Dams and Energy Sectors Interdependency Study

An Update to the 2011 Study

2017

Homeland Security

U.S. DEPARTMENT OF ENERGY

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Executive Summary

This study updates the September 2011 *Dams and Energy Sectors Interdependency Study*. The U.S. Department of Energy (DOE) and the U.S. Department of Homeland Security (DHS) collaborated to examine the interdependencies between two critical infrastructure sectors—Dams and Energy. Although hydroelectric facilities fall under the Dams Sector, they are also important to the Energy Sector because the electric power they generate is critical to maintaining the reliability of the Nation's electricity supply. This joint effort underscores the value of a cross-sector partnership model in the identification and discussion of issues significant to dam and utility owners and operators, which can help enhance resilience.

The study particularly focuses on the importance of hydroelectric power generation and the major risk factors that affect the ability of hydropower facilities to produce the electricity they need at the right time. The majority of owners and operators interviewed during this study identified changes in temperature and weather patterns as the biggest, long-term challenge facing the sector. Shifting weather and temperature patterns could fundamentally change the operations of existing facilities, and—as water sources continue to deplete—threaten their viability. Concurrently, increasing competition for water resources, requirements for environmental stewardship, an evolving power industry, and other factors may continue to affect hydropower operations. The study identified the following key risk factors for hydropower:

- **Weather variability and extreme weather events:** Increased temperatures, persistent droughts, and shifts in weather patterns—such as earlier snowmelt and winter rain replacing snow—can greatly affect water resource availability. Continued droughts may deplete water while increasing water demand; conversely, shifting rainfall patterns can create dangerous flooding or make water available earlier in the season during off-peak demand, decreasing hydropower's ability to provide a competitive peaking product in summer months.
- **Shifts in hydroelectric power generation patterns:** Lower streamflows resulting from drought, upstream dams, and diversions decrease water availability and can reduce hydropower production, particularly when exacerbated by competing demands and operational constraints. Shifting precipitation and snowmelt patterns may increase hydropower generating capacity during periods of low demand and/or decrease capacity during peak periods. Flooding can make it difficult for owners and operators to manage hydropower production since water often needs to be released from reservoirs to accommodate flood water.
- **Competing water resource needs, authorities, and requirements:** Hydroelectric facilities draw water from dams that may serve multiple purposes, including flood control, recreation, industrial and community water supply, irrigation, and transportation. Environmental regulations can constrain operations, including water releases to protect fish species. Conflicting demands for water use, levels, flows, and conditions may limit the availability of water for hydropower generation.
- **Effects from the evolving power industry and growing renewable resource use:** Growth in the wind and solar industries—including potential future growth spurred by the Clean Power Plan (CPP)—and the development of more efficient thermoelectric technologies may change the energy mix in regions that depend heavily on hydroelectric power and affect when and how hydropower is primarily used. Lower natural gas prices could also affect the demand for hydropower.
- **Additional emerging risks:** Cybersecurity is particularly critical for hydropower operations that use digital systems to control physical power generation and delivery processes. Aging dams can also have seepage and growth issues that affect generation, and must be assessed regularly. Hydropower facilities also need to address the potential workforce skills gap that could emerge as experienced workers retire.

Many owners and operators are undertaking long-term planning to identify ways to sustain operations and maintain or grow generation of electricity despite changing weather conditions, competing demands, and an evolving industry.

Technology advancements and modernization efforts can allow hydro plants to produce power more efficiently using less water, store off-peak energy, and increase the cost competitiveness of hydroelectricity.

Case studies of three major river systems—the Columbia River, the Colorado River, and the Tennessee River—provide context for various issues affecting hydro dam functions and operations, and show how owners and operators are addressing emerging risks. Additionally, Appendix D presents major findings from the DOE's 2016 *Hydropower Vision Report*, which comprehensively describes the state of the U.S. hydropower industry, models hydropower's contributions and future potential, identifies the positive benefits of hydropower to the Nation, and outlines the path forward through its roadmap activities.

Acknowledgements

This document was developed with input, advice, and assistance from the council members of the Dams Government Coordinating Council (GCC) and Sector Coordinating Council (SCC), which included representatives from public and private sector owners and operators, as well as representatives from DOE and DHS.

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- Avista
- Bonneville Power Administration
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- National Hydropower Association
- Pacific Gas and Electric Company
- Southern California Edison
- Southwestern/Southeastern Power Administrations
- Tennessee Valley Authority
- U.S. Army Corps of Engineers
- U.S. Bureau of Reclamation
- U.S. Federal Energy Regulatory Commission
- Western Area Power Administration
- Xcel Energy

1. Introduction

Hydroelectric power generation managed by the Dams Sector is intricately linked to the Energy Sector's generation and distribution of electric power—particularly in regions where hydropower contributes a significant portion of the electricity generated. Due to these strong interdependencies, a changing risk environment in one sector can affect critical planning and operations in the other.

The *National Infrastructure Protection Plan 2013: Partnering for Critical Infrastructure Security and Resilience* (NIPP 2013) provides an overarching framework for public-private collaboration on security and resilience efforts in the Nation's 16 critical infrastructure sectors.[1] Under the NIPP 2013 framework, each critical sector has developed a public-private partnership, providing a mechanism for owners and operators and other critical infrastructure stakeholders to share information and to actively address sector-wide and cross-sector issues. This study complements the ongoing security and resilience efforts of the Energy and Dams Sectors by examining persistent and emerging risks that may affect interdependent operations, with a particular focus on hydropower operations.

The U.S. Department of Energy (DOE) and the U.S. Department of Homeland Security (DHS) are the designated Sector-Specific Agencies (SSAs) for the Energy and Dams Sectors, respectively. As the SSAs, DOE and DHS support and coordinate security and resilience activities for the Energy and Dams Sectors' critical infrastructure operations:

- Dams Sector assets include dams projects, hydropower generation facilities, navigation locks, levees, dikes, hurricane barriers, mine tailings and other industrial waste impoundments, and other similar water retention and water control facilities.[2]
- Energy Sector assets include the production, refining, storage, and distribution of oil, gas, and electric power, except for hydroelectric and commercial nuclear power facilities.[3]

Hydroelectric facilities are part of the Dams Sector, but are also important to Energy Sector companies, which may own/operate hydropower facilities or depend on the electric power they generate to maintain the reliability of the Nation's electricity supply. The SSAs for the Energy and Dams Sectors collaborated in this report to examine the sectors' shared concerns and interests in hydroelectric power generation.

In addition to reviewing the 2016 *Hydropower Vision: A New Chapter for America's First Renewable Electricity Source* report (see Appendix D. 2016 Hydropower Vision Report), the SSAs conducted exhaustive open-source research on several related topics, including drought, precipitation, weather changes, streamflow regulation, water management and uses, and the operation of hydroelectric facilities (see Appendix E. Sources and References). The SSAs also examined U.S. Energy Information Administration (EIA) annual electricity survey forms 906, 920, 923, and 860 databases to investigate the historical pattern of electric power generation and generating capacity. This analysis focused on hydroelectric power generation at the State level and the plant level from 1990 to 2015.

Following a literature review, DOE and DHS conducted phone interviews with senior personnel from 13 Dams Sector organizations, both public and private, to ascertain the most critical issues they face today and in the near future in the operation of their hydroelectric facilities. Drafts of the study were presented at the Dams Sector Joint Council meeting so

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[1] Critical infrastructure sectors are identified in The White House, Presidential Policy Directive (PPD) 21, 2013.

[2] DHS, *2015 Dams Sector-Specific Plan*, 2015.

[3] DOE and DHS, *2015 Energy Sector-Specific Plan*, 2016.

public and private sector owners and operators could review the report and contribute feedback and additional information.

Hydroelectric power generation is affected by extreme fluctuations in water flow, as well as long-term issues surrounding the management and use of water supplies. Recent droughts affected stakeholders in both the Dams and Energy Sectors. Although recent drought conditions have not caused a serious problem in terms of electricity supply and reliability, they have the potential to affect the operation of dams by decreasing hydropower production, which could result in higher electricity costs to utilities and customers.[4] Other weather-related variables such as air temperature, precipitation, and runoff conditions also affect future water supplies and demands, and may impose operational constraints on dams and utilities that rely on hydroelectric power generation.[5]

The report investigates current and emerging risks to the operation of hydroelectric facilities and the supply of hydroelectric power, especially drought and other extreme weather events. Topics in this report include:

- The increasing frequency of extreme weather events;
- The relationship between hydroelectric power generation and shifts in hydrology and weather patterns;
- How regulations, competing resource needs, and a changing energy mix affect hydroelectric generation; and
- Emerging risks such as cyberattacks, aging infrastructure, staff retention, and an aging workforce.

This joint study highlights the value of the partnership model for identifying and discussing challenges and concerns to cross-sector owners and operators. The ultimate goal of this effort is to help the two sectors enhance their resilience.

1.1 Scope of the Study

This report focuses primarily on issues that relate to electric power generation at hydroelectric dams, including the overall management of reservoirs and streamflows at dams that are affected by the variability of weather patterns. In-depth analysis of certain topics considered outside of the scope of the study is omitted from the report. These include new hydropower technologies, renewable energy credits, the value of hydropower's avoided greenhouse gas emissions, and the effects of reduced hydropower generation on the overall power market.

There are three types of hydroelectric power plants: conventional, pumped storage, and diversion facilities. This report focuses mainly on conventional hydroelectric facilities, which are the most common type of hydroelectric power plant.[6] EIA defines a conventional hydroelectric power plant as a plant in which all of the power is produced from natural streamflow as regulated by available storage.[7] Most pumped storage units have closed-loop systems where water is stored and reused; therefore, electricity production at pumped storage is more resistant to drought or changing weather patterns. The importance and benefits of pumped storage to grid security and operation is described in Section 2.1. Additionally, while the operation of thermoelectric plants is significantly affected by the availability of water, they are not the primary subject of this report.

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[4] DHS, *2010 Dams Sector-Specific Plan*, 2010. For more information about the possible effects of droughts, see U.S. Library of Congress, *Apalachicola-Chattahoochee-Flint (ACF) Drought*, 2007 and DOE, *An Analysis of the Effects of Drought Conditions*, 2009.

[5] United States Army Corps of Engineers (USACE), *Addressing Climate Change in Long-Term Water Resources Planning and Management*, 2011.

[6] Throughout this report, "hydroelectric power," "hydropower," and "hydroelectricity" are used interchangeably.

[7] EIA, "Glossary."

2. Hydroelectric Power in the United States

This section provides an overview of hydroelectric power generation in the United States and the significance of hydroelectric dams in the Energy Sector. It also includes a discussion of where hydropower production is concentrated in key States and regions, and how hydroelectric capacity compared to generation has shifted over the last 15 years.

2.1 Importance of Hydroelectric Dams for Power Generation

Historically, hydroelectricity has been a vital source of electric power generation, accounting for as much as 40 percent of the Nation's electricity supply in the early 1900s.[8] Although the share of hydropower generation has declined to about 6 percent of total U.S. electric power generation, as production from other types of power plants grew at a faster rate, hydroelectric dams remain an important U.S. power source.[9]

Hydropower is critical to the national economy and overall energy reliability because it is:

- The least expensive source of electricity, as it does not require fossil fuels for generation;
- An emission-free renewable source, accounting for about 48 percent of total U.S. annual net renewable generation;[10]
- Able to shift loads to provide peaking power (it does not require ramp-up time like combustion technologies); and
- Often designated as a black start source that can be used to restore network interconnections in the event of a blackout.

U.S. Hydropower Facts:

- As of 2016, hydropower accounted for more than 6% of net U.S. power sector electricity generation, nearly 9% of U.S. electric generating capacity, and 97% of U.S. utility-scale electrical storage capacity.
- Half of the installed capacity is located in three States—Washington, California, and Oregon.
- The top five hydropower-generating States produce more than 65% of total U.S. hydroelectric generation.
- The 20 largest hydroelectric dams produce almost half of total U.S. hydroelectric generation.
- Hydroelectric power generation has declined considerably in the Southwest during the 2013 to 2015 period compared to the historical average, due to severe drought conditions.

Sources: DOE, *Hydropower Vision*, 2016; EIA-906, EIA-920, EIA-923, and EIA-860 databases.

Hydroelectric power uses the force of moving water and is considered a "renewable" source because water on the Earth is continuously replenished by precipitation.[11] A typical hydro plant serves multiple functions and consists of a power plant where the electricity is produced, a dam that can be opened or closed to control water flow, and a reservoir where water can be stored.[12] The water behind a dam flows through an intake and pushes against blades in a turbine, causing them to turn. The generator attached to the turbine then produces electricity. The

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[8] Reclamation, *Hydroelectric Power*, 2005.

[9] National Hydropower Association, "Frequently Asked Questions."

[10] However, the share of hydro sources in the net renewable generation has fallen from 65 percent in 2009 to 48 percent in 2015. EIA, "Electric Power Monthly," 2016.

[11] It is important to note that each State treats and defines renewable energy differently. As of April 2016, 29 States and three territories have policies in place to provide certain incentives for "eligible renewable sources" (ERS). See National Conference of State Legislatures (NCSL), "State Renewable Portfolio Standards and Goals," 2016. However, electricity generation from large hydropower facilities or those that were operational prior to the implementation of the Renewable Portfolio Standard (RPS) often do not qualify as an ERS. For example, in Washington State, hydro sources generally do not qualify as an ERS, except for incremental electricity produced from efficiency improvements at hydropower facilities owned by qualifying utilities if the improvements were completed after March 31, 1999. See Washington State Senate, *Renewable Portfolio Standards and Renewable Energy Credits*, 2010.

[12] The National Energy Education Development Project, *Hydropower*, 2016.

amount of electricity that can be generated depends on how far the water drops and how much water moves through the system.

2.1.1 Black Start Capabilities of Hydropower

In addition to providing clean electricity production, hydropower serves an essential purpose of enhancing electric grid reliability. Hydropower can rapidly adjust output to meet changing real-time electricity demands and provide "black start" capability to help restore power during a blackout event. Black start capability is the ability to start generation without an outside source of power.[13] Because hydropower plants are the only major generators that can dispatch power to the grid immediately when all other energy sources are inaccessible, they can provide essential back-up power during major electricity disruptions. For example, when an estimated 50 million people were affected during the 2003 blackout, hydropower facilities in northeastern States operated continuously through the blackout and helped restore power.[14]

2015 U.S. Hydropower by the Numbers:

- At the end of 2015, 48 States had hydropower installed.
- There were 2,198 active hydropower facilities with a total capacity of 70.6 gigawatts (GW) at the end of 2015, and 42 pumped storage hydropower plants totaling 21.6 GW.
- As of 2015, 97% of utility-scale storage is pumped storage hydropower (PSH).
- Hydropower supports 143,000 jobs, including 118,000 ongoing full-time equivalent jobs in operations and maintenance and 25,000 temporary jobs in construction and upgrades, as of 2013.

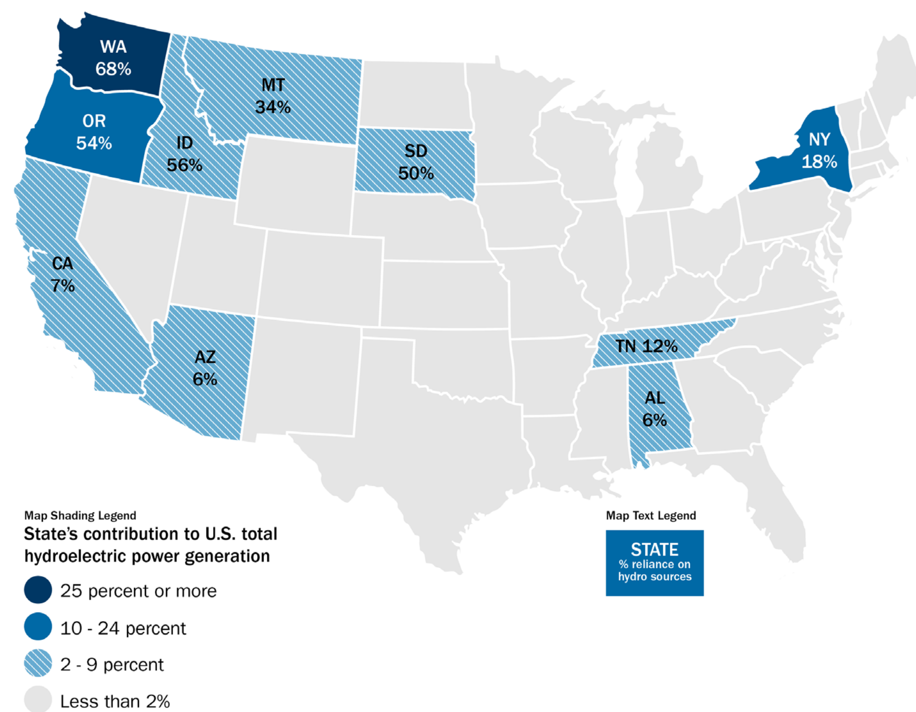
Source: DOE, *Hydropower Vision*, 2016.

2.2 Hydropower Dependence Concentrated in Key States and Regions

2.2.1 Top Hydropower Producing States

Figure 1 shows hydropower generation in the top 10 hydropower-producing States in 2015. The 10 highlighted States together produced about 79 percent of the Nation's total hydroelectric power. The different shades represent the level of the State's contribution to U.S. hydropower generation. The numeric values represent each State's dependence on hydro sources for electricity generation. For example, Washington State produced the highest level of hydropower, contributing to 30 percent of the total hydropower in the United States and 68 percent of total electricity generation in the State of Washington in 2015. Likewise, hydro sources in

Figure 1.—Top 10 Hydropower-Generating States and the States' Reliance on Hydro Sources for Electricity in 2015.



Source: Derived from EIA-906, EIA-920, EIA-923 databases.

[13] International Hydropower Association, *Hydropower and the World's Energy Future*, 2000

[14] National Hydropower Association, "Hydropower is Reliable."

Idaho, Montana, and South Dakota each contributed less than 5 percent of the Nation's hydroelectric generation; however, their dependence on hydro sources were relatively high, ranging from 34 percent to 56 percent. Conversely, Alabama and Arizona each produce more than 2 percent of the Nation's hydroelectricity, but their reliance on hydro sources for electric power generation is relatively low.

2.2.2 Largest Hydropower Dams

There are around 87,000 dams in the United States, but only about 3 percent—or about 2,200 dams—produce electricity.[15] Approximately half of U.S. hydropower generation capacity is owned and operated by Federal entities, including the U.S. Army Corps of Engineers (USACE), Bureau of Reclamation (Reclamation) of the U.S. Department of the Interior (DOI), and Tennessee Valley Authority (TVA); the other half consists of non-Federal projects that are regulated by the U.S. Federal Energy Regulatory Commission (FERC).

U.S. Hydropower Ownership:

- Federal agencies, including USACE, Reclamation, and the TVA, own 49% of installed capacity.
- Public utility districts, irrigation districts, States, and rural cooperatives own 24% of installed capacity.
- Investor-owned utilities, independent power producers, and industrial companies own 27% of installed capacity.

Source: DOE, *Hydropower Vision*, 2016.

Table 1 provides a list of the 20 largest hydroelectric dams in the United States ranked by summer capacity as of December 2015. These 20 hydroelectric facilities accounted for about 31 percent of the Nation's hydroelectric power capacity; they provided an annual average of 44 percent of the hydropower generated in the United States from 1990 to 2012. The majority of the 20 largest hydroelectric power plants are located in the Columbia River basin in the Pacific Northwest. Hydropower generation between 2013 and 2015 at these dams varied widely, ranging from a decrease of 28 percent at the Shasta Dam in California to an increase of 7 percent at the Wells Dam in Washington.

The largest hydroelectric facility in the United States is the Grand Coulee Dam with a summer capacity of 7,079 megawatts (MW), located in the Columbia River basin.[16] It is also the largest hydropower producer, generating about 8 percent of the Nation's hydropower. To compare the magnitude of the Grand Coulee, the next two largest dams, Chief Joseph and Robert Moses Niagara, each have about one-third of Grand Coulee's capacity. However, the capacity factor[17] at hydro plants varies significantly, generally in the range of 20 to 60 percent, with an average capacity factor of about 40 to 45 percent.[18] For example, the capacity factor of the Grand Coulee Dam is about 30 percent, whereas the Robert Moses Power Dam has a relatively high capacity factor of 87 percent.[19]

[15] DOE, *Hydropower Vision*, 2016

[16] Note that Reclamation, the owner and operator of the Grand Coulee Dam, lists that the total generating capacity of the dam as 6,809 MW. Reclamation, *Grand Coulee Dam Statistics and Facts*, 2015.

[17] "The ratio of the net electricity generated, for the time considered, to the energy that could have been generated at continuous full-power operation during the same period," U.S. Nuclear Regulatory Commission (NRC), "Capacity factor (net)," 2017.

[18] Annual average capacity factor derived from EIA data.

[19] Derived from EIA-906, EIA-920, EIA-923, and EIA-860 databases.

Table 1.—20 Largest Hydroelectric Dams in the United States.

Plant Name	Owner	State	Initial Operating Year	Summer Capacity (MW)	Comparison of Historical Average (Avg.) Annual Generation (Gen.) (MWh)		Difference in Avg. Gen. (%) 2013-2015 vs. 1990-2012	Capacity Factor
				2015	1990-2012	2013-2015		2015
Grand Coulee	Reclamation	WA	1941	7,079	21,480,886	20,071,124	-7%	30%
Chief Joseph	USACE	WA	1955	2,456	11,342,217	11,764,519	4%	53%
Robert Moses Niagara	NYPA	NY	1961	2,439	14,391,974	13,747,917	-4%	68%
John Day	USACE	OR	1969	2,160	9,787,873	9,015,092	-8%	46%
Hoover Dam	Reclamation	AZ-NV	1936	2,079	4,090,731	3,769,886	-8%	20%
The Dalles	USACE	OR	1957	1,823	6,939,162	6,619,420	-5%	40%
Glen Canyon Dam	Reclamation	AZ	1964	1,312	4,247,380	3,505,360	-17%	33%
Rocky Reach	PUD	WA	1961	1,254	6,029,166	6,200,995	3%	54%
Bonneville	USACE	OR	1938	1,154	4,880,063	4,558,514	-7%	41%
Boundary	Seattle	WA	1967	1,072	3,830,082	3,722,878	-3%	36%
Wanapum	PUD	WA	1963	1043	4,983,638	4,643,793	-7%	55%
Robert Moses Power Dam	NYPA	NY	1958	1,026	6,800,711	6,886,141	1%	87%
McNary	USACE	OR	1953	990	5,866,591	5,261,718	-10%	59%
Priest Rapids	PUD	WA	1959	956	4,612,677	4,726,525	2%	55%
Wells	PUD	WA	1967	840	4,116,019	4,406,021	7%	59%
Lower Granite	USACE	WA	1975	810	2,421,019	1,887,844	-22%	24%
Little Goose	USACE	WA	1970	810	2,367,127	1,875,298	-21%	24%
Lower Monumental	USACE	WA	1969	794	2,456,988	1,875,782	-24%	24%
Oahe	USACE	SD	1962	714	2,295,845	2,339,423	2%	37%
Shasta	Reclamation	CA	1944	714	1,802,378	1,301,460	-28%	18%
Total 20 Dams				**31,556**	**124,654,672**	**124,177,456**	**-5%**	
Total U.S.				**102,239**	**282,721,444**	**253,688,673**	**-10%**	
20 Largest Dams as percent of U.S. Total Hydro				**31%**	**44%**	**49%**		

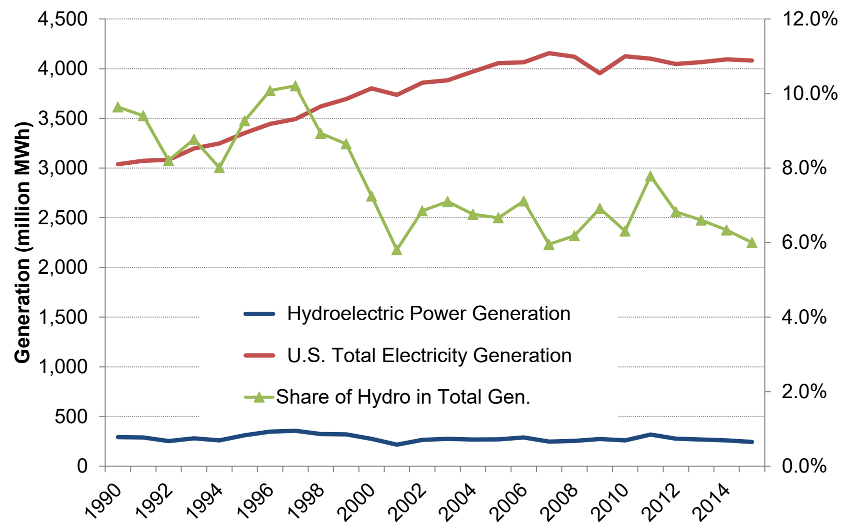
Note: The initial operating year represents the year in which the first unit(s) at the plant became operational and does not document the years in which additional units were brought online at the same facility. The capacity factor was calculated using the 2015 summer capacity and generation data, except for Robert Moses Power Dam, for which the nameplate capacity of 912 MW is used. Owner abbreviations in the table are: the New York Power Authority (NYPA), Public Utility District (PUD), Seattle City of Light (Seattle), U.S. Army Corps of Engineers (USACE), U.S. Bureau of Reclamation (Reclamation).

Source: Derived from EIA-906, EIA-920, EIA-923, and EIA-860 databases.

2.3 Shifting Hydroelectric Power Capacity Compared to Generation

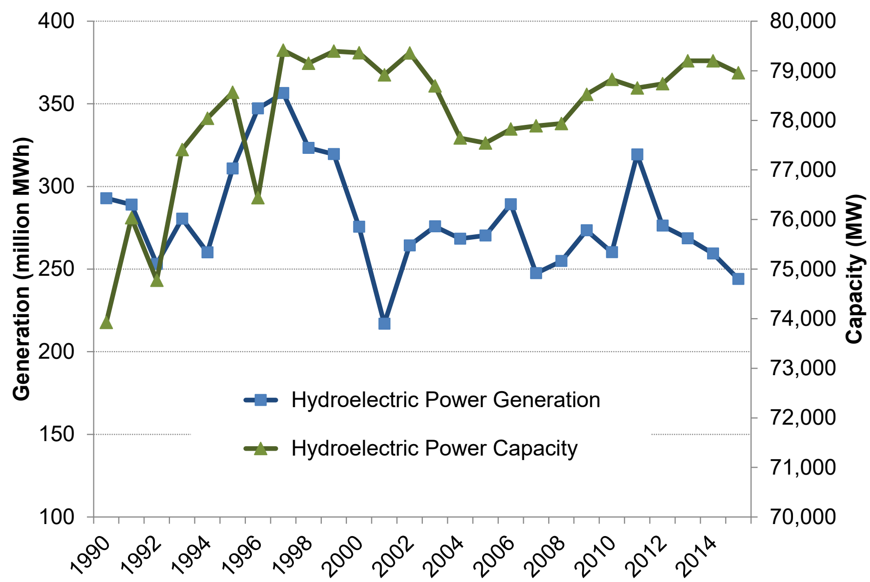
Figure 2 and Figure 3 show the growth pattern of hydropower generation and capacity between 1990 and 2015 in comparison to total electricity generation in the United States. As seen in these graphs, total U.S. electricity generation has grown by a 1.4 percent annual rate during the 25-year period. During the same period, hydropower generation has declined from 293 million megawatt hours (MWh) to 244 million MWh, an annual rate of 0.7 percent, while hydropower generating capacity has grown from 73,925 MW to 78,957 MW, an annual rate of 0.3 percent. EIA projects a minimum growth in hydroelectric generation capacity (0.1 percent annual rate) and a slightly greater increase in hydropower generation, with an annual growth rate of 0.8 percent over the next 25 years.[20] Despite these forecasts, it is almost impossible to predict the interannual variability of hydropower generation in the United States because the operation of hydroelectric facilities is directly linked to the amount of precipitation.

Figure 2.—Electricity Generation Growth between 1990 and 2015.



Source: EIA-906, EIA-920, EIA-923, and EIA-860 databases.

Figure 3.—Comparison of Hydropower Capacity vs. Generation from 1990 to 2015.



Source: EIA-906, EIA-920, EIA-923, and EIA-860 databases.

U.S. energy consumption across all sectors will grow at a modest rate through 2040, with the exception of a slight decline in the Transportation Sector's consumption.[21] This decrease will likely be the result of improved efficiency and accessibility of technologies related to electric vehicles and infrastructure maintenance.

In July 2016, the DOE released *Hydropower Vision: A New Chapter for America's First Renewable Electricity Source*, which outlines an expanded role for hydropower and pumped storage as part of a clean energy future. The report analyzed potential growth scenarios and includes a roadmap that outlines how hydro facilities can achieve higher levels of hydropower deployment. The report broke future hydropower growth into four categories: upgrading and optimizing

[20] EIA, "Annual Energy Outlook 2016; Table: Renewable Energy Generating Capacity and Generation."

[21] EIA, *Annual Energy Outlook 2016 with Projections to 2040*, 2016.

existing power plants and dams, building new power plants at existing non-powered dams and other water conveyance sites, installing new pumped storage hydropower (PSH) facilities or upgrading existing ones, and having new stream-reach development. In interviews conducted for this report, owners and operators stressed the importance of upgrading and optimizing existing dams, especially USACE and Reclamation dams.

The *Hydropower Vision* report found that U.S. hydropower could increase from 101 gigawatts (GW) to nearly 150 GW of combined electricity generation and storage capacity by 2050 if technology advancements and innovative market mechanisms are employed. [22] With the release of the report, DOE also announced that $9.8 million in funding is available to develop innovative technologies to reduce costs and timelines for PSH and non-powered dams, including exploring the feasibility of closed-loop PSH systems.[23]

[22] DOE, "Energy Department Releases New Hydropower Vision Report," 2016. See Appendix D. 2016 Hydropower Vision Report for a summary of the report.
[23] Ibid.

3. Risk Factors Affecting Interdependent Dams and Energy Operations

Hydroelectric power generation depends foremost on the availability of local water sources that are susceptible to changes in local hydrology and weather patterns—changes that have increasingly veered from historical norms in the past decade. Beyond water availability, several key factors may also constrain the use of water for hydroelectric generation: operational policies (i.e., flood control as the primary mission), regulations and resource agreements (e.g., instream flow requirements for fish protection), and multiple competing water uses (e.g., drinking water supply, irrigation, and recreation) that are specific to each river.[24]

The insights of owners and operators of hydroelectric facilities are essential in understanding not only the day-to-day operation of critical hydropower infrastructure, but also the key issues that the owners and operators must consider in long-term planning. For that reason, DOE and DHS engaged in discussions with senior personnel from 13 public and private hydropower organizations who volunteered to participate in this study. These owners and operators provided insight into the current and emerging hydropower generation risks they face and potential mitigation efforts.

3.1 Shifting Weather and Temperature Patterns

The effects of shifting weather and temperature patterns on water resources could reduce the generating capacity of hydropower plants and exacerbate competing demands for water resources. The overall increase in temperatures across the United States, changes in precipitation, shifting snowmelt and stream flows, and an increase in demand for cooling water all place a significant strain on water resources for hydropower plants, especially during the summer.

Several U.S. regions have experienced severe weather during the last few years, including persistent droughts in the West, heavy Midwest flooding, and destructive Northeast storms. Increasing global temperatures throughout the 21st century may intensify weather events for nearly all regions of the country. As studies by Federal, private, and academic institutions continue to provide greater insight into how a changing climate is affecting the United States, Dams Sector owners and operators are examining how these changes will affect infrastructure in the coming decades.

The majority of dams owners and operators identified shifting weather and temperature patterns as the most significant, long-term challenge facing the sector. These shifts could fundamentally change the operations of existing facilities, and—as water sources continue to be depleted—threaten their viability. Many owners and operators in the Dams Sector are undertaking long-term planning to identify ways to sustain operations and generation despite more frequent extreme weather conditions.

3.1.1 Increasing Global Temperatures

According to the Intergovernmental Panel on Climate Change, the overall average global temperature has risen over 1.5 degrees Fahrenheit from 1880 to 2012,[25] and further temperature increase is predicted. Seven of the 10 warmest years on record took place since 1998.[26] Increasing ambient air temperatures may create growing peak electricity demand in

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[24] DOE, *Energy Demands on Water Resources*, 2006.

[25] National Center for Atmospheric Research and University Corporation for Atmospheric Research, "How Much Has the Global Temperature Change Risen since 1880?"

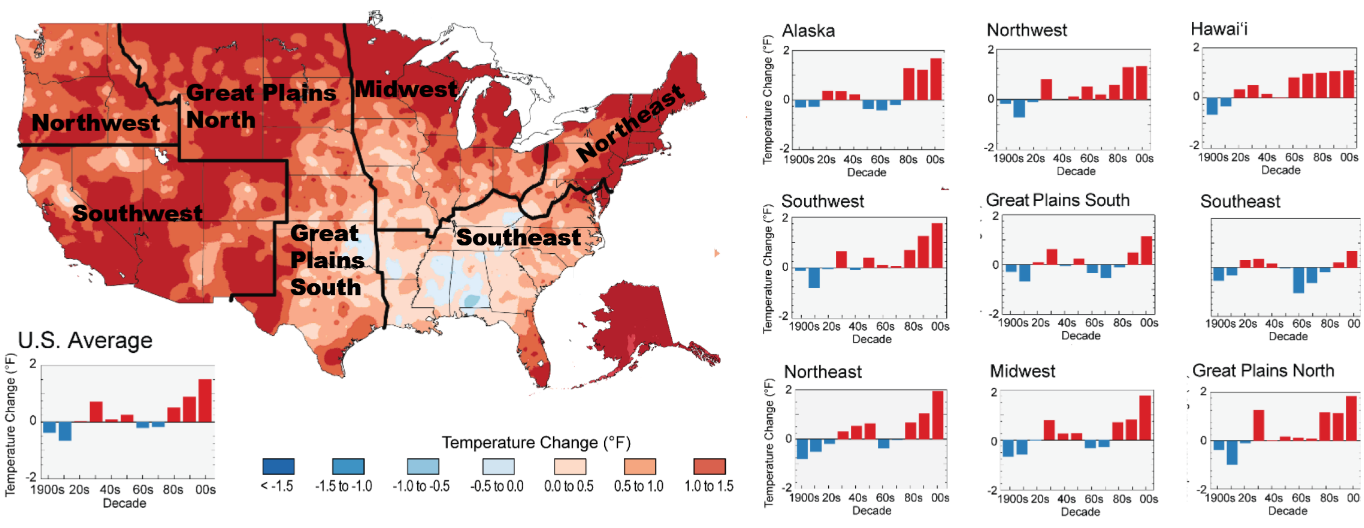
[26] EPA, "Climate Change Indicators: Weather and Climate."

summer months, and may also result in higher water temperatures and rates of evaporation, causing water sources contained in wide, flat reservoirs to evaporate faster.[27] Researchers predict that in the next two decades, western and northern regions of the United States will experience the highest temperature increases.[28] DOE regional analysis predicts all U.S. regions will experience increased average temperatures over the course of the next century.[29]

3.1.2 Extreme Heat Waves and Prolonged Droughts

Extreme heat waves are occurring more frequently, which can cause significant spikes in cooling demand and strain energy resources. Figure 4 shows observed temperature changes in the United States over the 21st century. National Oceanic and Atmospheric Administration (NOAA) analysis predicts the following U.S. regions will experience extreme heat waves over the course of the next century: Southeast, Southern, and Great Plains.[30]

Figure 4.—Observed U.S. Temperature Change throughout the 21st Century.



Source: U.S. Global Change Research Program (USGCRP), *National Climate Assessment*.

In recent decades, the availability of water resources has shifted. Many parts of the contiguous United States are experiencing less rainfall than in prior years. Combined with higher temperatures, this causes drought conditions that deplete reservoirs and create competing needs for a limited water supply. The Southwest region, in particular, has recently been hit hardest by drought conditions.[31] A decrease in seasonal precipitation in California, a highly developed agricultural center for the Nation, would require irrigation from sources other than rainwater. The Southern Great Plains will also experience less rainfall over the next century.[32] Wildfires in the Pacific Northwest and Southwest will also increase with drier conditions, requiring further allocation of water resources, and in some cases depletion of reservoirs to fill helicopters to help suppress wildfires. The lack of vegetation after wildfires also results in more runoff, including dirt; sediment; and, in some cases, trees entering water sources. This debris may build up against dams, causing operational delays.

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[27] DOE, *U.S. Energy Sector Vulnerabilities to Climate Change,* 2013.

[28] National Oceanic and Atmospheric Administration (NOAA), *Regional Climate Trends and Scenarios for the U.S. National Climate Assessment*, 2013.

[29] DOE, *Climate Change and the U.S. Energy Sector*, 2015.

[30] NOAA, *Regional Climate Trends and Scenarios for the U.S. National Climate Assessment*, 2013.

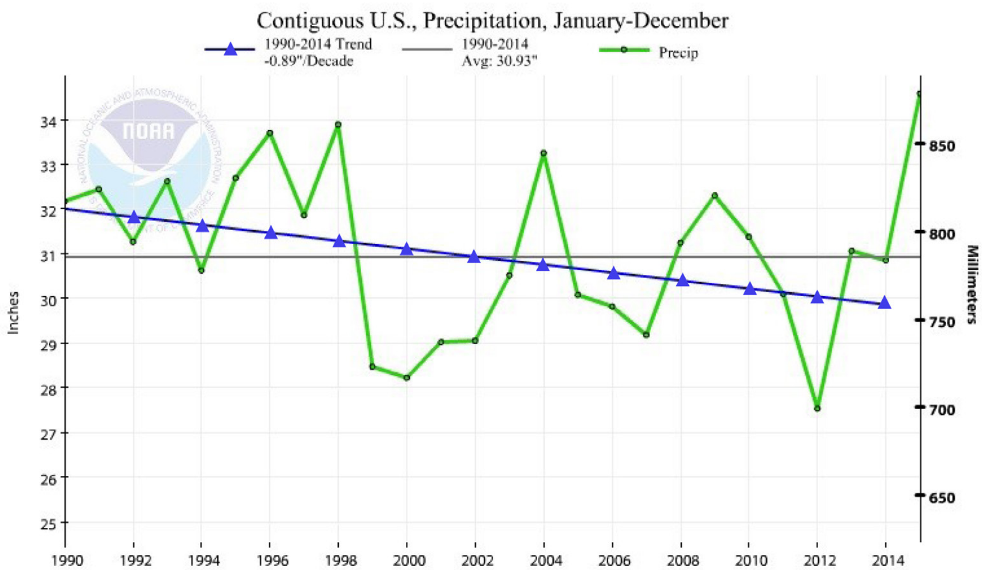
[31] DOE, *Climate Change and the U.S. Energy Sector*, 2015.

[32] Ibid.

Thermoelectric power plants may experience curtailments due to a lack of cooling water in periods of peak demand. DOE regional analysis predicts most U.S. regions will experience seasonal drought over the course of the century.[33]

According to a 2014 study by the EPA, precipitation in the contiguous 48 States has increased at a rate of 0.5 percent per decade since 1901.[34] However, year-to-year fluctuation in natural weather and climate patterns can produce a period that does not follow long-term trends (see Figure 5). The inter-annual variability of hydropower generation in the United States is high—a drop of 59 million MWh (or 21 percent of total U.S. hydropower generation) was seen from 2000 to 2001. Sensitivity of hydroelectric power generation to changes in precipitation and river discharge is high; in the range of 1.0+.[35] Although precipitation is a determining factor in available hydropower generation for a given period of time, the variability of weather patterns imposes uncertainty in the operation of hydroelectric facilities.

Figure 5.—Precipitation in the Contiguous United States between 1990 and 2014.



Source: NOAA, "Climate at a Glance."

Owners and operators are using a range of methods to mitigate the effects of droughts. For example, one operator keeps strategic reserves of water for emergency summertime power surges, such as the demand for air conditioning, and may also start using cameras to monitor infrastructure for leaks to prevent unnecessary water loss.

Western States continue to grapple with prolonged drought and reduction in available water resources. For example, in 2015, Lake Mead hit its lowest elevation since 1938. In response, States and dams owners and operators that share water resources are taking a regional approach to planning by developing drought contingency plans and drought commissions as a way to share strategies, resources, and communications efforts. These commissions improve the ability of stakeholders to share resources and information.

Hydropower operations are also affected indirectly by changes in air temperature, humidity, and wind patterns, which change water quality and reservoir dynamics.[36] For example, reservoirs with large surface areas (such as Lake Mead in the

[33] DOE, *Climate Change and the U.S. Energy Sector*, 2015.

[34] EPA, *Climate Change Indicators in the United States, 2014*, 2014.

[35] A sensitivity level of 1.0 means that 1 percent change in precipitation results in 1 percent change in generation. U.S. Climate Change Science Program, *Effects of Climate Change on Energy Production and Use*, 2008.

[36] U.S. Climate Change Science Program, *Effects of Climate Change on Energy Production and Use*, 2008.

lower Colorado River) are more likely to experience greater evaporation, which affects the availability of water for all uses, including hydropower.

3.1.3 Shifting Snowfall/Rainfall and Snowpack Melt Patterns

Changing snowfall patterns and associated runoff from snowpack melt can disrupt electricity generation planning, particularly in the Pacific Northwest, where snow is melting earlier and the proportion of precipitation in the form of snow is decreasing.[37]

Over the next century, northern States, particularly the Northeast, may see an increase in year-round precipitation levels.[38] Although this may increase water availability and generation capacity, unexpected increases can force operators to generate more electricity than they expect to sell during certain seasons, which is often based on historical data. Water levels must not exceed the capacity of reservoirs, so dams operators are required to release water—generating unused electricity—at the cost of hydropower plant operators.

Higher global temperatures may increase winter precipitation in the form of rain versus snow. Winter precipitation in the form of snow is also less likely to stay frozen until spring and summer, when snowmelt has traditionally bolstered hydropower generation capacity on hot summer days.[39] In certain regions, shifting precipitation and snowmelt patterns may increase hydropower generating capacity during periods of low demand and/or decrease capacity during peak periods.

One operator said that instead of melting gradually, snowpack has been releasing all at once, and peak runoff may be one or two months earlier than usual—in March instead of in April or May. Snowpack melt used to help with increased demand in the summer. However, his organization now relies on low natural gas prices to bolster the need for energy in hotter months; however, they may eventually have to rely on more fossil fuel resources to meet energy needs.

Operators also stated that increased rain events, rather than snow, can increase the frequency of floods. This leads to water being released during periods of low demand, and as noted above, less snowpack melt to aid in periods of high demand. Flooding also adds costs, as increased flows and debris buildup can result in greater dams maintenance issues and safety concerns, and may affect rates (see High Water Condition Effects in Section 3.2).

The shifting weather patterns also mean it is more difficult for owners and operators to manage reservoirs. Forecasts are less accurate since weather does not fit past patterns, said one operator, and operators need to adjust how they fill reservoirs. Filling reservoirs less to better control for water if a flood occurs may mean facilities capture water less efficiently during rain events. Filling a reservoir too much may mean operators need to release more water during periods of low demand. Advances in prediction technology—such as using satellite images and more advanced computer modelling—are helping to mitigate these effects.

DOE regional analysis predicts the following U.S. regions will experience heavy precipitation events over the course of the century: Midwest, Northern Great Plains, and Southeast.

3.1.4 Additional Considerations: Storms, Rising Sea Levels, and Earthquakes

Severe storms and hurricanes: An increase in the number of and severity of hurricanes,[40] particularly along the Gulf Coast, increases the chances of widespread outages, particularly outages that may require black start capabilities for

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[37] DOE, *Climate Change and the U.S. Energy Sector*, 2015.
[38] DOE, *U.S. Energy Sector Vulnerabilities to Climate Change,* 2013.
[39] DOE, *Climate Change and the U.S. Energy Sector*, 2015.
[40] DOE, *Climate Change and the U.S. Energy Sector*, 2015.

restoring power. Hydropower dams are unique in that they are mechanical by nature and can serve as the black start for electric grids or plants that have lost power.

Rising sea levels: Rising sea levels may not directly affect hydropower plant infrastructure. However, coastal areas may prematurely erode components of the grid that allow transmission of hydroelectricity to consumers.[41] Flooding can overwhelm the storage capacity of reservoirs, impoundments, and levee systems, causing a possible dam or levee breach. Severe multi-State floods in the Midwest in 1993, 2008, and 2011 generated record or near-record flood stages that overtopped levees and overwhelmed floodways. In many of these cases, Dams Sector assets operated as designed to prevent more severe damage. However, more frequent and severe flooding increases potential consequences.[42]

Earthquakes: Severe earthquakes, particularly near river basins, could cause structural damage to hydropower dams—delaying operations and potentially disrupting black start capability.[43] A broken dam releasing a large reservoir of water may also impair downstream transmission activities and cause large amounts of infrastructure damage. A number of high hazard potential assets are located within active seismic areas, where a severe earthquake could damage dam infrastructure. Despite progress in seismic analysis methods and assessment procedures, predicting the behavior of dams and levees under earthquake conditions remains a significant challenge.[44]

3.2 Shifting Hydroelectric Power Generation Due to Changing Weather Patterns

The dependability of hydroelectric power generation is often challenged by unusual and unpredictable weather patterns, including droughts, floods, and early snowpack melts. The increase of extreme weather events and changing weather patterns means hydroelectric facility operators need to make both high and low water accommodations more frequently. Events including droughts, extreme heat waves, and shifting snowpack melt can result in low water condition accommodations. Increased rain instead of snowfall, severe storms and hurricanes, and rising sea levels can contribute to high water condition accommodations. This section goes into more detail regarding how owners and operators are addressing both extremes, and how these conditions affect hydropower generation.

3.2.1 Low Water Condition Accommodations

Lower streamflows resulting from drought, upstream dams, and diversions will reduce the amount of storage in a reservoir, which lowers the amount of water available to produce hydropower. Coupled with operational constraints under certain streamflow requirements, the diminished streamflows can reduce hydropower production. Such a decline may complicate electricity providers' ability to meet their power supply commitments, especially in service areas that depend heavily on hydroelectric power. Reduced hydropower generation caused by regional drought conditions may often be replaced by increased fossil fuel-based generation. Even though the total generation may change significantly from year-to-year based on water availability, its geographical and seasonal distribution usually remains relatively stable.[45] In other words, the top hydro-producing dams and States continued to supply the largest amount of hydroelectric power generation, despite severe drought conditions in recent years in certain parts of the United States.

Figure 6 shows recent changes in hydroelectric power production in the top hydropower-generating States. Hydroelectric power generation between 2013 and 2015 was compared to historical average hydropower production from 1990 and

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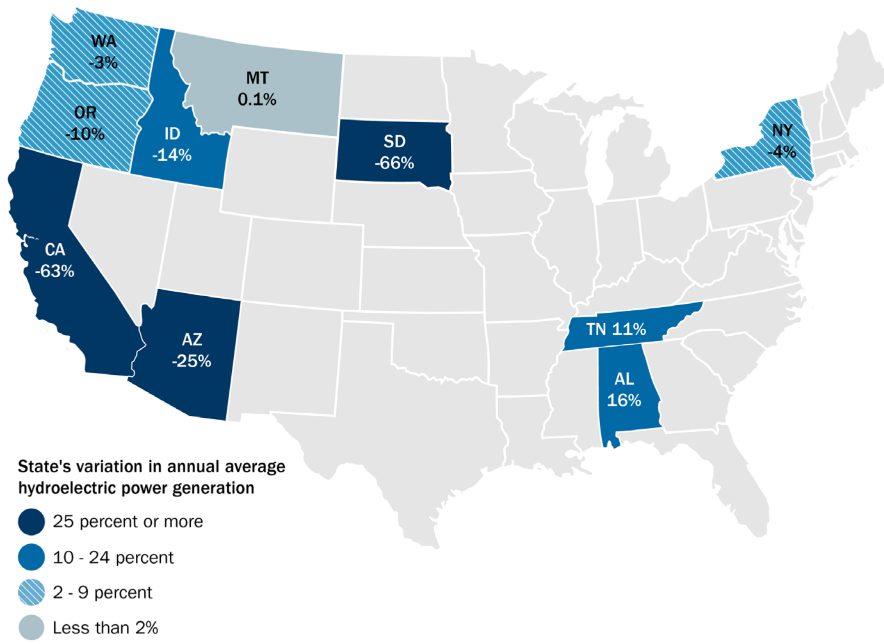
[41] DOE, *U.S. Energy Sector Vulnerabilities to Climate Change,* 2013.
[42] DHS, *2015 Dams Sector-Specific Plan*, 2015.
[43] DHS, *2015 Dams Sector-Specific Plan*, 2015.
[44] Ibid.
[45] DOE, *2014 Hydropower Market Report*, 2015.

2012 at the State level. The analysis indicates the national annual average of hydroelectric power generation between 2013 and 2015 was around 10 percent less than the historical average between 1990 and 2012.

Figure 6 also illustrates the shifting pattern of hydropower generation in different parts of the Nation between 2013 and 2015 in comparison to the prior two decades. Specifically, the Southwest has experienced severe drought, resulting in a significant drop in hydropower production. During this three-year period, hydropower production in California and Arizona was down by more than 63 percent and 25 percent from the historical average, respectively, as a result of a long-lasting drought in the region. The science of accommodating hydropower production to low water conditions lies in the increasingly sophisticated modeling that allows optimization of the water that is available to produce power. Satellite images more accurately track rainfall and its effects, which allows for better, quicker decisions and improved communication with partners such as USACE and the National Weather Service. Models also more accurately analyze small-scale processes, such as how a storm behaves when entering a basin.

Figure 6.—Variance in Annual Average Hydropower Generation in Top 10 States, 2013-2015 vs. Historical Average.



Source: Figures are calculated as percent change in hydropower generation between 2013 and 2015 in comparison to the historical average from 1990 to 2012. Derived from EIA-906, EIA-920, EIA-923 databases.

Technological advances can further optimize the use of available water through hydro plant modernization. Several operators reported that more generation can be achieved from lower head dams through turbine upgrades. One operator stated advanced engineering and computer modeling allows new turbines to use less water, resulting in an almost 10 percent increase in efficiency at the same or lower lake levels, resulting in 8 to 10 MW more at any given time. However, as further explained in 3.5.2 Aging Infrastructure, owners and operators indicated securing funding for modernization can be an issue.

3.2.2 High Water Condition Effects

High water conditions present a unique set of challenges that can also be problematic. Although operators want to retain as much water as possible in the reservoir for hydropower production, floods may lead to the overtopping of reservoirs or facility failures. Owners and operators need to have emergency action plans in place to deal with these events, such as having personnel available to open gates.

As mentioned in Section 3.1 Shifting Weather and Temperature Patterns, over the next century, northern States, particularly the Northeast, may see an increase in year-round precipitation levels.[46] Higher global temperatures may increase winter precipitation in the form of rain versus snow, creating higher water availability and increased generating

[46] DOE, *U.S. Energy Sector Vulnerabilities to Climate Change,* 2013.

capacity at a time when demand may be lower. These increased flows may also require downstream dams to pass through water and not be able to sell the resulting power at a reasonable price. Even if flood control is not a facility mission, owners do their best to avoid or minimize downstream harm when they manage high water conditions. Improved energy storage capabilities would reduce operator costs and help preserve reservoir levels.

Debris buildup associated with flooding can be dangerous to facility infrastructure and affect operations. Trees, lumber, sheds, animals, and other debris can be swept into rivers from floods and can build up against dams. The cost and personnel resources required to remove this debris can be significant. The increased flows and buildup can also result in greater dams maintenance issues and safety concerns. This adds to operating costs and may affect rates. One operator mentioned facilities need to invest in more repairs after floods, including fixing damaged equipment and clearing tunnels filled with silt from diversions off a river. The operator's reservoirs also did not have enough storage capacity, resulting in a lot of water being passed through during one large flooding event.

3.2.3 Resilience of Pumped Storage Hydropower to Changing Weather Patterns

Pumped storage facilities are more resilient than conventional hydropower plants to unexpected weather pattern changes, including reduced precipitation or low water events, because the water used to produce power is stored (in reservoirs) and recycled (not released into the natural stream flow). In pumped storage facilities, water from the lower reservoir is pumped up to the higher elevation reservoir using low-cost, off-peak electric power. Then the water stored in a higher elevation reservoir is released through turbines to a lower elevation reservoir to produce power during high demand periods.

More energy is spent pumping up the water than is generated when releasing it back down. Therefore, pumped storage plants are considered net consumers of energy. They typically generate when the price of electricity is high enough relative to the cost paid for the pumping energy to cover pumping losses. In addition to taking advantage of the arbitrage opportunities enabled by the peak-to-off-peak price differential of electricity, pumped storage units can provide other useful grid services. These include inertial response, primary frequency control, operating reserves, reduced cycling of thermal generating units, reduced transmission congestion, voltage support, black start capability, and other portfolio effects.[47] The DOE's *Hydropower Vision* report focuses on the potential benefits of increasing pumped storage, and more facilities are applying for pumped storage licenses through FERC.[48] In April 2016, FERC "initiated Docket No. AD16-20-000 to examine whether barriers exist to the participation of electric storage resources—including PSH—in the capacity, energy, and ancillary service markets, potentially leading to unjust and unreasonable wholesale rates."[49] FERC is currently analyzing responses to this docket.[50] Environmental, regulatory, and economic hurdles may affect the growth of this technology.[51]

3.3 Regulations and Competing Water Resource Demands

Hydroelectric facilities serve multiple purposes that can include flood control, recreation, industrial and community water supply, irrigation, and transportation. The demands for water for these uses can come into conflict with hydropower production in terms of how much water can be used for nonpower generation and the condition of the water associated with power generation.

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[47] Argonne National Laboratory, *Modeling and Analysis of Value of Advanced Pumped Storage Hydropower*, 2014.

[48] See Appendix D. 2016 Hydropower Vision Report.

[49] Ibid.

[50] FERC, "Docket No. AD16-25-000," 2016.

[51] Trabish, Herman K., "A lot of dam potential: Renewables growth could drive massive hydro buildout," 2016.

For multifunction facilities, the combination of existing water rights, treaties, contracts, laws, or court cases determines which entity gets how much water and when they receive it. Modifying these controlling forces to consider reduced water availability can be difficult because they may involve multiple States and parties and, sometimes, international partners. In addition to these legally binding obligations on water delivery, softer forces, such as providing or storing water to protect recreational uses or the value of residences around the reservoir, can also limit the availability of water for hydropower generation.

Competing demands for water are already evidenced in several parts of the United States. The operational constraints associated with natural resource and environmental protection will only increase in their intensity if projected shifts in weather and temperature patterns result in increasingly unpredictable water availability.

3.3.1 Wildlife and Environmental Regulations

The condition of the water used in producing hydropower may also be heavily controlled through Federal and State laws and regulations, operating permits and licenses, environmental agreements, environmental stewardship, and court decisions requiring certain protection of natural resources and the environment. These controlling forces may stipulate how dam owners and operators must maintain water conditions such as tail water temperature, streamflow, and dissolved oxygen levels. Operating stipulations are primarily designed to protect species designated as threatened or endangered under Federal or State laws. They may also serve to protect downstream banks, channels, and river branches.

For example, the Northwest will face water resource allocation challenges to preserve streamflow for fish. Freshwater hydropower plants may share resources with local and Federal wildlife authorities, as a way to ensure the amount of water used does not endanger fish. Fish conservation efforts could contribute to up to a 20 percent reduction in hydropower production in 2080, according to a USGCRP report.[52]

Operators support natural resources and environmental protection; however, they are concerned that hydropower production interests are not evenly represented when these environmental protection requirements are developed. Specifically, compliance with these operating restrictions limits optimal operation of hydropower facilities. One operator stated water release needed for fish spawn and environmental measures related to the Endangered Species Act forces them to generate at times of no or low demand. Another operator stated these measures add to the difficulty of paying back annual investment and operating costs in a market that pays them a lower rate. Additionally, an owner stated hydropower producers may have to buy supplemental power at higher market prices if they lose access to water due to mixed use water needs.

However, turbine and hydropower equipment modernization can also reduce the environmental effects of hydropower generation. For example, some owners and operators are installing aerating turbines that increase oxygen in the water, which helps support downstream fisheries, and new gap runner technologies in development could increase the survival rate of fish that get caught in turbine water flows.

3.3.2 Population Growth

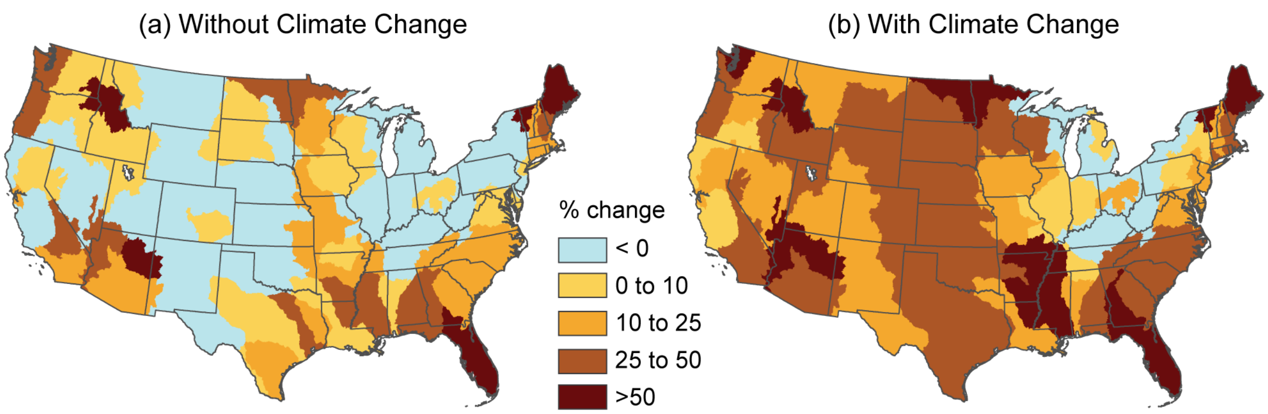
The U.S. population is projected to rise to 417 million by 2060.[53] Despite an increase in consumer technology that aids conservation efforts, water consumption for basic health and usage purposes will increase in relation to population growth. The Southeast in particular will experience a significant amount of growth; U.S. Census Bureau data shows the

[52] USGCRP, *Climate Change Impacts in the United States*, 2014.
[53] Colby, Sandra L. and Jennifer M. Ortman, *Projections of the Size and Composition of the U.S. Population: 2014 to 2060*, 2015.

population is projected to increase by 57 percent between 2000 and 2030.[54] Growing populations will increase competition for water resources for recreation and from reservoirs for drinking water and other agricultural uses.

Population increases coupled with droughts can lead to water shortages, which could cause policy and regulation changes to specify who will receive the water. This increases operational risks for hydro plants. Figure 7 shows projected changes in water withdrawals between 2005 and 2060.

Figure 7.—Projected Changes in Water Withdrawals between 2005 and 2060.



Source: Brown, et. al, "Projected freshwater withdrawals in the United States under a changing climate."

3.3.3 Cooling Water for Thermonuclear Plants

Thermonuclear plants use boiling water to generate steam that moves through turbines, creating electricity. This steam needs to be cooled and recondensed so water can be reused or discharged.[55] Once-through cooling systems, which are commonly found in the Southeast, require more water than recirculating cooling systems. Although newer power plants are likely to use a recirculating or hybrid cooling system to conserve water, some water is consumed in the evaporation of heated water.[56] As a result, water resources are also shared between hydroelectric and thermoelectric power plants, which will both experience similar periods of peak demand.

3.4 Evolving Power Industry and Renewable Resource Growth

Federal, State, and local governments have implemented several environmental regulations and guidelines to reduce carbon emissions and greenhouse gases. Owners and operators within the Dams and Energy Sectors continue to adapt to a changing regulatory environment, and the power industry as a whole continues to develop new technology that complies with new regulations.

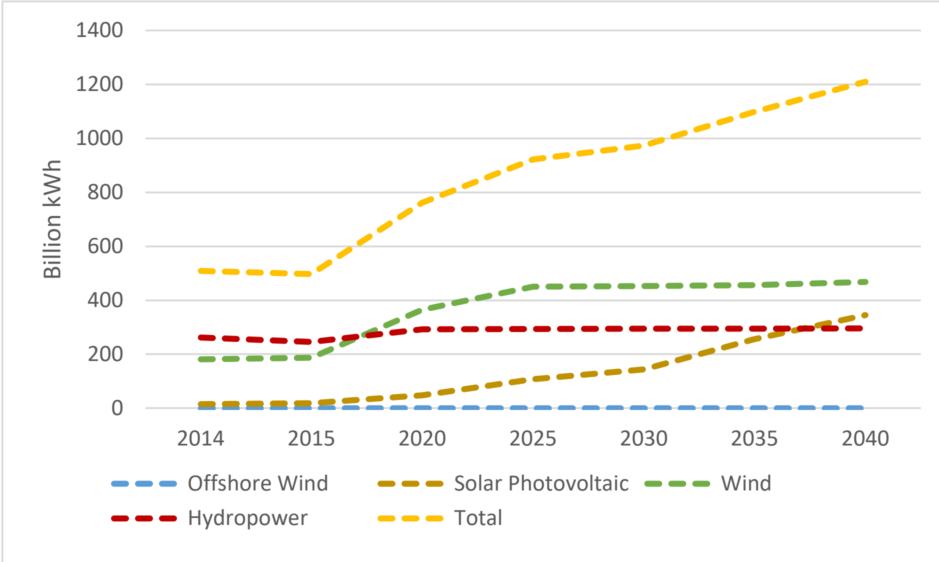
3.4.1 Growth in Wind and Solar Generation and Distributed Generation

Growth in the wind and solar industries, and the development of more efficient thermoelectric technologies, may change the energy mix in regions that depend heavily on hydroelectric power and affect when and how hydropower is primarily used in a region. EIA projects a growth of 12.3 percent in solar photovoltaic and 3.7 percent in onshore wind power generation within the electricity sector.[57] Comparatively, EIA predicts hydropower generation growth will remain

[54] DOE, *Climate Change and the U.S. Energy Sector*, 2015.
[55] Averyt, Kristen et al., *Freshwater Use by U.S. Power Plants: Electricity's Thirst for a Precious Resource*, 2011.
[56] Ibid.
[57] EIA, "Annual Energy Outlook 2016; Table: Electric Power Sector—Generation."

relatively flat in the coming decades. Figure 8 shows the generation projections based on a reference case for wind, solar (photovoltaic), and hydropower electricity generation as a part of the total electricity output.

Figure 8.—Projections for Renewable Electric Power Sector Generation by Type.



Source: EIA, "Annual Energy Outlook 2016."

Owners and operators stated the amount of wind and solar penetration will vary according to region, but the reduced cost of purchasing wind and solar power and the restriction of some hydropower sources, such as Glen Canyon Dam (see Section 4.2 The Colorado River System), may decrease the role of hydropower in the overall energy mix. Historically, hydropower has been a lower-cost option to meet peak demand, especially since there is no start up time required. However, the surge in solar and wind, and the low cost of natural gas (presented in the next subsection), have all increased competition on hydropower as a lowest-cost option. Multipurpose hydro projects have historically been able to sell energy from flood releases at a lower price. However, a greater infusion of renewables that produce electricity during off-peak times means energy produced from these releases may not be the most cost-competitive, and is less desirable to customers. For example, in the Southwest, the influx of wind power generated throughout the night can force market prices into the negative.

Hydropower facilities are also competing against renewables to meet Renewable Portfolio Standards as part of the Clean Power Plan (CPP), with qualifying generation sources varying from State to State. The CPP, enacted in 2015, sets interim and final goals for U.S. power plants to reduce carbon emissions by lowering emission rates on traditional coal- and natural gas-fired power plants and incentivizing the implementation and use of clean and renewable power generation sources.[58] The CPP has set interim emissions goals to be reached by 2029, with final goals in place by 2030. Each State has a varied composition of generation sources, and as a result, the EPA set emissions rates for each State based on its unique characteristics. The final goals could achieve a 35 percent reduction in carbon emissions from power plants and an increase in renewable energy as well as distributed generation sources.[59]

To achieve the long-term benefits of the CPP, States must adjust their generation mix, including sources and capacity of each type of generation. Many States have already seen increased adoption of renewable technologies such as wind and

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[58] EPA, "Overview of the Clean Power Plan," 2015.

[59] Ibid.

solar to offset the reduced generation capacity from traditional generation sources. One of the challenges for hydropower is that it does not always qualify as a renewable energy source, despite its lack of greenhouse gas emissions or other air pollution. The EPA CPP Final Rule designated "new hydropower generating capacity installed after 2012" and capacity increases in rates, or uprates, as part of relicensing permits as eligible types of renewable energy.[60] State-level clean energy plans will also drive generation portfolio shifts. If hydropower is not eligible, it decreases the value of using hydropower, since it will not help customers meet the standard.

More residential customers are also producing energy with rooftop solar panels, reducing overall power consumption and demand. Although this is not directly affecting hydropower, it is part of a larger trend in the Electricity Subsector shifting away from coal-fired power and toward more affordable, widespread renewable generation. It has created uncertainty for customers and may make them hesitant to commit to long-term hydropower contracts.

To adapt to this changing role, there is growing discussion about PSH facilities to supplement the intermittent nature of renewables, such as generating power when the sun is not shining or the wind is not blowing. Traditional hydropower has also been used as an ancillary source to support intermittent resources. However, increases in unscheduled generation can increase operations and maintenance costs at the expense of owners and operators, who are not paid a premium for ancillary services. Along with supporting intermittent resources, hydropower maintains its added advantage of black start capability in case of a grid failure.

The Electricity Subsector continues to improve its efficiency and reliability to meet growing demand and consumer expectations. Although many of the renewable energy sources on the market may not directly affect water demands for hydropower generation, new technologies implemented in thermoelectric power generation, such as an increased use of biofuel, may require a higher demand for water.[61]

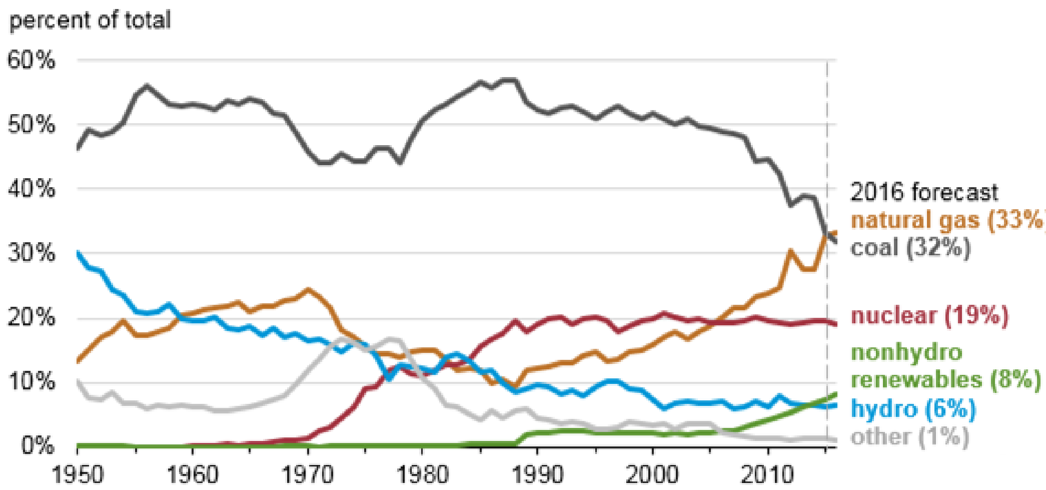
3.4.2 Lower Cost and Rising Use of Natural Gas

Natural gas prices have hit historic lows, and as a result, EIA is forecasting that 2016 will be the first year that natural gas-fired electricity generation exceeds coal generation in the United States on an annual basis.[62] Lower natural gas prices could make hydroelectric generation less competitive, particularly to meet peak demand, when hydropower has historically had a cost advantage.

Today, with historically low natural gas prices, hydropower is often not the most cost-effective source for meeting peak demand. In some cases, to meet customer demand requirements, a hydropower plant will purchase power from neighboring utilities that use natural gas because the prices are lower. Figure 9 shows annual U.S. electricity generation shares.

[60] EPA, "The Clean Power Plan," 2015.
[61] Gasper, John, "Energy-Water Science & Technology Research Roadmap."
[62] EIA, "Natural gas expected to surpass coal," 2016.

Figure 9.—Annual Share of Total U.S. Electricity Generation by Source (1950-2016).



Source: EIA, "Natural gas expected to surpass coal in mix of fuel used for U.S. power generation in 2016."

3.5 Additional Emerging Hydropower Risks

3.5.1 Cyberattacks

Cyber risks from outside attackers and insider threats represent one of the most serious operational risks facing modern organizations. Strong cybersecurity is particularly essential for organizations that use cyber systems to manage or control critical physical processes. Larger and medium hydropower facilities typically keep operational supervisory control and data acquisition (SCADA) systems separate from other information technology (IT) systems and the Internet. Some Federal and non-Federally owned hydropower facilities are also subject to North American Electric Reliability Corporation (NERC) cybersecurity standards. Facilities also employ their own methods for responding to cyber threats, including using a suite of tools that can monitor attempts to penetrate the network.

Owners and operators stated cyberattacks may be more of a risk for smaller companies, who may have trouble meeting increased cybersecurity-related costs and keeping up with changes in regulation. Although these facilities may be at a higher risk, they would likely have a smaller impact if they were the victim of a cyberattack that manipulated or halted project operations. FERC recently implemented a program for its owners/operators that evaluates the cybersecurity of the non-Federal dams it regulates. This will help ensure remotely operated and automated project features are evaluated and appropriate cybersecurity measures are applied.

3.5.2 Aging Infrastructure

Most hydropower generation was installed between 1950 and 1990, and the majority of PSH was installed between 1960 and 1990.[63] Aging dams can have seepage and growth issues that need to be corrected. Owners and operators said conducting regular inspections and instituting maintenance schedules allows for this work to be done in a way that does not cause major disruptions to operations; however, unexpected failures or needs for repairs may result in a plant being shut down for an extended period of time. Operators need to continually assess the state of equipment to efficiently stagger upgrades and minimize downtime and unplanned costs or outages.

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[63] DOE, *Hydropower Vision*, 2016.

Dams owners and operators are also conducting modernization programs to upgrade equipment, including sometimes replacing entire machines, depending on the improvements needed. In 2015, the National Hydropower Association started an Operational Excellence program that uses voluntary event reporting to help hydro plant owners and operators network and share corrective action plans, lessons learned, and best practices regarding maintenance and other operational issues.[64] More than 220 organizations are currently part of the information sharing program.

However, facilities typically have limited resources for infrastructure modernization. Financial resources to design and implement facility upgrades generally come through public funds and/or power sales for non-Federal, publicly held hydropower infrastructure, and from rate increases approved by public utility commissions for privately held facilities. Although payback periods could be as short as three to five years for technology upgrades, securing the initial investment can be challenging. The increased challenges hydropower operators face—outlined in previous sections—decrease revenue and available resources at a time when additional upgrades are needed.

Congress controls the revenue stream generated by USACE hydropower facilities. As a Congressional Research Service report noted, "Financing major upgrades and expansions … beyond immediate maintenance needs is difficult to accomplish without congressional appropriations and, in some cases, authorizations."[65] Modernization projects at USACE facilities are often funded through agreements with customers and end users; however, uncertainty surrounding future water availability has made some end users hesitant to invest in large infrastructure projects for a potentially diminishing resource.

3.5.3 Staff Retention and Aging Workforce

Many Dams Sector jobs are highly technical or specialized and have limited turnover. Facilities are losing institutional knowledge as experienced workers retire. Operators find it is increasingly difficult to hire highly trained engineers and technicians with the right expertise who are also willing to relocate to the remote areas where many large hydro plants are located. This may lead to shortages of skilled and trained staff in the future.

[64] Zayas, David and Jim Miller, "Operational Excellence Program—Avoiding Events by Information Sharing," 2015; National Hydropower Association, "OpEx NHA Operational Excellence Program."

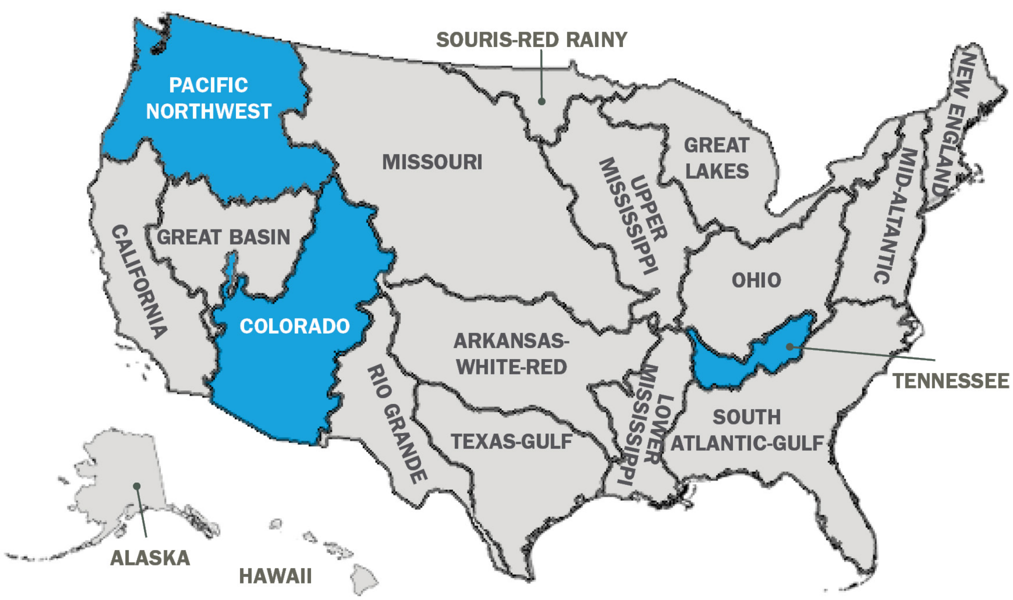
[65] Congressional Research Service, *Hydropower: Federal and Nonfederal Investment*, 2015.

4. Snapshot of Hydroelectric Dams Operations in Selected Major Watersheds

The operation of a hydroelectric power plant is subject to various internal and external factors. Internal factors include upstream and downstream conditions and controlling the volume and timing of water retained or released. External factors include constraints imposed by alternative uses of water (i.e., navigation, irrigation, water supply, fish habitat, recreation) that may lead to restricted flow rates.[66] As described earlier, droughts affect both water flow conditions and the need to distribute water designated for hydropower to other purposes, such as drinking water or irrigation.

The operation of a river system and hydroelectric plants on that river are guided by a set of complex rules, policies, and agreements that vary vastly by the location and functions of each river system. Although certain Federal laws apply to all major watersheds, numerous State and local laws specifically govern each river. In addition, river systems that cross national borders are subject to international policies and agreements. Each watershed faces distinct issues and policies. To explore these unique factors, this section provides a brief overview of three major river systems—the Columbia River, the Colorado River, and the Tennessee River—and the various issues affecting the hydro dam functions and operations in each watershed. Figure 10 shows major watersheds in the United States and highlights the areas included in this report. This section also discusses the hydroelectric potential of the Mississippi River region.

Figure 10.—Selected Major Watersheds in the United States.



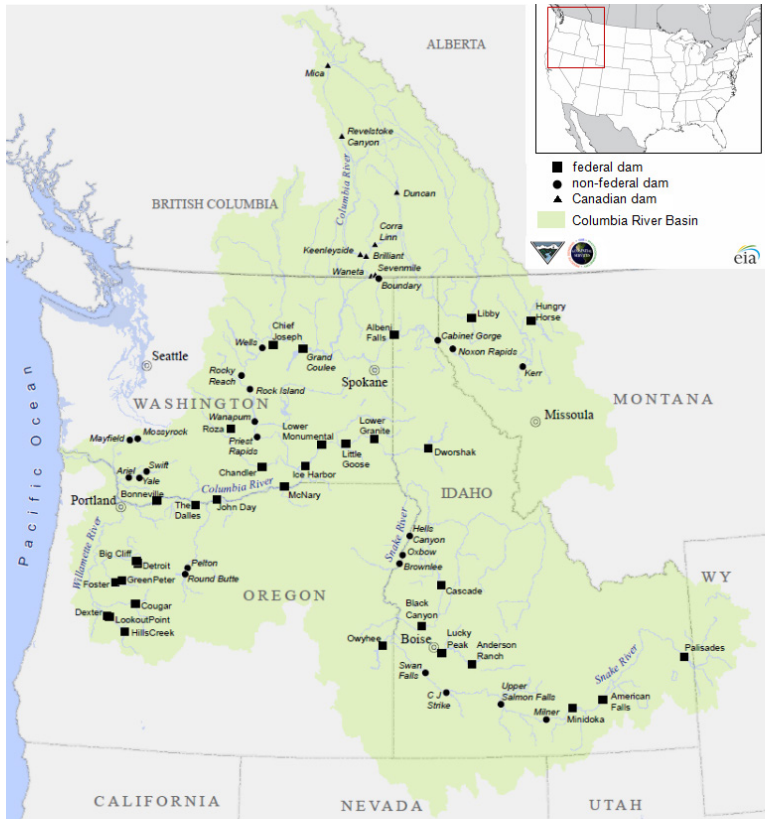
Source: Data gathered from the U.S. Geographic Service (USGS), "National Water Information System: Mapper."

[66] Martin-Amouroux, Jean-Marie, *The Economics of Hydroelectricity*, 2004.

4.1 The Columbia River System

The Columbia River basin is the predominant river system in the Pacific Northwest, encompassing over 400 dams that provide up to 80 percent of electricity needs in the Northwest.[67] The system spans seven western States: Washington, Oregon, Idaho, Montana, Wyoming, Nevada, and Utah, as well as British Columbia, Canada (see Figure 11).[68] USACE and Reclamation are the owners and operators of the 31 federally owned hydro projects in the river system; the Bonneville Power Administration (BPA) markets and distributes power generated at Federal dams in the region.[69]

Figure 11.—Major Dams within the Columbia River Basin.



Source: EIA, "The Columbia River Basin provides more than 40% of total U.S. hydroelectric generation."

Today, Columbia River system operations serve multiple purposes—flood control and mitigation, power production, navigation, recreation, and environmental needs—that are guided by a complex and interrelated set of laws, treaties, agreements, and guidelines. These include the Endangered Species Act, a Federal law that protects threatened or endangered species—protection that can result in setting restrictions on the time and amount of allowed flow and spill—as well as numerous treaties and agreements with Canada dealing with flood control and division of power benefits and obligations.[70]

Streamflow in the Columbia River system does not follow the region's electricity demand pattern, in which the peak occurs during winter when the region's homes and businesses need heating. Although around 60 percent of the natural runoff occurred during May, June, and July between 2009 and 2013, streamflows were significantly lower in 2015 than in previous years (see Figure 12). Typically, the objective of reservoir operation is to store snowmelt runoff in the spring and early summer for release in the fall and winter, when streamflows are lower and electricity demand is higher. However, on account of warmer than average weather in 2015, power demand was lower in the region overall, partially offsetting the low streamflow conditions.[71] In addition, BPA projects the water supply in 2016 to return to a normal level.[72]

[67] The term Columbia River System used in this report encompasses the tributaries of the Columbia River and the Snake River, as seen in Figure 9.

[68] BPA, et al., *The Columbia River System: Inside Story*, 2001.

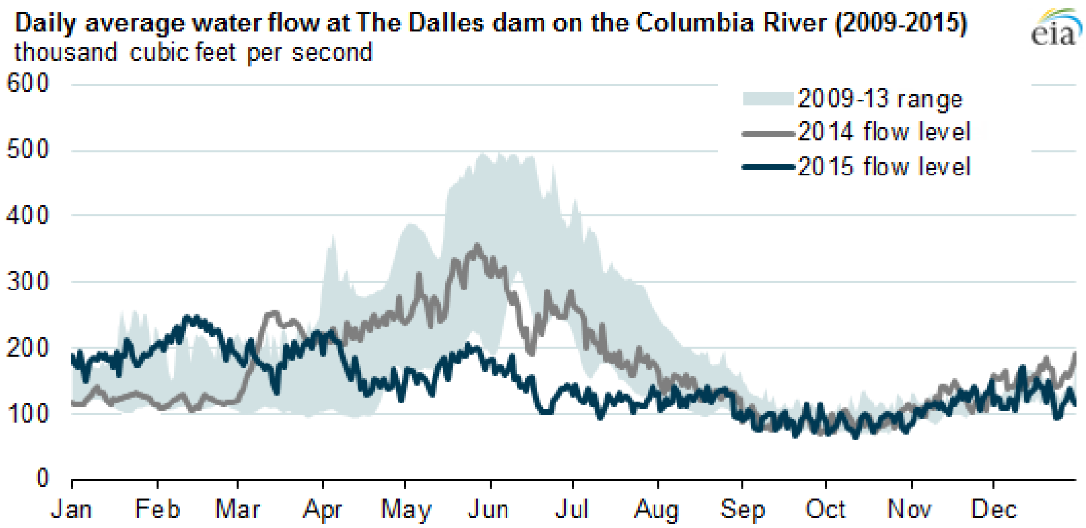
[69] BPA, "Federal Columbia River Power System."

[70] On average, about 25 percent of the Columbia River flow comes from Canada. See BPA, et al., *The Columbia River System: Inside Story*, 2001.

[71] BPA, "BPA expecting normal water year operations," 2016.

[72] Ibid.

Figure 12.—Daily Average Streamflows at The Dalles Dam on the Columbia River between 2009 and 2015.



Source: EIA, "Wholesale power prices decrease across the country in 2015."

4.1.1 Hydropower Operation and Planning

Hydropower supplies up to 80 percent of the electricity in the Pacific Northwest.[73] In the Columbia River system, power generation operations are increasingly affected by water resource sustainability and abnormal weather conditions.[74] In particular, warmer weather may strain fisheries and natural ecosystems.[75] Additionally, more extreme weather patterns, a trend that started in the last decade, are making it more difficult to keep reservoirs filled for power generation while avoiding flooding in downstream areas.[76] In response, Reclamation and other owners and operators on the Columbia River are using and further developing strategies that incorporate water management flexibility.[77]

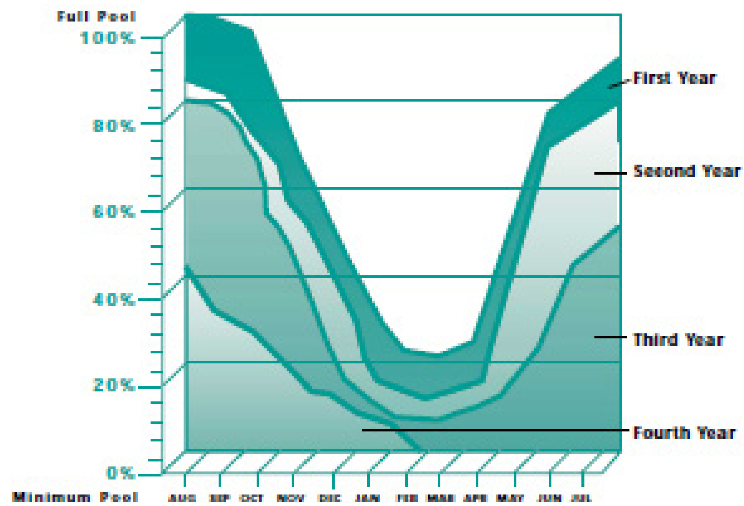
The current strategy requires increased water storage in the fall and winter and increased flows and spill during the spring and summer to benefit migrating juvenile salmon. For example, in spring 2015, there had been less precipitation than usual, and extra water was released to maintain fish populations.[78] (See Figure 13 for critical rule curves applied at a typical Columbia River reservoir.) This approach does not provide an optimal operating strategy for power generation, as it results in more water for fish protection but reduced hydropower generation during peak demand periods. Due to this strategy, BPA purchased power during high load periods in the winter and sold surplus power in the spring and summer. In 2015, low snowpack and early runoff led to low streamflows and warm water in the summer that killed 90 percent of returning sockeye salmon, despite attempts to cool the water with additional releases from the Dworshak Reservoir in Idaho.[79]

Two agreements, the Pacific Northwest Coordination Agreement (PNCA) and the Columbia River Treaty, underpin how the Columbia River system functions in a coordinated fashion. The Columbia River Treaty enables improved water

[73] Reclamation, *Basin Report: Columbia River*, 2016.
[74] Ibid.
[75] Ibid.
[76] Ridler, Keith, "Wild Times for Water Managers," 2016.
[77] Reclamation, "Chapter 4: Columbia River Basin," 2016.
[78] BPA, *Path to Success: 2015 Annual Report*, 2015.
[79] Ridler, Keith, "Wild Times for Water Managers," 2016.

storage and annual planning for river projects with Canada, from which 25 percent of the streamflow originates. The treaty can be amended or ended with 10 years' notice.

Figure 13.—Critical Rule Curves for a Typical Columbia River Reservoir



Source: BPA, *The Columbia River System Inside Story*.

PNCA directs the coordination among the Federal project operators and hydroelectric generating utilities in the region, and enables the optimization of system reliability and power production, provided that it is consistent with requirements for nonpower uses or functions.[80] The PNCA Coordinating Group, composed of BPA, USACE, Reclamation, and major generating utilities in the Pacific Northwest and Canada, oversees planning and operation for power production. Annually, the group develops a set of operating guidelines called "operating rule curves" to guide reservoir operations for power production. Such planning is based on the possibility that the lowest historical streamflow conditions ("four-year critical period" from 1928 to 1932) could recur. The guidelines also include a flood control curve that requires an adequate space in the reservoir to regulate the predicted runoff for the year without causing flooding downstream.

4.1.2 Effects of Changing Streamflow on Hydroelectric Power Generation

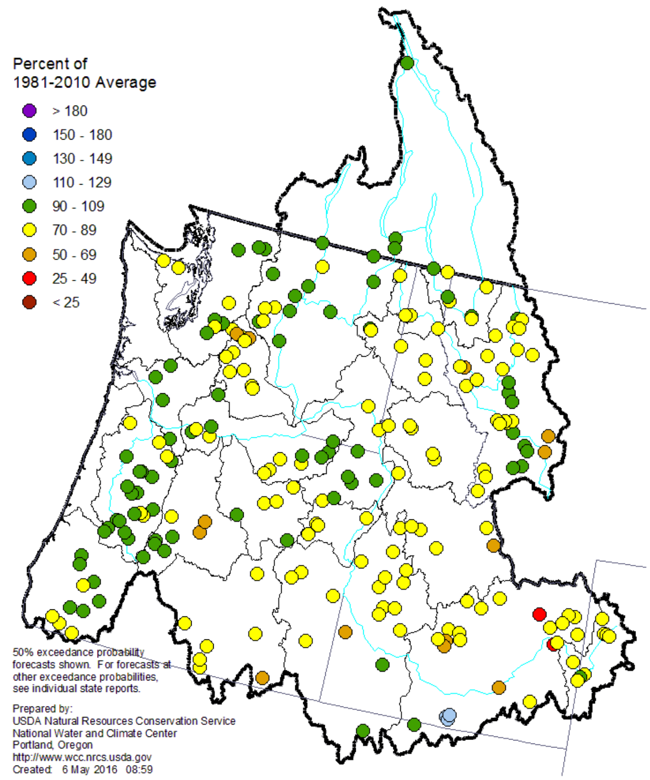
The Pacific Northwest has been affected by reduced snowpack levels, increased temperatures, and changing runoff patterns. On account of lower-than-average snowpack levels measured in May 2016, spring and summer streamflows are also projected to be average or below average in many areas (see Figure 14). Reclamation's 2016 *Columbia River Basin Climate Impact Assessment* indicated that warmer temperatures will be increasingly common in future years, with more precipitation during the winter and less during the summer. [81] Although the level of yearly precipitation is unlikely to change significantly, the timing of precipitation could shift drastically over time.[82] The study covered 157 locations over the next seven decades.[83] Simultaneously, Reclamation led basin studies on the Yakima and Snake Rivers through the WaterSMART program, which were designed to inform long-term risk-mitigation strategies.[84] Reclamation has also started to address these climate effects with "adaptation actions," which include water conservation, efforts to support water development in rural areas, and future operations planning.[85]

The runoff levels in the second half of fiscal year 2015 were the lowest in nine years, on account of warm weather in the fall and winter and drought conditions during the spring and summer.[86] In most of the Columbia Basin, peak streamflows

[80] USACE, *1997 Pacific Northwest Coordination Agreement*, 1997.
[81] Geranios, Nicholas K, "Study looks at future water in Columbia River Basin," 2016.
[82] Ibid.
[83] Geranios, Nicholas K, "Study looks at future water in Columbia River Basin," 2016.
[84] Reclamation, *Basin Report: Columbia River*, 2016.
[85] Ibid.
[86] BPA, *Path to Success: 2015 Annual Report*, 2015.

occurred one month earlier than usual in 2015.[87] Although extra water was released to stabilize flood management and power generation operations,[88] this weather pattern is indicative of the larger trend identified in Reclamation's climate impact assessment, with increased precipitation in winter months making flood control more difficult.[89]

Figure 14.—Projected Streamflow in Columbia River Basin in Spring and Summer 2016.



Source: National Resources Conservation Service, "Spring & Summer Streamflow Forecast Maps for The Columbia River Basin."

In 2015, the Northwest Power and Conservation Council, an organization developing a fish and wildlife program and a 20-year regional power plan for the Columbia River Basin,[90] released a Power Supply Adequacy Assessment for the Pacific Northwest region for the 2020 to 2021 operating years. The Council determined the power supply "is expected to be adequate through 2020." However, according to the assessment, the probability of a power supply shortage in 2021 will rise to over 8 percent, in part because of the planned retirements of the Boardman and Centralia-1 coal plants.[91]

Currently, several hydro power generation facilities are undergoing upgrades that will expand production capacity over the next decade or so. This includes a potential increase of 510 MW to the Grand Coulee Dam, the largest hydroelectric facility in the United States, and a turbine replacement at Palisades Dam and Reservoir that will extend the facility's lifespan by at least 50 years and return the facility to its full potential of 176.5 MW, among other modernization projects.[92] BPA, generally a net exporter of energy, often has a balancing authority generation that exceeds load, as shown in Figure 15. In the meantime, BPA has denied a proposed rate segmentation policy by some larger and more urban customers, asserting that it would not change its tiered rate policies to disadvantage lower-income and rural customers.[93]

In fiscal year 2015, purchased power expenses totaled $76 million, which was $123 million less than fiscal year 2014.[94] The primary reason for this substantial decrease was the warmer and wetter weather between October 2014 and March

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[87] Ridler, Keith, "Wild Times for Water Managers," 2016.

[88] BPA, *Path to Success: 2015 Annual Report*, 2015.

[89] Reclamation, *Basin Report: Columbia River*, 2016.

[90] The Northwest Power and Conservation Council, "Mission and Strategy."

[91] The Northwest Power and Conservation Council, "Pacific Northwest Power Supply Adequacy Assessment for 2020-21," 2015.

[92] Reclamation, "Chapter 4: Columbia River Basin," 2016; Bedwell, Jamie, "Despite Troubled Past, Hydro Remains Dominant Renewable Energy Source in West," 2011.

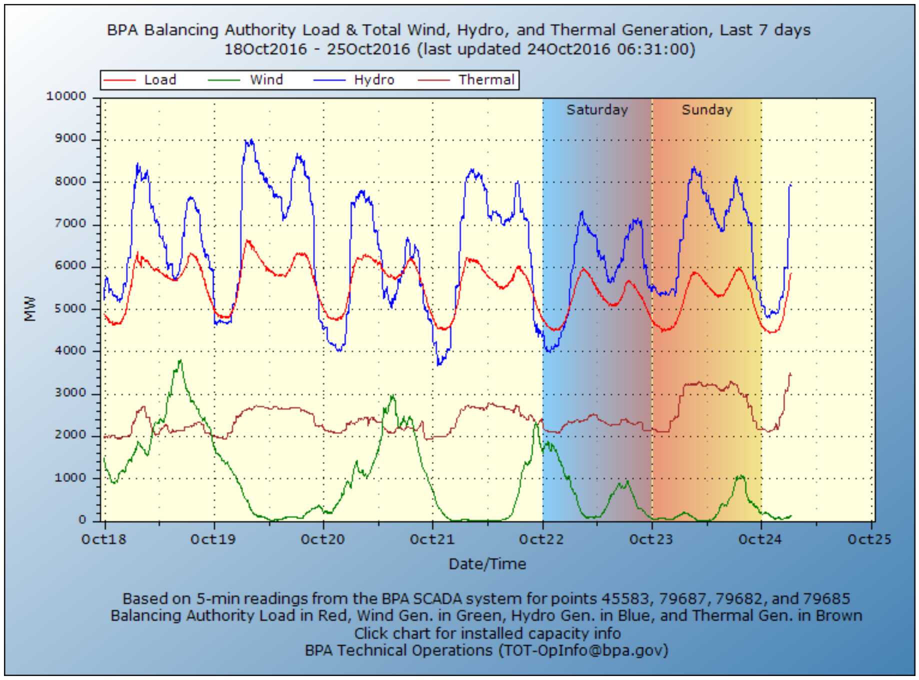
[93] Columbia River PUD, *Transmission Segmentation Discussion and Proposed Principles*, 2014.

[94] BPA, *Path to Success: 2015 Annual Report*, 2015.

2015. In addition to climate patterns, low power prices resulted in greater than usual water storage. Among other effects, this led to a dam in British Columbia, which usually receives credit from BPA, instead owing expenses to BPA.[95]

The Columbia River Basin is likely to face many climate-related challenges in the coming years. Overall, warmer temperatures could cause "increased stress" on salmon habitats and increase electricity demand, water demands for power production, and the potential for invasive species to take hold in the ecosystem.[96] In March 2016, DOI and Reclamation released the *SECURE Water Act Section 9503(c)—Reclamation Climate Change and Water* report, which provides a basin-by-basin analysis characterizing adaptation strategies to better protect major river basins in the West. The report identifies specific problems, such as increasing temperatures in the area; an increase in precipitation in areas with higher elevation; and rain instead of snow at lower elevations, which will increase winter runoff levels.[97] In response to altered water supply patterns, Reclamation is developing a process for evaluating what modifications are necessary at regional facilities. A pilot operations study in 2016 to 2018 will examine a specific river basin.[98]

Figure 15.—BPA Balancing Authority Load, October 18-October 25, 2016.



Source: BPA, "BPA Balancing Authority Load and Total Wind, Hydro, and Thermal Generation, Near-Real-Time."

4.2 The Colorado River System

The Colorado River is considered one of the most legally complex river systems in the world, governed by multiple interstate and international compacts, legal decrees, and prior appropriation allocations, as well as federally reserved water rights for Native Americans.[99] The river basin extends over seven U.S. States—Arizona, California, Colorado, Nevada, New Mexico, Utah, and Wyoming—and parts of northwestern Mexico (see Figure 16), serving about 25 million people in the Southwest. Its water yield is only 8 percent of the annual flow of the Columbia River, yet it is arguably the most regulated river in the country.[100]

The river is governed by the "Law of the River" that consists of the 1922 Colorado River Compact (Compact) and the 1948 Upper Colorado River Basin Compact, along with the 1944 International Treaty with Mexico, a number of Federal

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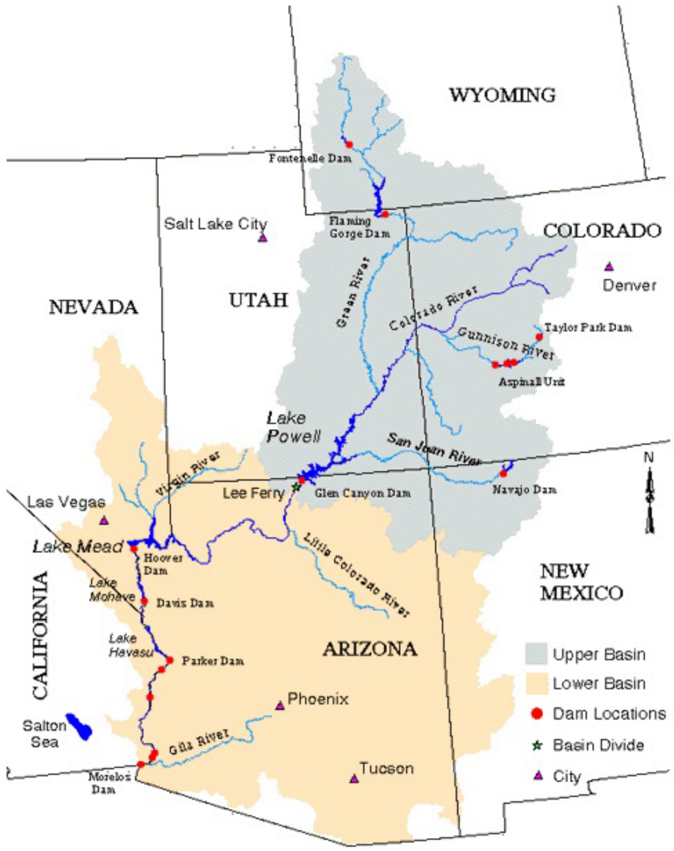
[95] BPA, *Path to Success: 2015 Annual Report*, 2015.
[96] Reclamation, *Basin Report: Columbia River*, 2016.
[97] Reclamation, *Secure Water Act*, 2016.
[98] Reclamation, "Chapter 4: Columbia River Basin," 2016.
[99] Western Water Assessment, "Management and Policy."
[100] Western Water Policy Review Advisory Commission, *Colorado River Basin Study: Final Report*, 1997.

laws, and U.S. Supreme Court decisions.[101] The river is divided into two areas, upper Colorado and lower Colorado, and water is allocated equally between the two regions based on historical rainfall patterns. However, the Compact that regulates the water allocation is believed to have been negotiated in a period of abnormally high rainfall, resulting in allocation of water greater than a sustainable quantity.[102] Consequently, the river has been a source of disputes among States, between the United States and Mexico, between cities and farms, between power users and conservationists, and between Native American tribes and non-tribal water users.[103]

Figure 16.—Colorado River Basin.



Source: Colorado River Commission of Nevada, "Maps."

4.2.1 Drought in the Southwest

The Southwest has been experiencing an extended period of drought since 2000. According to a 2016 study published in in the journal *Geophysical Research Letters*, weather systems that typically bring moisture to the southwestern United States are forming less often, resulting in a drier climate across the region.[104] The map in Figure 17 depicts the portion of overall changes in precipitation across the United States that can be attributed to these changes in weather system frequency. The gray dots represent areas where the results are statistically significant. The Southwest, particularly California, has experienced a significant drop in precipitation since 1980. Conversely, the Northeast has experienced an increased level of precipitation during the same period.

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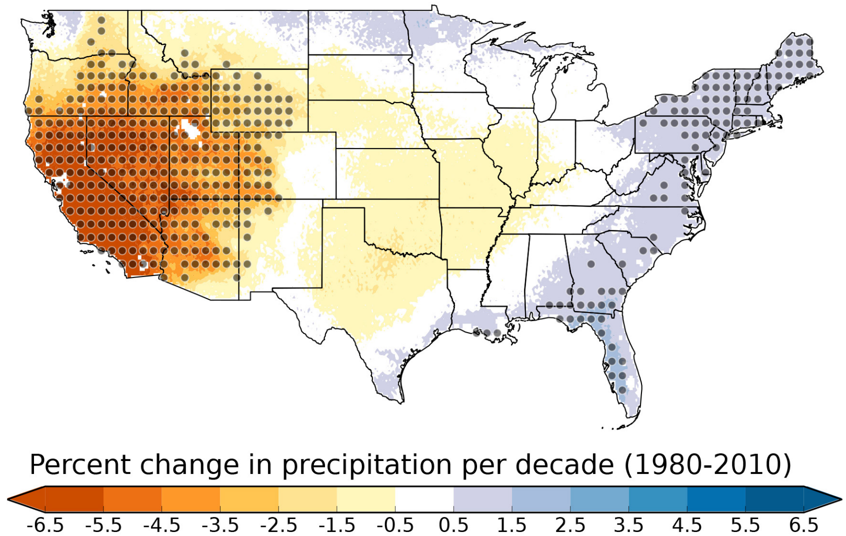
[101] Reclamation, "The Law of the River," 2008.

[102] The Colorado River Water Conservation District, *Colorado River Compacts*, 2014.

[103] Western Water Policy Review Advisory Commission, *Colorado River Basin Study: Final Report*, 1997.

[104] Prein, Andreas F., et al., "Running Dry: The U.S. Southwest's Drift into a Drier Climate State," 2016.

Figure 17.—Map of Changing Precipitation Pattern in the United States between 1980 and 2010.



Source: National Center for Atmospheric Research, "Southwest Dries as Wet Weather Systems Become More Rare."

According to scientist Greg Holland, "As temperatures increase, the ground becomes drier and the transition into drought happens more rapidly. In the Southwest, the decreased frequency of rainfall events has further extended the period and intensity of these droughts."[105]

4.2.2 Effects of Droughts on Hydroelectric Power Generation

The various tributaries and reservoirs along the Colorado River are controlled by a number of dams. The Glen Canyon Dam is a major dam on the main stem of the Colorado River above Lee's Ferry in the Upper Basin; the Hoover Dam controls Lake Mead, which is the major reservoir for all of the States found in the Lower Basin of the Colorado River (see Figure 16).[106]

Figure 18 shows the annual flow volume at Lee's Ferry between 1905 and 2016. Since 2000, the Colorado River Basin has been experiencing a historic, extended drought that has affected regional water supply and other resources, such as hydropower, recreation, and ecological services. During this time, the Basin has experienced its lowest 16-year period of inflow in the 100-year recorded history, and reservoir storage in the Colorado River system has declined from nearly full to about half of capacity. During this period of drought, water use issues intensified as the Colorado River region experienced some of the Nation's highest population growth.[107] The likely causes of low flows since 2000 are mainly due to the below average precipitation received, which is likely natural variability, and the above-average temperatures.[108] The Colorado River region is of particular concern because of the continuing trend of rising temperatures seen across the region that contributes to increased evaporative losses from snowpack, surface reservoirs, irrigated land, and vegetated surfaces.[109] Although certain temperature trends are evident, the projections of future precipitation remain unclear, leading to uncertainty in possible changes in future streamflow in the Colorado River.

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[105] National Center for Atmospheric Research, "Southwest Dries as Wet Weather Systems become More Rare," 2016.

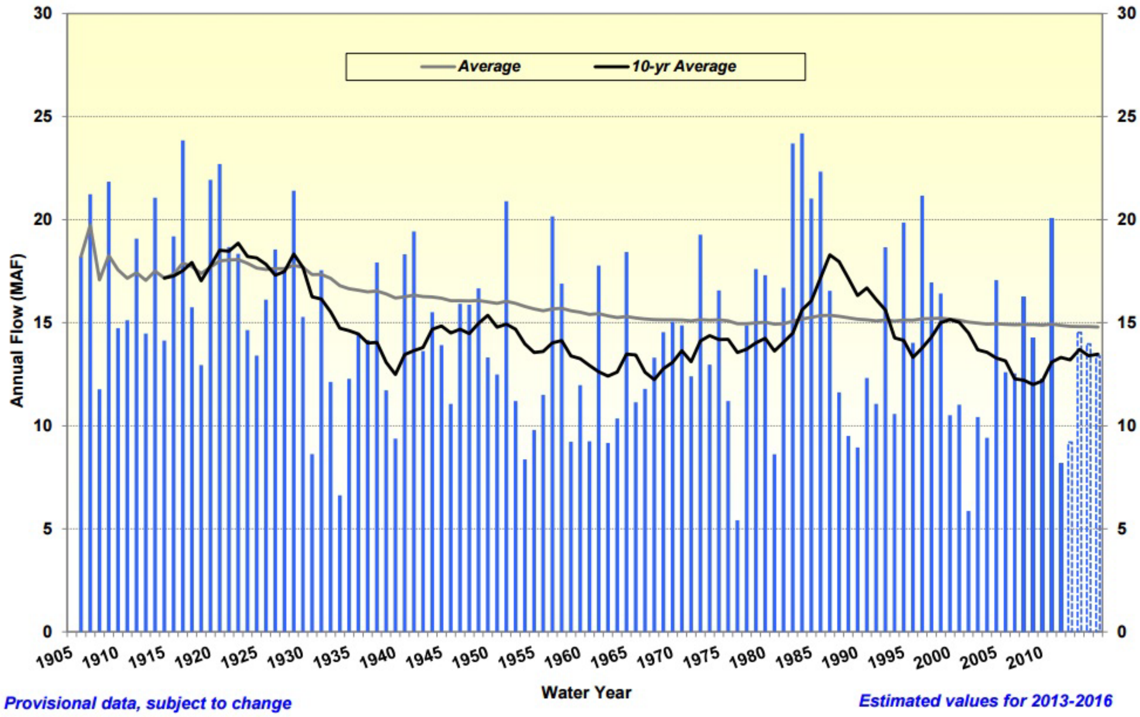
[106] Massachusetts Institute of Technology, "Colorado River."

[107] U.S. Census Bureau, "Map."

[108] Kenney, Doug, et al., "Challenges for the Colorado River Basin," 2013.

[109] Committee on the Scientific Bases of Colorado River Basin Water Management, *Colorado River Basin Water Management*, 2007.

Figure 18.—Annual Flow Volume in the Colorado River at Lee's Ferry from 1905 to 2016.



Source: Time-series plot of the annual flow volume (in millions of acre-feet) for the Colorado River at Lee's Ferry. Reclamation, "The Colorado River System: Projected Future Conditions 2017-2021."

To ascertain what the future consequences might be, Reclamation and the National Park Service (NPS) completed an environmental impact statement to analyze dam operations and inform "a framework for adaptively managing operations of Glen Canyon Dam over the next 20 years."[110] DOI's Glen Canyon Dam Adaptive Management Program also conducted long-term research and experimental programs to "authorize changes in flow releases from the dam to meet water and power needs, but also to allow better conservation of sediment downstream; more targeted efforts to control non-native fish predation; and continued scientific experimentation, data collection, and monitoring to better address the important resources in the Colorado River below Glen Canyon Dam."[111] In 2015, Lake Powell was at less than half its capacity than when the dam was first erected, due to water delivery obligations and drought conditions.[112] Since 1996, for environmental purposes, hydropower generation at the dam has been restricted by about one third. The *Record of Decision for the Long-Term Experimental and Management Plan Environmental Impact Statement*, signed by the Secretary of the Interior on December 15, 2016, will further restrict hydro generation at the dam.

According to the *SECURE Water Act* report, temperatures in the Colorado River Basin are projected to increase by five to six degrees Fahrenheit during the 21st century on average.[113] The report also forecasts that precipitation in the Colorado River Basin will remain variable with a slight increase in the Upper Basin. Further, snowpack in high-altitude and high-latitude areas of the Colorado River Basin is projected to increase during the 21st century, while warmer conditions at

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110 Reclamation and NPS, "About the LTEMP EIS."

111 DOI, "Salazar Announces Improvements to Glen Canyon Dam Operations to Restore High Flows and Native Fish in Grand Canyon," 2012.

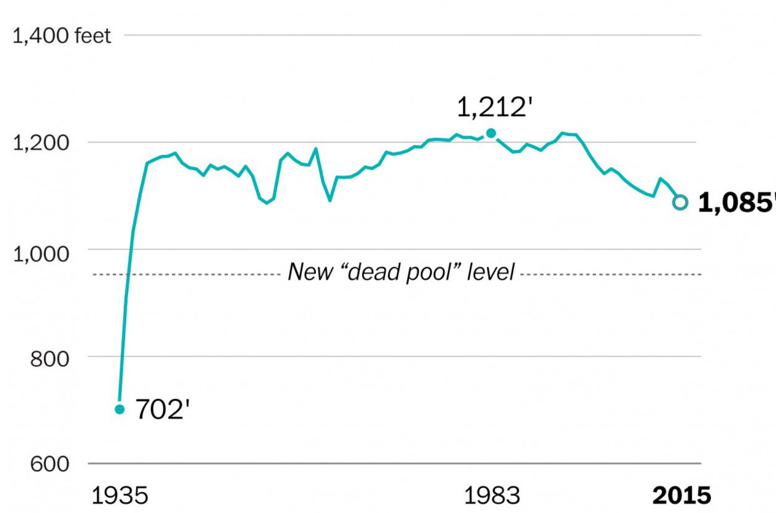
112 However, hydrologic variability results in constantly changing reservoir levels. The current information can be found at https://www.usbr.gov/uc/water/index.html.

113 Bureau of Reclamation, *Basin Report: Colorado River*, 2016.

lower elevations are projected to transition snowfall to rainfall, producing more runoff in December to March and less in April to July.[114] The *SECURE Water Act* report also predicts that future projected development of water supplies and increased consumptive use in the Upper Basin, combined with potential reductions in future supply, will result in reduced volumes of water stored in system reservoirs and a vulnerability to water delivery shortages in the Colorado River Basin.[115]

A wide variety of measures have been implemented to alleviate the effects of drought in the Colorado River Basin. Because engineers were worried that Lake Mead would hit a 1,050-foot "dead pool" level where the water is too low to efficiently turn the dam's turbines (see Figure 19), Reclamation installed five $3.5 million wide-head turbines at the Hoover Dam since 2010.[116] These newly installed turbines would allow the generating units to operate more efficiently over a wide range of water levels, enabling Hoover Dam to generate power at lake levels as low as 950 feet. The older turbines are rated for 130 MW, but are only able to generate closer to 100 MW; however, the new turbines are seeing closer to 90 percent energy conversion.[117]

Figure 19.—Lake Mead Elevation, 1935-2015.



Source: Todd C. Frankel, "Western drought steals clean energy along with fresh water at power plants."

A recent Reclamation report predicts Lake Mead may hit a water shortage in 2018—declared when its water levels fall below 1,075 feet—as the elevation will reach around 1,079 feet at the end of December 2016, and fall to 1,074 in December 2017.[118] Officials are currently negotiating to extend a 2012 agreement between the United States and Mexico—Minute 319—in which "Mexico stores water in Lake Mead to help bolster the reservoir's falling water levels," and takes part in "both surpluses and shortages as they're declared for the reservoir."[119] Additionally, a 2014 Reclamation Pilot System Conservation Program—involving lower Colorado River basin projects in California, Nevada, and Arizona—estimates it has conserved more than 16 billion gallons of water through "storage initiatives and demand reduction."[120]

Figure 20 illustrates the projected future supply and demand in the Colorado River Basin, as a result of the *Colorado River Basin Water Supply and Demand Study* (Basin Study). The Basin Study was conducted from January 2010 through December 2012 in a joint effort by Reclamation and the Basin States. Directed in collaboration with a diverse range of stakeholders, the Basin Study described current and future water supply and demand imbalances in the basin through the year 2060 and presented options and strategies to resolve those imbalances.[121] The Basin Study confirmed that without timely action, there is likely to be significant shortfalls between projected water supplies and demands in the basin in

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[114] Ibid.

[115] Reclamation, *SECURE Water Act*, 2016.

[116] Cartledge, James, "Hoover Dam Turbines Set for Upgrade to Cope with Drought," 2010.

[117] McManes, Chris, "Modern Technology Helps American Icon Generate More Power," 2014.

[118] Harvey, Chelsea, "Climate Change is Water Change," 2016.

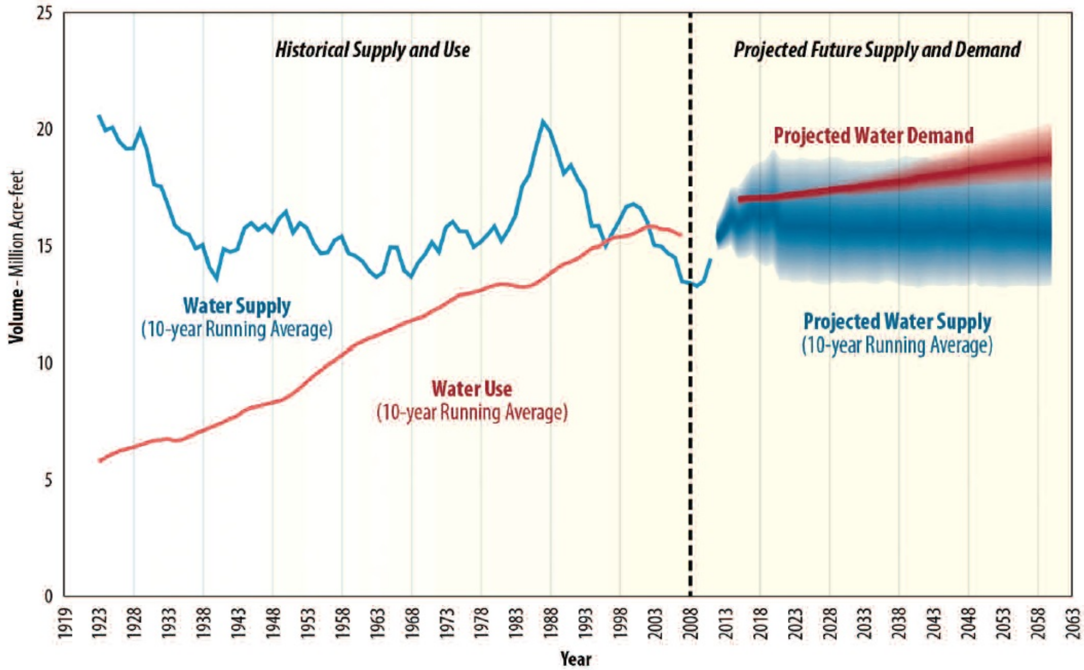
[119] Ibid.

[120] Ibid.

[121] Bureau of Reclamation, *Basin Report: Colorado River*, 2016.

coming years. Such shortfalls are likely to affect a number of sectors, including Energy, which depend on the Colorado River and its tributaries.

Figure 20.—Colorado River Supply and Demand Projected to 2063.



Source: Reclamation, *Basin Report: Colorado River*.

The Basin Study concluded that addressing such imbalances and pending shortfalls cannot be resolved through any single approach or option. Rather, the implementation of a broad range of options would enhance the Basin's resilience to dry hydrologic conditions while meeting increasing demands in the Basin.[122] The options are:

- Resolve uncertainties related to water conservation, reuse, water banking, and weather modification concepts.
- Identify and investigate costs, permitting issues, and energy needs related to large-capacity augmentation projects through feasibility-level studies.
- Pursue opportunities to enhance the resolution of future climate projections and the operational and planning tools used in the Colorado River system to better understand vulnerabilities.
- Consider projects, policies, and programs that provide a wide range of benefits to water users and healthy rivers for all users.[123]

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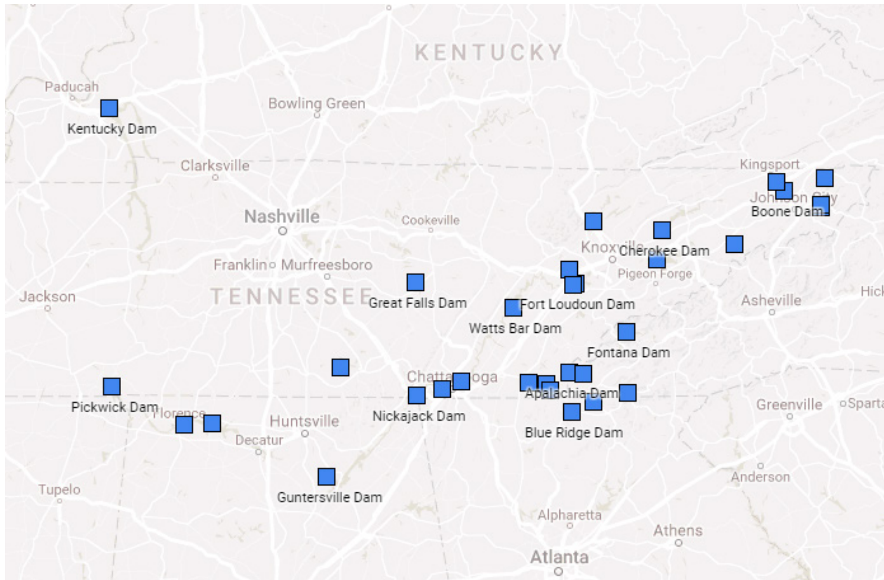
[122] Reclamation, *Colorado River Basin Water Supply and Demand Study: Executive Summary*, 2012.
[123] Ibid.

4.3 Tennessee River System

The Tennessee River system territory includes most of Tennessee and parts of Alabama, Georgia, Kentucky, Mississippi, North Carolina, and Virginia. The Tennessee Valley Authority (TVA) manages the Tennessee River and its reservoirs as a whole, regulating the flow of water through the river system for flood control, navigation, power generation, water quality, and recreation. Serving more than 9 million people, TVA is one of the Nation's largest public power providers.[124] Wholly owned by the U.S. Government, it maintains 29 conventional hydroelectric dams and one pumped storage plant.[125]

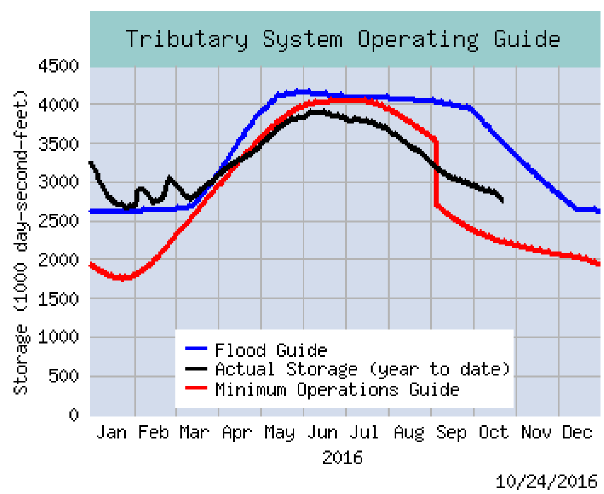
Figure 21.—Tennessee Valley Authority Hydroelectric Dam Locations.



Source: TVA, "Our Power System."

TVA monitors and controls the flow of the Tennessee River and the water levels of individual reservoirs within the system, ensuring riverbeds below each dam do not dry out and that enough water flows through the river system to meet downstream needs. To meet these requirements, TVA constantly monitors factors affecting reservoir inflows, including precipitation and weather patterns, to forecast river conditions and to ensure adequate preparation and planning (see Figure 22 for the year-to-date 2016 TVA operating curves). On average, the Tennessee Valley gets 51 inches of rain a year, with the Gulf of Mexico and hurricanes and tropical storms in the Southeast providing most of this moisture.[126]

Figure 22.—Tennessee River Operating Curves.



Source: TVA, "How TVA Manages Water Levels."

Though the Tennessee Valley typically experiences above-average rainfall compared to the rest of the United States, the region is significantly affected in dry years. During these times, the TVA system of dams and reservoirs is critical to ensuring the reliability of water supply throughout the region. For example, due to the southeastern drought of 2007 to 2008, rainfall in the Tennessee Valley in 2007 was almost 17 inches below normal.[127] Several States in the Tennessee Valley, including Tennessee, Alabama, Georgia, and North

[124] TVA, "About TVA."
[125] TVA, "Hydroelectric."
[126] TVA, "Valley Rainfall."
[127] Bach, Chuck, "The Drought: 2007 Impacts, 2008 Outlook," 2008.

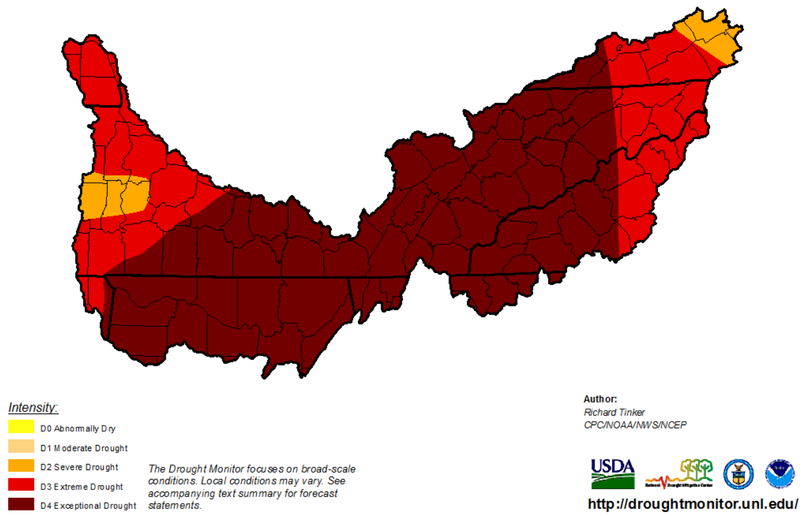
Carolina, implemented water conservation measures or declared drought disasters or states of emergency during this time.[128] Water supply concerns in the region continue to increase due to population growth and interbasin transfers, especially since the Tennessee River is surrounded by areas that may require more water to accommodate growing needs. TVA and the U.S. Geological Study estimate that by 2030 about 1.2 million people will be added to the Tennessee River Watershed's existing 4.7 million residents.[129]

4.3.1 Effects of Droughts on Hydroelectric Power Generation

The 2007 to 2008 droughts in the TVA region were among the worst on record (see Figure 23). Even as the drought began to ease in early 2008, TVA hydroelectric generation was still only at 49 percent of normal operation.[130]

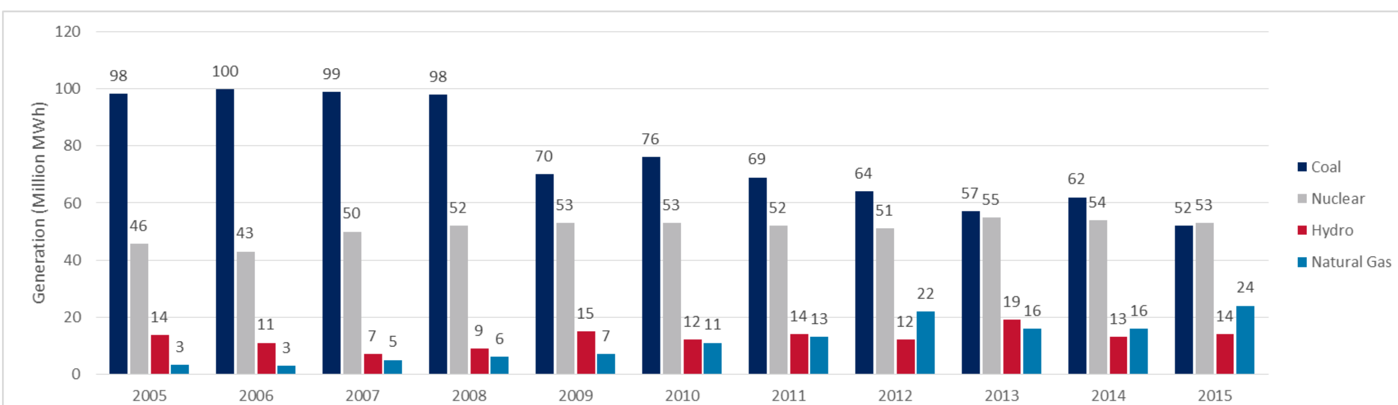
During the drought, coal prices also more than doubled, forcing TVA to rely on additional natural gas purchases to meet electric generation needs while keeping prices as low as possible. Even with the increased reliance on natural gas as opposed to coal, TVA raised rates by 20 percent in October 2008 to absorb more than $2 billion of increased costs for coal, natural gas, and purchased power.[131] Figure 24 shows TVA's generation profile from 2005 to 2015.

Figure 23.—Drought Observed in the Tennessee Watershed on September 11, 2007.



Source: The National Drought Mitigation Center, "U.S. Drought Monitor: Tennessee Watershed."

Figure 24.—TVA Generation Profile, 2005-2015.



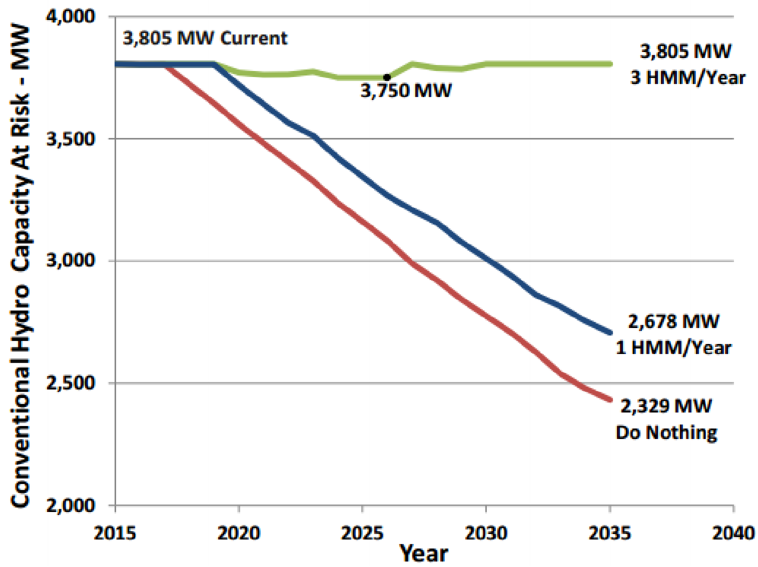
Source: EIA-923 database.

[128] NOAA, *State of the Climate: Drought for Annual 2007*, 2008.
[129] TVA, "Managing Water Supply."
[130] Bach, Chuck, "The Drought: 2007 Impacts, 2008 Outlook," 2008.
[131] Flessner, Dave, "Tennessee Valley Authority Boosts Rates Again Due to Higher Fuel Costs," 2008.

To address these and other water supply issues, the Tennessee Valley Water Partnership Drought Committee was formed in 2004. The committee consists of representatives from the following States and agencies: TVA, Alabama, Georgia, Kentucky, Mississippi, North Carolina, Tennessee, Virginia, the EPA, and the USGS.[132] The committee is activated when drought conditions are severe or worse with tributary reservoir levels below the system minimum operating guidelines. The committee allows participants to share strategies and resources and to coordinate information sharing.

From 1992 to 2014, TVA conducted a Hydro Modernization Program to complete major refurbishments to restore the power train and to increase capacity, upgrading about 60 units.[133] Due mostly to installing more efficient turbines, TVA increased its capacity by 536 MW and improved average efficiency by 5 percent.[134] It is currently conducting a Hydro Major Maintenance (HMM) Program that will extend critical assets beyond their life cycle, prioritizing maintenance by condition and risk to upgrade about three units per year (Figure 25 shows how these upgrades may affect hydro capacity).[135]

Figure 25.—Capacity Projections for HMM Unit Upgrades.



Source: Alex D. Mosley, "Hydro Capacity Preservation & Expansion."

This demonstrates the importance of maintenance on aging infrastructure and how upgrades increase the efficiency of hydro facilities and their ability to produce electricity using less water.[136] TVA is also exploring other ways to increase capacity, including by expanding existing dams, adding capacity to non-hydro dams, and increasing pumped storage capacity.[137]

4.4 Mississippi River Region: Untapped Hydroelectric Potential

Energy companies have harnessed the power of the Mississippi River for over a century. The Keokuk Renewable Energy Center near Keokuk, Iowa, is the largest hydroelectric generating plant on the river, with a net capacity of 142 MW.[138] Built in 1913 and inducted into the Hydro Hall of Fame in 2013,[139] Keokuk Energy Center and Dam currently supplies enough electricity each year for 75,000 homes and controls water levels to enable barge traffic up and down the river.[140] Many other locks and dams on the Mississippi River that were built to aid transportation have untapped potential for hydropower generation. According to a study by the DOE Wind & Water Power Program, the hydroelectric generation

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[132] Tennessee Department of Environment and Conservation, *Drought Management Plan*, 2010.
[133] Mosley, Alex D., "Hydro Capacity Preservation & Expansion," 2016.
[134] Ibid.
[135] Ibid.
[136] Mosley, Alex D., "Hydro Capacity Preservation & Expansion," 2016.
[137] Ibid.
[138] Martin, Kent, "Keokuk Energy Center: Harnessing the Power of the Mississippi," 2013.
[139] Ibid.
[140] Ameren Missouri, "Keokuk Renewable Energy Center."

capacity of existing non-powered dams in the Mississippi River region is more than 12 million MWh per year. The Melvin Price Locks & Dam alone has nearly 300 MW of capacity.[141]

Since the Mississippi River Basin covers nearly half of the United States,[142] it can be significantly affected by major regional droughts. In 2012 to 2013, levels of the Middle Mississippi River dropped 30 to 50 feet compared with 2011 levels,[143] which threatened barge cargo transports, including 60 percent of U.S. farm exports that are transported by the Mississippi River at some point in their journey.[144] Though hydroelectric power could expand power generation from renewables in the Mississippi River Basin, this energy source could be affected by droughts and other unpredictable events.

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141 DOE, *An Assessment of Energy Potential at Non-Powered Dams in the United States*," 2012.
142 Ibid.
143 Sosnowski, Alex, "2012 Drought Impacting Mississippi River Barges," 2012.
144 Rizzo, Johnna, "How Drought on Mississippi River Impacts You," 2013.

Appendix A. Acronyms and Abbreviations

Avg.	Average
Basin Study	Colorado River Basin Water Supply and Demand Study
BPA	Bonneville Power Administration
CIPAC	Critical Infrastructure Partnership Advisory Council
Compact	1922 Colorado River Compact
CPP	Clean Power Plan
DHS	U.S. Department of Homeland Security
DOE	U.S. Department of Energy
DOI	U.S. Department of the Interior
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
ERS	Energy Renewable Standards
FERC	U.S. Federal Energy Regulatory Commission
GCC	Government Coordinating Council
Gen.	Generation
GW	Gigawatt
HMM	Hydro Major Maintenance Program
IT	Information technology
MW	Megawatt
MWh	Megawatt hours
NCSL	National Conference of State Legislatures
NERC	North American Electric Reliability Corporation
NIPP 2013	*National Infrastructure Protection Plan 2013: Partnering for Critical Infrastructure Security and Resilience*
NOAA	National Oceanic and Atmospheric Administration
NPS	National Park Service
NRC	U.S. Nuclear Regulatory Commission

NYPA	New York Power Authority
PNCA	Pacific Northwest Coordination Agreement
PSH	Pumped storage hydropower
PUD	Public Utility District
Reclamation	U.S. Bureau of Reclamation
RPS	Renewable Portfolio Standard
SCADA	Supervisory Control and Data Acquisition
Seattle	Seattle City of Light
SCC	Sector Coordinating Council
SSA	Sector-Specific Agency
TVA	Tennessee Valley Authority
USACE	U.S. Army Corps of Engineers
USGCRP	U.S. Global Change Research Program
USGS	U.S. Geographic Service

Appendix B. Glossary of Terms

Black start capability: Ability of a generating unit or station to start operating and delivering electric power without assistance from the electric system. Black start units are essential to restart generation and restore power to the grid in the event of an outage.

Critical rule curve: Reservoir elevations that must be maintained to ensure that firm hydro energy requirements can be met under the most adverse streamflows on record.

Drought: Period of unusually persistent dry weather that causes serious problems, such as crop damage and/or water supply shortages. The severity of a drought depends on the degree of moisture deficiency, the duration, and the size of the affected area.

Drought can be defined in four different ways:

- Meteorological: A departure from normal precipitation. Due to climatic differences, what might be considered a drought in one location of the country may not be a drought in another location;
- Agricultural: The amount of moisture in the soil no longer meets the needs of a particular crop;
- Hydrological: Surface and subsurface water supplies are below normal; and
- Socioeconomic: Physical water shortages begin to affect people.[145]

Flood control curve: The drawdown required to ensure adequate space is available in the reservoir to regulate the predicted runoff for the year without causing flooding downstream.

Peaking capacity: Capacity of generating equipment normally reserved for operation during the hours of highest daily, weekly, or seasonal loads. Some generating equipment may be operated at certain times as peaking capacity and at other times to serve loads on an around-the-clock basis.

Renewable Energy Credits: The property rights to the environmental, social, and other nonpower qualities of renewable electricity generation. A Renewable Energy Credit, and its associated attributes and benefits, can be sold separately from the underlying physical electricity associated with a renewable-based generation source.

Streamflow: Rate and volume of water flowing in various sections of a river.

Watershed: Area of land that drains to a particular water body. A watershed is defined by the highest elevations surrounding a water body, consistent with the concept that "water runs downhill."

[145] NOAA, "What is Meant by the Term Drought?"

Appendix C. Study Methodology

The U.S. Department of Energy (DOE) initiated this study in collaboration with the U.S. Department of Homeland Security (DHS) under the Critical Infrastructure Partnership Advisory Council (CIPAC) framework.[146] Under CIPAC, critical infrastructure stakeholders in government and private sectors formed a partnership model and a forum in which they can engage in a broad spectrum of activities to support and coordinate critical infrastructure protection, security, and resilience.[147]

In addition to reviewing the 2016 *Hydropower Vision: A New Chapter for America's First Renewable Electricity Source* report (see Appendix D. 2016 Hydropower Vision Report), the Sector-Specific Agencies (SSAs) conducted exhaustive open-source research on several related topics including drought, precipitation, weather changes, streamflow regulation, water management and uses, and the operation of hydroelectric facilities (see Appendix E. Sources and References). The SSAs also examined the U.S. Energy Information Administration's (EIA's) annual electricity survey forms 906, 920, 923, and 860 databases to investigate the historical pattern of electric power generation and generating capacity. This analysis focused on hydroelectric power generation at the State level and the plant level from 1990 to 2015.

Operations and planning at hydroelectric facilities are driven by factors that are often unique to each watershed; therefore, the SSAs assessed several watersheds to better understand the function of hydroelectric dams in the context of a large river system. Based on the amount of hydropower generation and the gravity of water-related concerns affecting hydropower, the following three rivers were selected as an example: Columbia River, Colorado River, and Tennessee River. The reservoirs in these rivers serve multiple purposes, many of which often conflict with one another, including public water supply, irrigation, flood control, fish habitat protection, and power generation. The SSAs considered these issues that are often heightened during low water periods when the availability of water diminishes. The study also discusses the hydroelectric potential of the Mississippi River.

Following a literature review, DOE and DHS conducted phone interviews with senior personnel from 13 Dams Sector organizations, both public and private, to seek their expertise and insight. The goal of the discussions was to ascertain the most critical issues they face today and in the near future in the operation of their hydroelectric facilities. Drafts of the study were presented at the Dams Sector Joint Council meeting so public and private sector owners and operators could review the report and contribute feedback and additional information.

[146] CIPAC is an operational mechanism that allows the discussion of sensitive information between public and private sectors by providing a shield from the Federal Advisory Committee Act requirements.
[147] DHS, "Critical Infrastructure Partnership Advisory Council," 2016.

Appendix D. 2016 Hydropower Vision Report

In July 2016, the U.S. Department of Energy (DOE) released *Hydropower Vision: A New Chapter for America's First Renewable Electricity Source*, which outlines an expanded role for hydropower and pumped hydropower storage as part of a clean energy future. The report analyzed potential growth scenarios and includes a roadmap that outlines how hydro facilities can achieve higher levels of hydropower deployment. With the release of the report, DOE also announced that $9.8 million in funding is available to develop innovative technologies to reduce costs and timelines for pumped storage hydropower (PSH) and non-powered dams, including exploring the feasibility of closed-loop PSH systems.[148]

The *Hydropower Vision* report comprehensively describes the state of the U.S. hydropower industry, models hydropower's contributions and future potential, identifies the positive benefits of hydropower to the Nation, and outlines the path forward through its roadmap activities. Below is a brief overview with some key information from the report; please see the full report for more detail. Unless otherwise noted, all information included is pulled from the *Hydropower Vision* report.[149]

Public, Market, and Policy Trends

Hydropower is a scalable, highly reliable generation technology, and it offers significant operational flexibility to maintain grid reliability and integration of variable generation resources. However, the vast majority of the 87,000 dams in the United States do not include hydropower generation plants with only 3 percent—or about 2,200—generating electricity. As the U.S. electricity generation sources shift with the retirement of coal and nuclear power plants and increase in natural gas generation and renewables, hydropower has an important role to play. For example, hydropower generation and PSH can provide flexibility and balance for variable generation sources, such as wind and solar.

Key market drivers for energy storage for grid and ancillary storage—which PSH provides—include:

- Substantial growth in variable generation.
- Governmental focus on initiatives to reduce carbon emissions.
- The need for grid infrastructure modernization.
- The need to improve the resilience of the electric grid to unforeseen interruptions.

Opportunities and Challenges for Hydropower

For hydropower to compete with other electricity generating sources, capital and operating expenses will need to be reduced through technical innovation. Technical innovation is also crucial in reducing or mitigating the adverse environmental effects of hydro facilities to protect fish and wildlife, and in meeting larger sustainability objectives. Improving public perception and knowledge of hydropower will also be crucial, such as by showcasing the value hydropower provides in helping stabilize the grid or the societal benefits from avoided air pollution and greenhouse gas emissions.

Hydropower also faces market and regulatory challenges. For example, uncertainty in licensing-related processes and outcomes may adversely affect development costs, timelines, and financing options. In April 2016, the Federal Energy Regulatory Commission (FERC) initiated Docket No. AD16-20-000 to examine whether barriers exist to the participation

[148] DOE, "Energy Department Releases New Hydropower Vision Report," 2016.
[149] DOE, *Hydropower Vision: A New Chapter for America's First Renewable Electricity Source*, 2016.

of electric storage resources—including PSH—in the capacity, energy, and ancillary service markets, potentially leading to unjust and unreasonable wholesale rates.

The long-term outlook for the hydropower industry is also affected by the uncertainty created from shifts in weather and temperature patterns and their effect on water availability.

Modeling Hydropower's Contributions and Future Potential

For the report, analytical modeling methods were used to evaluate a range of possible future outcomes for hydropower deployment based on potential technical innovation, economic factors, national priorities, stakeholder action or inaction, market forces, and requirements of environmental mitigation and environmentally sensitive areas. Growth potential is tied to a set of complex and unpredictable variables; as a result, modeling results serve as a basis to identify key factors and drivers that could influence future pathways.

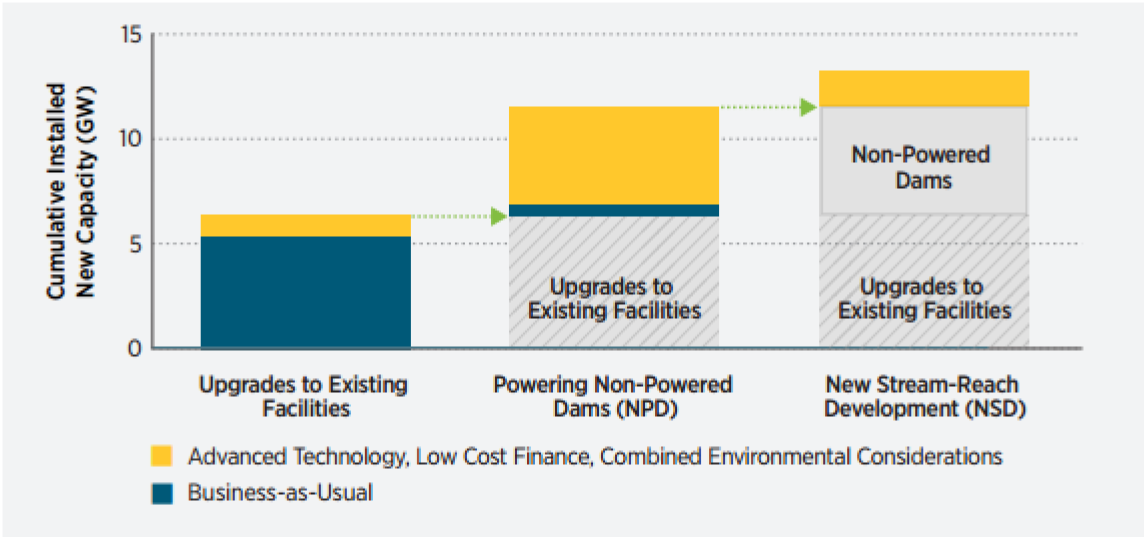
Hydropower resource opportunities for potential growth fall into four distinct categories:

1. Existing power plants and dams that can be upgraded and optimized for increased production and environmental performance;
2. New power plants at existing non-powered dams and water conveyances, such as canals and conduits that are not powered but could be cost-effectively leveraged to support hydroelectric facilities;
3. New and existing PSH facilities and upgrades, including reservoirs and pumping/generating plants; and
4. New stream-reach development, including diversionary methods, new multi-purpose impoundments, or instream approaches.

Key modeling takeaways:

1. Across the breadth of scenarios, new hydropower capacity could add several billion dollars in societal value in the form of avoided greenhouse gas and air pollution emissions, avoided water consumption, and avoided water withdrawals;
2. Investments in the hydropower industry are expected to be on the order of $4.2 billion per year under Business as Usual, and $9.9 billion per year under the Advanced Technology, Low Cost Finance, Combined Environmental Considerations scenario; and
3. The existing fleet will continue to contribute a substantial majority of the societal benefits of hydropower as a whole.

Figure 26.—Regional Energy Deployment System Modeled Cumulative 2050 Deployment of New Hydropower Generation Capacity by Resource Category (GW).



Risks of Inaction

Although the industry is mature, many actions and efforts remain critical to further advancement of domestic hydropower as a key energy source of the future. This includes continued technology development to increase efficiency, advance sustainability, and drive down costs, as well as the availability of market mechanisms that take into account the value of grid reliability services, air quality and reduced emissions, and long asset lifetimes.

The Opportunity

U.S. hydropower could grow from 101 GW combined generating and storage capacity in 2015 to almost 150 GW by 2050, realizing more than 50 percent of this growth by 2030, under the Advanced Technology, Low Cost Finance, and Combined Environmental Considerations scenario modeled. This includes 13 GW of new hydropower generation capacity (upgrades to existing plants, adding power at existing dams and canals, and limited development of new stream-reaches), and 36 GW of new pumped storage capacity.

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