g., SAIDI, SAIFI, CAIDI) often exclude major outage events, making it harder to justify investments that would improve resilience to these types of events. Moreover, poor understanding of costs and benefits can undermine the ability of energy companies to make resilience investment decisions, which requires comparing critical infrastructure damage or loss that could occur in the absence of such actions. Behavioral challenges include overcoming and

Technological/Financial
➢ **Lack of cost-effective, commercially available technologies**: There is a lack of commercially available climate-resilient technologies with acceptable capital, operation, and maintenance costs.
➢ **Early mover risk:** Unproven or untested performance of first-of-a-kind solutions increases risks and decreases access to, or cost of, financing.
➢ **Business interruption costs:** Implementing resilience solutions at existing operations may require temporary downtime and loss of revenue.
Informational/Behavioral
➢ **Lack of relevant information:** Available information is insufficient to identify vulnerabilities and support informed decision making about climate resilience solutions.
➢ **Poor understanding of costs and benefits:** Limited information is available on the costs to design, implement, and operate new resilience technologies and practices, and on how to evaluate the associated benefits.
➢ **Lack of trained workforce**: Few personnel possess expertise in climate impacts, vulnerabilities assessment, and resilience planning and implementation.
➢ **Established practices:** Entrenched methods and priorities, along with limited understanding by affected parties of climate change, may influence resilience decision making.
Institutional
➢ **Limited knowledge-sharing platforms:** The diverse, competitive, and fragmented energy sector impedes information sharing and slows technological change and coordination.
➢ **Competing objectives of different stakeholders:** Differing incentives for participants in the energy economy can lead to conflicting objectives.
Policy
➢ **Lack of policies that internalize social benefits:** Current policies may not sufficiently help energy system owners and operators internalize the social benefits associated with improving climate resilience.
➢ **Policy uncertainty:** Lack of clarity regarding future public policy can create uncertainty and adversely affect investments in climate resilience.
➢ **Competing policy goals:** Climate resilience may conflict or compete with other policy goals.

Figure 11-2. Key challenges to enhanced climate resilience in the energy sector

[2] Various frameworks have been developed to help stakeholders understand the challenges of increased climate resilience, including one presented in the Third National Climate Assessment for the economy as a whole (USGCRP 2014).

updating entrenched methods, proecedures, practices, and priorities.

A knowledgable workforce with a better understanding of climate change and the real-world interactions of complex energy systems will facilitate successful identification of climate change vulnerabilities. For example, improved understanding of how both electricity demand and system capacity respond to changes in temperature in different regions would help utilities and markets prepare for potential climate change impacts. Characterizing these relationships would assist resource planning by the utilities. Similarly, planners need economic models that consider energy demand relative to other factors, such as population growth and new technology adoption. Key weaknesses in current climate models include the projection of non-cyclonic storms (e.g., convective storms, winter storms, and tornados), which are especially important for some energy subsectors and regions, and detailed projections of hydrology-precipitation interactions, particularly in watersheds with significant hydropower generation.

Improved informational resources are needed to assess the potential limitations of resilience actions over a range of spatial and temporal scales (including high-impact/low-probability events). Improved approaches could better characterize both the individual and aggregate climate change vulnerabilities of energy systems and better understand the interdependencies among sectors (e.g., manufacturing, transportation, communications, water supply and treatment, and health care) that can lead to cascading impacts.

<u>Institutional challenges</u>, such as the lack of comprehensive platforms for open information exchange, may impede organizations from sharing information. Competing interests among stakeholders—both internal and external—can also hinder organized responses to climate risks. Such fragmentation can prevent certain resilience solutions from becoming more widespread.

<u>Policy challenges</u> include uncertainty about future policy decisions or the duration of current policies that can undermine confidence in otherwise justified business decisions, diminishing the effectiveness of government incentives. For example, the rate of new U.S. wind power installations over the past two decades reflect the multiple lapses in and reinstatement of federal incentives for construction of new wind capacity. Competing objectives among policymakers can also inhibit resilience investments. For example, new transport capacity that may alleviate a critical chokepoint in a fuel supply chain may be opposed by stakeholders for environmental, safety, or other reasons.

The federal government can help address these challenges and fill an important role in protecting the nation's economy and natural resources, promoting sound management of climate risks, and supporting local efforts to build stronger communities and infrastructure. Accordingly, the U.S. Department of Energy is taking the following actions:

- Facilitating basic scientific discovery
- Enhancing research, development, demonstration, and deployment of innovative energy technologies that strengthen climate resilience
- Providing technical information and assistance
- Fostering the adoption of enabling policies
- Convening and partnering with states, communities, and the private sector

These actions will help to ensure that energy system planners, owners, and operators act on the most relevant and geographically-specific information available and use cost-effective and appropriate energy technologies to address climate change risks. Local and regional energy investments need to consider climate vulnerabilities and resilience options to implement the technologies and designs best suited to the unique needs of each region.

While government agencies as well as non-governmental organizations and the academic community have roles to play in overcoming these challenges, companies that own and operate the energy systems are primarily responsible for proactively assessing their assets for vulnerabilities and implementing resilience actions. Active information exchange will contribute to a positive feedback loop and improve access to critical information needed for decision making (Figure 11-3).

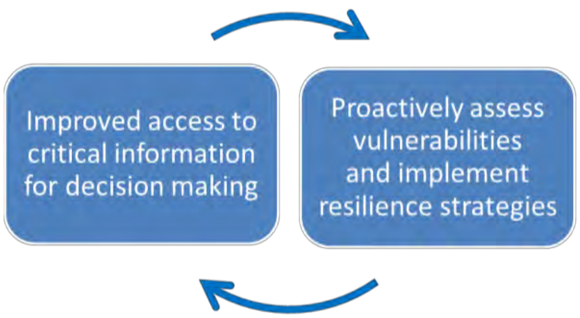

Figure 11-3. Process of increasingly effective planning and investments in climate resilience

Regional Interdependencies

Interdependencies across regions and sectors affect the ability of decision makers to incorporate regional climate projections into their risk management approaches. Components of the U.S. infrastructure for energy generation, transmission, storage, and distribution are growing increasingly complex and interdependent. Connections can span regions (interregional dependencies), energy subsectors (intrasectoral dependencies), and economic sectors (intersectoral dependencies). Energy

Table 11-1. Examples of regional dependencies

Dependencies	Energy Subsectors	Resilience and Vulnerability Examples
Interregional	Electric Grid	**Resilience:** Interregional power transmission allows power to be imported when local capacity for generation is curtailed. **Vulnerability:** The Northeast blackout of 2003 started with transmission line failures due to high heat in the Midwest, spreading the vulnerability across regions (DOE 2004).
	Oil and Gas Exploration and Production	**Resilience:** In 2005, Hurricanes Katrina and Rita disrupted production and refining activities in the Gulf of Mexico, and petroleum prices increased; however, demand could still be met from production in other regions (EIA 2005, EIA 2015).
	Electricity Demand	**Resilience:** Increased summer electricity demand in the Southwest is met using hydropower production from the Northwest, where summer temperatures are more moderate .
Intrasectoral	Electric Grid and Fuel Transport	**Vulnerability:** Power outages in the Northeast following Hurricane Sandy interrupted both the supply of petroleum products to the region (via the Colonial Pipeline) and the distribution of fuel through pumping stations.
	Fuel Transport and Thermoelectric Power Generation	**Vulnerability:** Damage to the Joint Line Railroad in Wyoming's Powder River Basin in 2005 delayed deliveries of coal, forcing power plants in the Midwest to draw down stockpiles and reduce summer production (DOE 2007).
	Electric Grid and Electricity Demand	**Vulnerability:** A 2007 wildfire in California halted operation of a major transmission line that supplies power to San Diego, requiring the area's utilities to reduce demand by 500 MW and nearly causing rolling blackouts (PPIC 2008).
Intersectoral	Health Care	**Vulnerability:** Following Hurricane Katrina in 2005, extended power outages shut down New Orleans' Memorial Medical Center for several days (Fink 2009).
	Emergency Services	**Vulnerability:** During the northeast blackout of 2003, Detroit's computer-aided dispatch system for the police and fire departments failed to operate reliably and communications were disrupted when cellular sites lost power (Kilpatrick 2003).
	Financial Systems	**Vulnerability:** Power outages in New York City's Financial District caused by Hurricane Sandy resulted in a two-day halt in trading on the New York Stock Exchange (NYSE)—the longest weather-related shutdown in more than a century (Brown 2012).

sector interdependencies can exacerbate—or ameliorate—the vulnerability of energy systems to climate impacts. Table 11-1 lists examples of these interdependencies affecting energy sector vulnerability or resilience.

Interregional dependencies are evident in the electric grid. The contiguous United States is served by three independent grids: the Eastern Interconnection (serving the Northeast, Southeast, and Midwest, as well as parts of the Northern and Southern Great Plains), the Western Interconnection (serving the Northwest, Southwest, and some of the Northern Great Plains), and the Electricity Reliability Council of Texas (ERCOT). These three grids allow power generated in one part of a grid to serve loads elsewhere. In so doing, they spread out variations in demand and supply, minimizing costs and the likelihood of shortages. For example, annual hydropower production in the Northwest peaks in early summer, but that region's temperate climate means that few households regularly use air conditioning (EIA 2011, EIA 2013a); as a result, some of California's peak summer air conditioning demand can be met by importing low-cost hydropower from the Northwest over the grid (EIA 2011). This interregional connection makes California's electricity sector less vulnerable to high summer temperatures. Conversely, power grids also extend energy system vulnerabilities from one region to another. For example, synchronized transmission grids must be carefully balanced so that disruptions at any point on these grids do not affect the rest of the network. In August 2003, high heat and transmission line outages in the Midwest caused power outages for 50 million customers across the northeastern United States and Canada (DOE 2004).

The fuel supply network offers another example of interregional dependency. The Gulf Coast is home to more than 50% of U.S. refining capacity, supplying oil products across the eastern half of the country. The high density of oil infrastructure that supplies a large area means that a single event, such as a strong hurricane making landfall in the Gulf region, can disrupt fuel supply across several regions. One strategy to mitigate risks related to this interregional dependency may be to develop strategic regional stockpiles of oil and refined petroleum products to help respond to shortfalls. For example, the federal government has established regional product reserves (e.g., Northeast Home Heating Oil Reserve, Northeast Gasoline Supply Reserve), and New York State, NYPA, and others are planning to set up a strategic fuel reserve for gasoline and diesel fuel to provide short-term supply in the event of a shortage (NYPA 2014, DOE 2015, NY Storm Recovery 2015).

Intrasectoral dependencies reflect the interplay between energy subsectors, such as power plants that rely on fuel delivered by gas pipeline or fuel stations that rely on the electric grid. The impacts of Hurricane Sandy on the Northeast's energy system illustrate such vulnerabilities (see text box on next page). Although the region's main sources of gasoline were temporarily disrupted following the storm (including petroleum terminals and the Colonial Pipeline), the primary cause of gasoline shortage in the area was the lingering power outages that prevented use of (electrically powered) gasoline pumps at fueling stations.

Mitigation of energy disruptions has become increasingly important as interdependencies grow and put other critical sectors at risk. Intersectoral dependencies affect nearly every sector of the economy (e.g., transportation, communications, food and agriculture, manufacturing, health care, and financial systems). For example, the transportation sector requires energy to supply motive power, while the energy sector relies on transportation to deliver the necessary coal, oil, and natural gas to operate. Likewise, the communications sector requires electricity to operate, while the energy sector increasingly requires communications systems to monitor and manage the electric grid. As a result, disruptions in energy supply can lead to cascading disruptions in multiple sectors. The crosscutting nature of these issues may illuminate opportunities for improvement and collaboration across government agencies, state and local planning authorities, universities, the private sector, and other organizatons.

Hurricane Sandy: Example of impacts from intrasectoral dependencies

Hurricane Sandy brought devastating storm surge flooding and high winds to the Northeast. The storm damaged more than 7,000 transformers and 15,000 poles across the region, and more than 8 million customers lost power in 21 states (DOE 2012, DOE 2013). The power outages caused extended fuel shortages, leading to fuel rationing in New Jersey, New York City, and Long Island.

The storm damage included significant impacts to petroleum infrastructure, and the area experienced major gasoline shortages. Flooding caused fuel terminals in New York City to lose power and delayed shipments for a week or more. The storm also shut down the Colonial Pipeline (a major source of gasoline for the region) for four days (ICF 2014, NYC 2013). Six refineries were either temporarily shut down or forced to reduce their output (DOE 2012). Even after many gas stations had been resupplied with gasoline, they could not provide fuel to customers because they did not have electricity to power the pumps (Nahmias 2013).

Planning in uncertainty

Any projection of the future carries inherent uncertainties. While many broad climate trends are projected with high certainty at a national scale (e.g., increasing temperatures), projections at the regional level are subject to a degree of uncertainty that can make it difficult for energy stakeholders to devise effective climate resilience strategies. On the other hand, planning and managing energy investments based on climate norms of the last century presents risks that could result in significant costs to local communities and the U.S. economy. The need to prepare now for a wide range of future climate impacts is heavily underscored by three factors: the typical service life of energy assets (several decades in most cases), the cost of the associated investments (e.g., more than a billion for some new power plants), and the pace and magnitude of the projected changes (EIA 2013b).

Planners often need to make decisions with limited knowledge of future conditions, and energy sector managers and investors are experienced at operating in the presence of unknowns. Given the long service lifetimes for most energy infrastructure, decision makers must consider long-term climate trends, such as those projected for 2050 and beyond. Recognizing this timeframe, near-term resilience actions should seek to extend system flexibility. For example, planners today might assess vulnerabilities and consider resilience as part of routine infrastructure improvement efforts (e.g., selecting less vulnerable locations when replacing critical energy infrastructure). Planners in all regions would benefit from identifying near-term opportunities to enhance energy sector resilience to climate change and extreme weather.

Resilience actions identified in this report are largely based on today’s technologies, which will evolve and expand over the next several decades. For example, advances in distributed generation and energy storage technologies may produce revolutionary shifts in the way electricity is generated, delivered, and used. As new technologies are increasingly adopted, validated, and standardized, barriers to their use can fall. In addition, energy demand patterns may change radically as a result of population shifts and new devices and technologies, such as electric vehicles. The Southwest, for instance, in addition to becoming hotter and significantly drier, is expected to increase its population 68% by 2050 (USGCRP 2014), greatly increasing demand and load. These changes may affect both energy sector vulnerability and the appropriateness of specific resilience actions.

A robust strategy for building energy sector resilience will need to be responsive to these changes. It will require regular dialogue and information sharing among industry, government, technical institutions, and non-government organizations active in basic and applied research, energy system planning, siting, and resilience policy development. It will need to embrace multiple elements, to include:

- Lower-carbon power generation
- Innovative technologies for improving the efficiency and reliability of operations
- Strategic rebuilding after disasters (e.g., siting key energy infrastructure in less vulnerable locations)
- Designing energy assets that can withstand more extreme events

Building a 21st-century energy system that is resilient to the impacts of climate change and extreme weather is not a quick or easy process; however, current and projected climate change impacts dictate a strong need for common sense to guide near-term actions and investments. Smart decisions today will help to provide a robust and resilient energy infrastructure that serves all citizens and economic goals at the local, regional, and national levels.

Chapter 11 References

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Appendix: Illustrative List of Energy Sector Climate Change Resilience Solutions

Type of Measure	Climate change impacts: *Increasing temperatures and heat waves*	*Increasing precipitation or heavy downpours*	*Decreasing water availability*	*Increasing wildfire*	*Increasing sea level rise and storm surge*	*Increasing frequency of intense hurricanes*
1. Oil and Gas Exploration and Production						
Hardening	• Engineer structures in permafrost areas with design criteria suited for warming • Insulate or ventilate underlying permafrost, such as construction of a gravel pad of appropriate depth or the use of thermal piles	• Enhance levees and floodwalls • Elevate critical equipment • Install emergency backup generators for critical operations	• Use alternative water supplies, such as degraded water, wastewater, brackish water, or produced water	• Install emergency backup power, such as diesel generators, for critical operations	• Install sea walls, riprap, and natural barriers such as vegetation • Elevate critical equipment	• Install emergency backup generators for critical operations • Incorporate more robust design specifications for equipment in hurricane zones • Locate rigs on more stable areas of sea floor • Brace vulnerable equipment to protect from wind damage
Planning and operations	• Update design and operations guides for equipment operating in Arctic Alaska	• Update design, siting, and operations plans to account for heavy runoff and possible increasing floods	• Update plans for securing water to consider decreasing water availability	• Update wildfire response plans to account increasing frequency and severity	• Update siting and operations plans to account for SLR	• Update design criteria for new equipment in hurricane zones to account for extreme wind loading • Update engineering and operations guidance and storm plans to account for higher frequency of intense hurricanes

	Climate change impacts					
Type of Measure	*Increasing temperatures and heat waves*	*Increasing precipitation or heavy downpours*	*Decreasing water availability*	*Increasing wildfire*	*Increasing sea level rise and storm surge*	*Increasing frequency of intense hurricanes*
2. Fuel Transport						
Hardening	• Upgrade thermosyphons to avoid damage from permafrost thaw	• Enhance berms, levees, and floodwalls • Install riprap along bridge piers • Elevate or relocate infrastructure, including railroads, pump stations, and bridges • Install emergency backup generators for critical operations such as pumping stations and refueling centers • Upgrade drainage systems and ensure culverts can handle increased runoff • Bury pipelines deeper underground using horizontal directional drilling • Install barriers or vegetation above pipelines to reduce the risk of erosion • Use pipeline materials that are less likely to leak or rupture from impacts (e.g., coated steel rather than cast iron or bare steel) • Anchor tanks or add product to increase tank weight and prevent floating	• Dredge critical sections of waterways prone to low water levels	• Protect selected above-ground pipeline segments with insulation and fire-resistant jacketing	• Install sea walls, riprap, and natural barriers such as vegetation • Elevate or relocate infrastructure (e.g., railroads, pump stations, and bridges) • Install watertight doors for low-lying equipment • Use pipeline materials that are less likely to leak or rupture from impacts (e.g., coated steel rather than cast iron or bare steel) • Relocate particularly vulnerable assets • Anchor tanks or add product to increase tank weight and prevent floating	• Install emergency backup generators for critical operations such as refueling centers • Install wind girders on fuel storage tanks

	Climate change impacts					
Type of Measure	*Increasing temperatures and heat waves*	*Increasing precipitation or heavy downpours*	*Decreasing water availability*	*Increasing wildfire*	*Increasing sea level rise and storm surge*	*Increasing frequency of intense hurricanes*
Planning and operations	• Incorporate future temperature projections into design when replacing road materials and rail equipment • Upgrade road and rail integrity and inspection programs • Update monitoring regimes for roads, pipelines, and other infrastructure located on permafrost • Reduce speed of freight trains on vulnerable rail segments during high temperatures	• Update design, siting, and operations plans to account for heavy runoff and possible increasing floods • Upgrade road and rail integrity and inspection programs • Identify alternative transport routes for use during flood events • Increase fuel stockpiles at or near customer sites • Increase use of local energy resources to reduce dependence on fuel transport	• Update design, siting, and operations plans to account for possible low-water conditions • Identify alternative transport routes for low-water periods	• Update design, siting, and operations plans to account for increasing wildfire • Utilize improved vegetation management practices that keep rights-of-way clear	• Update design, siting, and operations plans to account for SLR	• Apply extreme wind loading design criteria for critical equipment • Update storm plans, including alternative transport routes, to account for higher frequency of intense hurricanes • Increase fuel stockpiles at or near customer sites
3. Thermoelectric Power Generation						
Hardening	• Increase or install additional generation capacity	• Enhance levees and floodwalls • Install waterproofing measures such as concrete moat walls, floodgates and watertight doors, sluice gates, reinforced walls, pressure resistant/ submarine-type doors in deep basements, expansive polymer foam in conduits, submersible pumps • Elevate critical equipment	• Install water-saving cooling technology (e.g., closed-loop cooling, hybrid wet-dry cooling, dry cooling) • Install equipment capable of using alternate water sources (e.g. brackish groundwater, municipal wastewater) for cooling		• Install sea walls, riprap, and natural barriers such as vegetation • Install waterproofing measures, such as concrete moat walls, floodgates and watertight doors, sluice gates, reinforced walls, pressure resistant/ submarine type doors in deep basements, expansive polymer foam in conduits, submersible pumps • Elevate critical equipment	• Reinforce elevated structures (e.g., cooling towers, water towers, smokestacks, etc.) for greater wind loading and potential wind-driven debris

	Climate change impacts					
Type of Measure	*Increasing temperatures and heat waves*	*Increasing precipitation or heavy downpours*	*Decreasing water availability*	*Increasing wildfire*	*Increasing sea level rise and storm surge*	*Increasing frequency of intense hurricanes*
Planning and operations	• Update integrated resource plans to account for reduced available generation capacity from higher temperatures	• Update design, siting, and operations plans to account for possibility of increasing floods	• Secure back-up water supply in case of low flow conditions • Install monitoring systems on source water supplies • Develop operating procedures for low water conditions		• Update design, siting, and operations plans to account for SLR	• Develop alternative fuel delivery options • Maintain larger fuel inventory onsite • Apply extreme wind loading design criteria for critical equipment • Develop or update storm plans to account for higher frequency of intense hurricanes
4. Hydroelectric Power Generation						
Hardening		• Reinforce structures and upgrade equipment to accommodate high flow periods	• Increase storage capacity of reservoirs • Increase turbine efficiency and minimize water leaks at existing dams			
Planning and operations	• Update integrated resource plans to account for reduced available generation capacity • Incorporate thermal predictive models into reservoir level forecasts	• Update design and operation plans to account for altered precipitation patterns (e.g., heavy streamflow events, reduced snowpack; summer drought)	• Develop integrated water management plan that accounts for changing water availability • Manage reservoir capacity (e.g., maintain higher winter carryover storage levels, reduce conveyance flows in canals and flumes, and reduce discretionary reservoir water releases) • Install monitoring systems on rivers with telemetry to increase data availability, trending, and station response times • Develop operating procedures for low water conditions • Improve forecasts of snowmelt timing based on snowpack and temperature trends			

Type of Measure	Climate change impacts *Increasing temperatures and heat waves*	*Increasing precipitation or heavy downpours*	*Decreasing water availability*	*Increasing wildfire*	*Increasing sea level rise and storm surge*	*Increasing frequency of intense hurricanes*
5. Bioenergy and Renewable Power Generation						
Hardening	• Increase or install additional generating capacity	• Enhance levees and floodwalls • Elevate critical equipment	• Use alternative water supplies at biorefineries (e.g., degraded water or wastewater) • Employ sustainable agriculture methods including crop diversification, crop rotation		• Install sea walls, riprap, and natural barriers such as vegetation • Elevate critical equipment or enclose equipment in submersible casings	
Planning and operations	• Update design plans for increasing temperatures	• Develop alternative fuel delivery options • Maintain larger fuel inventory onsite	• Update plans for securing water considering decreasing water availability	• Account for increased wildfire risk when siting facilities • Incorporate increased wildfire risk into forest management practices, such as frequency of prescribed burns and reduction of hazardous fuels to prevent uncontrolled fire depleting woody biomass resources	• Update design, siting, and operations plans to account for SLR	• Develop alternative fuel delivery options • Maintain larger fuel inventory onsite • Apply extreme wind loading design criteria • Develop or update storm plans to account for higher frequency of intense hurricanes
6. Electric Grid						
Hardening	• Limit customers affected by outages by installing additional substations and breakaway equipment, and by sectionalizing fuses; develop island-able “microgrids” • Upgrade transformers (e.g., forced-air or forced-oil cooling) • Install smartgrid devices that to speed identification of faults and service restoration • Increase or install additional transmission capacity	• Increase redundancy in transmission system • Enhance levees and floodwalls • Limit customers affected by outages by installing technology such as microgrids, additional substations, sectionalizing fuses, and breakaway equipment • Underground critical transmission and distribution lines • Install waterproofing measures, such as floodgates and watertight		• Increase redundancy in transmission system • Limit customers affected by outages by installing additional substations and breakaway equipment, and by sectionalizing fuses; develop island-able “microgrids” • Replace wood poles and support structures with fire-resistant materials (e.g., steel or concrete) • Install smartgrid devices to speed identification of faults and service restoration	• Install sea walls, riprap, and natural barriers such as vegetation • Limit customers affected by outages by installing additional substations and breakaway equipment, and by sectionalizing fuses; develop island-able “microgrids” • Replace wood poles and support structures with stronger materials (e.g., steel or concrete) • Elevate or relocate critical equipment • Install smartgrid devices to	• Increase redundancy in transmission system • Limit customers affected by outages by install technology such as microgrids, additional substations, sectionalizing fuses, and breakaway equipment • Replace wood poles and support structures with stronger materials (e.g., steel or concrete) • Underground critical transmission and distribution lines • Replace ceramic insulators

	Climate change impacts					
Type of Measure	*Increasing temperatures and heat waves*	*Increasing precipitation or heavy downpours*	*Decreasing water availability*	*Increasing wildfire*	*Increasing sea level rise and storm surge*	*Increasing frequency of intense hurricanes*
	• Install breakable links and towers designed to tolerate lateral movement of foundation in event of uneven permafrost thaw and frost heave	doors, sluice gates, reinforced walls, pressure resistant/ submarine type doors in deep basements, expansive polymer foam in conduits • Elevate or relocate critical equipment			speed identification of faults and service restoration	with polymer • Install smartgrid devices to speed identification of faults and service restoration • Utilize mobile transformers and substations
Planning and operations	• Develop best operating practices for equipment at high temperatures • Include extreme temperature scenarios in future grid planning • Deploy future equipment and lines with higher design temperatures	• Site equipment in areas less prone to flooding • Install water level monitoring systems and communications equipment inside vulnerable substations		• Site equipment in areas less prone to wildfire • Enhanced vegetation management (e.g., tree trimming, forest thinning, and prescribed burning) • Develop fire response plans and tools; coordinate with local partners • Develop firefighting compounds safe to use near active power lines	• Site equipment in areas less prone to coastal flooding • Install water level monitoring systems and communications equipment inside vulnerable substations • Update siting and operations plans to account for SLR	• Apply extreme wind loading design criteria to critical infrastructure • Site equipment further from coast • Enhance vegetation management programs • Update storm plans to account for higher frequency of intense hurricanes
7. Electricity Demand						
Hardening	• Implement weatherization programs • Install energy efficient equipment • Increase generation and transmission capacity • Invest in grid-scale energy storage systems		• Implement water and energy efficient technologies and practices to reduce energy demand for water production, pumping, and filtration			
Planning and operations	• Update resource plans to accommodate projected increases in CDDs and decreases in HDDs • Implement programs that incentivize and encourage energy efficiency • Implement load management and demand side response programs		• Emphasize water efficiency in buildings, industrial processes, municipal utilities, and in other areas to reduce energy demand for water production, pumping, and filtration			

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