Environment Baseline Vol. 4:
Energy-Water Nexus

Prepared by the Office of Energy Policy and Systems Analysis,

U.S. Department of Energy

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Note: Some of the content in this baseline is adapted from *The Water-Energy Nexus: Challenges and Opportunities* report, released by DOE in 2014.

Quadrennial Energy Review 1.2 Baseline Reports

This report is a DOE EPSA product and part of a series of "baseline" reports intended to inform the second installment of the Quadrennial Energy Review (QER 1.2). QER 1.2 will provide a comprehensive review of the nation's electricity system and covers the current state and key trends related to the electricity system, including generation, transmission, distribution, grid operations and planning, and end use. The baseline reports provide an overview of elements of the electricity system.

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Executive Summary

Volume 4 of the Environment Baseline provides background information on aspects of the energy-water nexus that relate to electricity generation and use in the United States. This volume:

- Describes current water demands for electricity generation and electricity demands for water conveyance, treatment, and distribution, including discussion of relevant technologies and tradeoffs;
- Summarizes available energy-water data sources and data gaps;
- Summarizes policies related to water in electricity generation;
- Reviews impacts of future climate change and trends relating to the provisioning of water and electricity generation; and
- Concludes with a summary of findings.

Present day energy and water systems are tightly intertwined. Water is used in most phases of energy production and electricity generation. Energy is required to extract, convey, and deliver water of appropriate quality for diverse human uses, and then again to treat wastewaters prior to their return to the environment. Historically, interactions between energy and water have been considered on a regional or technology-by-technology basis. At the national and international levels, energy and water systems have been developed, managed, and regulated independently and without significant acknowledgement of the connections between them.

Several current trends are increasing the urgency to address the energy-water nexus in an integrated and proactive way. First, climate change has already begun to affect precipitation and temperature patterns across the United States. Second, U.S. population growth and regional migration trends indicate that the population in arid areas such as the Southwest is likely to continue to increase, further complicating the management of both energy and water systems. Third, introduction of new technologies in the energy and the water domains could shift energy and water demands. Finally, developments in policies addressing water rights and water impacts of electricity generation are introducing additional incentives and challenges for decision-making.

Flows of energy and water are intrinsically interconnected, due both to the characteristics and properties of water that make it so useful for producing energy, and to the significant amount of energy required to treat and distribute water for human use. This interconnectivity is illustrated in the Sankey Diagram in Figure 1, which captures the magnitude of energy and water flows in the United States on a national scale. As shown in the diagram, thermoelectric power generation withdraws large quantities of water for cooling[a] and also dissipates large quantities of primary energy due to inefficiencies in converting thermal energy to electricity. The intensity of water use and energy dissipated varies significantly with generation and cooling technology. In addition, water treatment and distribution for drinking water supply and municipal wastewater also require significant amounts of energy.

[a] "Withdrawal" designates any water diverted from a surface or groundwater source. "Consumed water" designates withdrawn water that is not returned to its source (e.g., because it has evaporated, been transpired by plants, or incorporated into products).

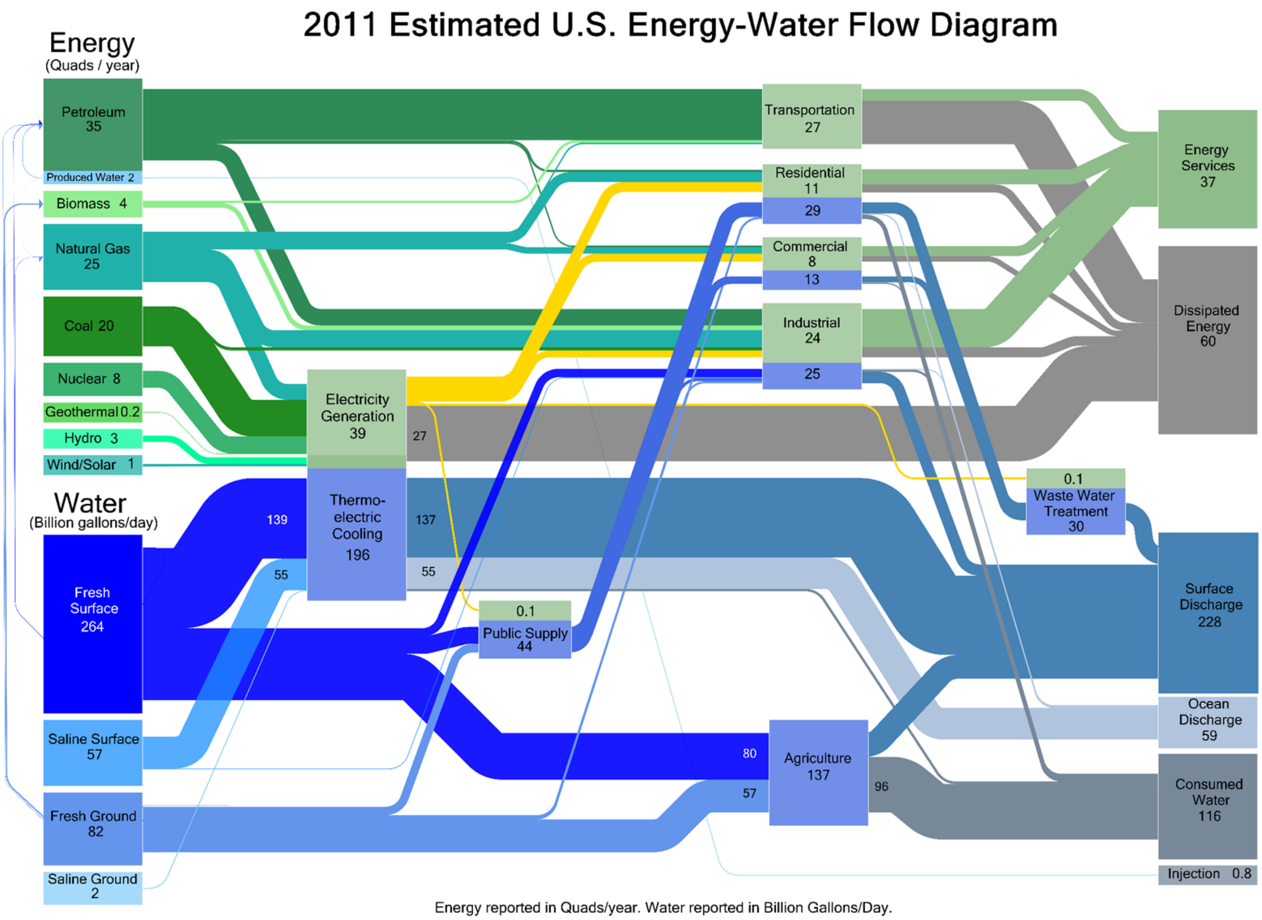

Figure 1. Hybrid Sankey diagram of 2011 U.S. interconnected water and energy flows.[1]
Significant fractions of surface freshwater withdrawals are for thermoelectric cooling and for agriculture, but agriculture consumes more water than thermoelectric cooling consumes. Most electricity is generated for residential, commercial, and industrial use, but significant fractions are used for public water supply and wastewater treatment. The Sankey diagram aids in visualizing these complex data streams and interconnections as a first step toward further analysis.
Source: The Water-Energy Nexus: Challenges and Opportunities (2014)

While Sankey diagrams such as these can map out flows of energy and water as a starting point for analysis, the dynamic nature of energy and water flows—due to changes in policy, economics, or technology, for instance—can be more challenging to capture and requires detailed data at high spatial and temporal resolution. For example, increased deployment of some energy technologies in the future, such as carbon capture and storage, could lead to increases in the energy system's water intensity, whereas deployment of other technologies, such as wind and solar photovoltaics, could lower it. In addition, there is significant regional variability in energy and water systems, their interactions, and resulting vulnerabilities.

Analysis in this volume has identified the following key findings:

1. **Data.** While EIA collects commercial and industrial energy use data through its surveys, it does not collect energy use data for municipal water conveyance, treatment, and distribution – making analysis of energy use and savings opportunities difficult. More broadly, improved harmonization

and integration of energy-water data sets, particularly among federal agencies such as EIA and USGS, is a critical need for improving confidence in energy-water data and allowing advanced analyses of regional variability and trends over time.

2. **Dry cooling.** There are a number of options to reduce the reliance of thermoelectric generation on fresh water. Dry and hybrid cooling systems allow zero- or low-water operation, but these systems impose higher capital costs and lower efficiencies. Improved technologies and/or deployment incentives could reduce the dependence of thermoelectric generation on water. It is particularly important to identify and pursue opportunities for lower-cost and more efficient dry and hybrid cooling (or other avenues for water efficiency) for technologies such as nuclear, geothermal, CSP, and CCS, all of which are components of a low-carbon future.

3. **Hydropower.** Existing hydropower facilities may be able to increase their contributions to zero-GHG electricity generation and grid flexibility if issues such slow technology upgrade, regulatory constraints, and challenges in valuation of ancillary services are addressed.

4. **Finance and Systems Integration.** Considering energy performance in decisions to finance water infrastructure, and vice versa, may bring opportunities to realize additional energy and water benefits. This approach could also provide a pathway for demonstration and deployment of energy efficiency and energy recovery technologies.

5. **Policy Alignment.** Although energy and water flows are often physically interconnected, the energy and water policy landscape is highly fragmented in the U.S., making it difficult for decision makers in industry and government to effectively balance energy and water goals. Improved understanding and alignment of federal and state policies affecting the energy-water nexus could allow decision makers to better balance energy and water goals and avoid unintended consequences.

The Scope

A brief framing of connections between electricity and water systems is described in Chapter 1. These connections form the outline for Chapters 2, 3, and 4. Chapter 2 describes water demands for thermoelectric generation, which includes plants powered by coal, gas, nuclear, concentrated solar power (CSP), and geothermal energy. Carbon capture and storage (CCS) technologies are also discussed in Chapter 2. Chapter 3 describes key characteristics of hydropower, including capabilities to provide zero-GHG generation as well as flexibility and ancillary services to balance an increasing share of variable renewables. Chapter 4 describes the electricity demand for various water systems, including water and wastewater conveyance, treatment, and distribution. The variation in energy demands between types of water treatment technologies is also examined.

Chapters 5, 6, and 7 explore complex coupled aspects of the energy-water system including data, policy, and impacts of climate change. Chapter 5 discusses several of the data sources available as well as data challenges associated with the energy-water nexus. Chapter 6 discusses relevant policies relating to water and electricity connections. Variations in surface water and groundwater governance policies throughout the country are described. This chapter also discusses water permitting for thermoelectric cooling, broad policies affecting hydropower, and finance opportunities for energy and water infrastructure. Chapter 7 describes future climate change impacts on thermoelectric and hydropower generation. Finally, Chapter 8 concludes with overarching findings identified in the preceding chapters.

Water temperature impacts are considered in this volume, but other aspects of water quality are not within the scope, and are instead treated in Environmental Quality and the U.S. Power Sector: Air Quality, Water Quality, Land Use and Environmental Justice (Vol. 2).

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Chapter 1. The Energy-Water Nexus

Present-day energy and water systems are tightly intertwined. Water is used in most phases of energy production and electricity generation. Energy is required to extract, convey, and deliver water of appropriate quality for diverse human uses, and then again to treat wastewaters prior to their return to the environment. Historically, interactions between energy and water have been considered on a regional or technology-by-technology basis. At the national and international levels, energy and water systems have been developed, managed, and regulated independently and without significant acknowledgement of the connections between them.

Several current trends are increasing the urgency to address the energy-water nexus in an integrated and proactive way. First, climate change has already begun to affect precipitation and temperature patterns across the United States. Second, U.S. population growth and regional migration trends indicate that the population in arid areas such as the Southwest is likely to continue to increase, further complicating the management of both energy and water systems. Third, introduction of new technologies in the energy and the water domains could shift energy and water demands. Finally, developments in policies addressing water rights and water impacts of electricity generation are introducing additional incentives and challenges for decisionmaking.

Recent trends have focused national attention on the connections between energy and water infrastructure. For example, when severe drought affected more than a third of the United States in 2012, limited water availability constrained the operation of some power plants and other energy production activities. Hurricane Sandy demonstrated that vital water infrastructure can be highly vulnerable to electricity outage.

These trends may present challenges, but they also present opportunities. An integrated, strategic approach can guide technology research and development (R&D) to address regional energy-water issues and also have impact at the national and global scale. Enhancing and integrating data, modeling, and analysis capabilities will better inform researchers, decision makers, and the public.

Flows of energy and water are intrinsically interconnected, due both to the characteristics and properties of water that make it so useful for generating electricity, and to the significant amount of energy required to treat and distribute water for human use. This interconnectivity is illustrated in the Sankey Diagram in Figure 2, which captures the magnitude of energy and water flows in the United States on a national scale.

As shown in the diagram, thermoelectric power generation withdraws large quantities of water for cooling[b] and also dissipates large quantities of primary energy due to inefficiencies in converting thermal energy to electricity. Water flows upstream of generation, such as for oil and gas production, are also included in Figure 2. The intensity of water use and energy dissipated varies with generation and cooling technology. As the largest single consumer of water, agriculture competes directly with the energy sector for water resources, particularly in water scarce regions.

Water conveyance, treatment, and distribution for drinking water supply and municipal wastewater also require significant amounts of energy. In some regions, delivery of water for agricultural use also requires significant energy.

On the other hand, important aspects of energy and water flows do not appear in Figure 2. First, because hydropower technically does not withdraw and consume water, its very significant reliance on water

[b] "Withdrawal" designates any water diverted from a surface or groundwater source. "Consumed water" designates withdrawn water that is not returned to its source (e.g., because it has evaporated, been transpired by plants, or incorporated into products).

resources is not shown in the diagram. Second, flows will change over time, and anticipated changes in flows are important to consider when prioritizing investment in technology and other solutions. Increased deployment of some energy technologies in the future, such as carbon capture and storage, could lead to increases in the energy system's water intensity, whereas deployment of other technologies, such as wind and solar photovoltaics, could lower it. Flows also have some seasonable variability. Furthermore, there is significant regional variability in the energy and water systems, their interactions, and resulting vulnerabilities.

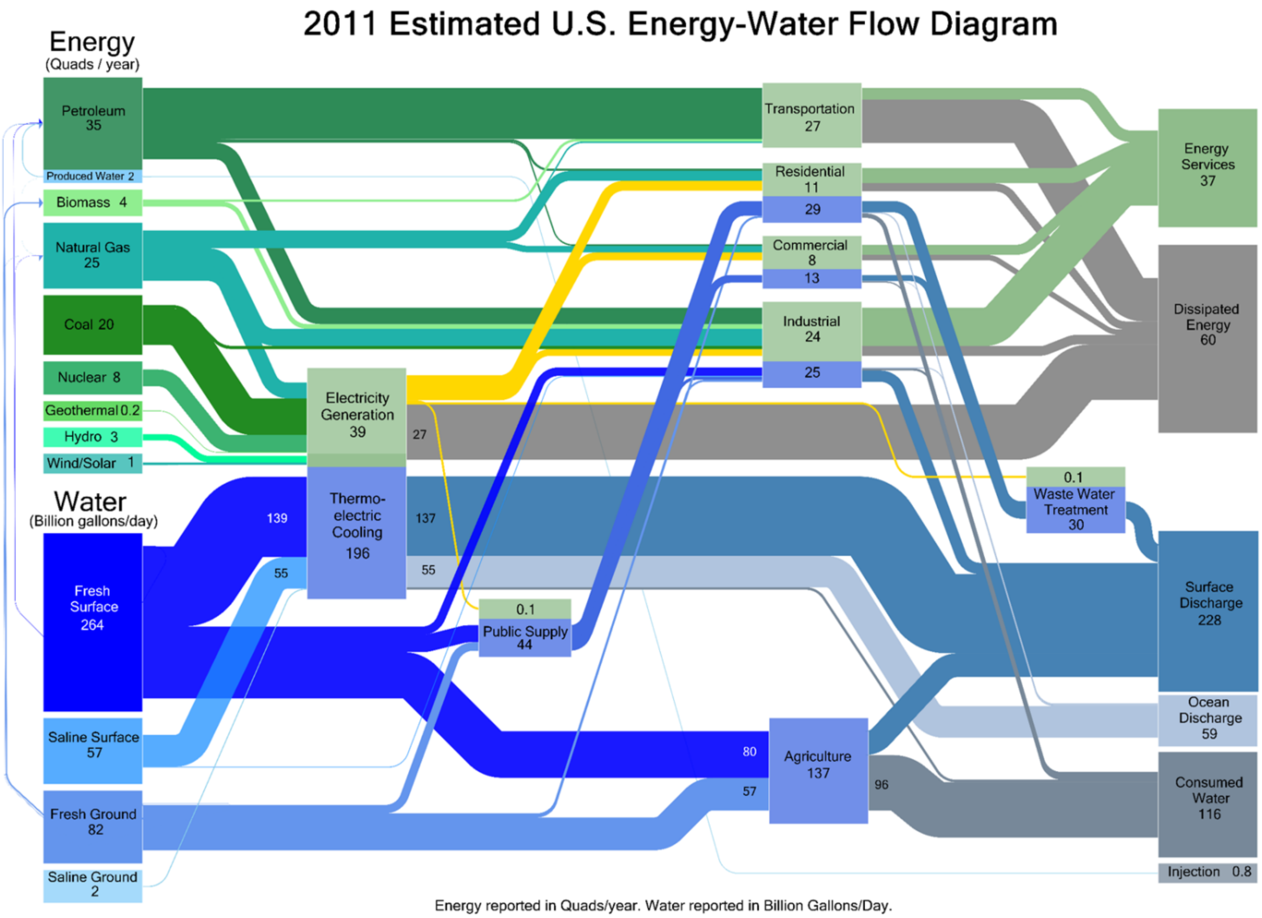


Figure 2. Hybrid Sankey diagram of 2011 U.S. interconnected water and energy flows.
Significant fractions of surface freshwater withdrawals are for thermoelectric cooling and for agriculture, but agriculture consumes more water than thermoelectric cooling consumes. Most electricity is generated for residential, commercial, and industrial use, but significant fractions are used for public water supply and wastewater treatment. The Sankey diagram aids in visualizing these complex data streams and interconnections as a first step toward further analysis.
Source: The Water-Energy Nexus: Challenges and Opportunities (2014)

Dynamics such as changing water availability under climate change will affect the future of the energy-water nexus. While there is significant uncertainty regarding the magnitude of effects, water resource availability and predictability may be altered by projected air temperature changes, shifting precipitation patterns, and more extreme weather. Shifts in precipitation and temperature patterns—including changes in snowmelt magnitude and timing—will likely lead to more regional variation in water availability for hydropower, thermoelectric generation, and other energy needs. Higher temperatures also have the potential to decrease the efficiency of thermoelectric generation, which could increase water requirements for thermoelectric cooling when water demand for non-energy purposes is also high. Such changes may pose challenges for energy infrastructure resilience.

Energy and water needs will also be shaped by population growth and migration patterns, as well as by changes in fuels used and energy technologies deployed. For example, projected population growth in the arid Southwest will likely intensify pressure on energy and water systems in that region. According to Energy Information Administration (EIA) data, planned retirements and additions of electricity generation units and cooling systems will likely decrease water withdrawals, increase water consumption, and increase the diversity of water sources used.

Addressing challenges and opportunities at the energy-water nexus will require informed decision-making by stakeholders and policymakers. The decision-making landscape for the energy-water nexus is shaped by political, regulatory, economic, environmental, and social factors, as well as available technologies. The landscape is fragmented, complex, and changing; the incentive structures are overlapping but not necessarily consistent. Water is inherently multi-jurisdictional, and managing water is primarily a state and local responsibility. States and localities vary in philosophies regarding water rights. There is also variation across states in relevant energy policies, including renewable portfolio standards and regulation of thermoelectric water intake and discharge. Regulations for thermoelectric water use are currently undergoing substantial change. Energy use for water conveyance, treatment, and distribution is also the subject of policy activity at multiple scales, from pump efficiency standards to municipal water treatment funding mechanisms. A more integrated approach to the interconnected energy and water challenges could stimulate the development and deployment of solutions that address objectives in both domains.

DOE's role in the energy-water nexus is primarily in technology R&D investment and data, modeling, and analysis. Many other departments are well-positioned to complement and coordinate with DOE. For example, the Environmental Protection Agency has both a regulatory and a research role related to water quality in drinking water and wastewater treatment, and thermoelectric cooling systems. The Department of Agriculture has a strong interest in understanding the effects of agriculture on water resources and vice versa. Within the Department of Interior, the U.S. Geological Survey has responsibility for water-related data and modeling and the Bureau of Reclamation has responsibility for beneficial use of nontraditional waters. Within the Department of Defense, the Army Corps of Engineers is responsible for managing hydropower and other uses of waterways. The Department of Defense also pursues energy-efficient water and wastewater treatment technologies appropriate for use on military bases. Relevant research throughout the energy-water nexus is supported by the National Science Foundation. The Department of Homeland Security is responsible for understanding factors underlying resilience and vulnerability of water and energy infrastructure. The National Oceanic and Atmospheric Administration and the National Aeronautics and Space Administration collect data, develop models, and support research relevant to the energy-water nexus.

Finally, the policy challenges related to energy and water are not unique to the United States; many other nations are addressing the nexus based on their own circumstances. Therefore, there may be benefits to sharing knowledge and insight internationally.

Chapter 2: Water for Thermoelectric Generation

This chapter describes water demands for thermoelectric generation technologies, including associated technologies such as carbon capture and storage (CCS). While other generation technologies such as wind and solar photovoltaic generation may have water requirements, these requirements are minimal (see Figure 2) and will not be discussed extensively in Chapter 2.

2.1 Thermoelectric Cooling

Two-thirds of total U.S. electricity generation—including many thermoelectric generation sources such as coal, natural gas, nuclear, concentrated solar power (CSP), and geothermal plants—requires water for cooling. However, water demands vary significantly by region, technology, and operational strategy. The changing profile of the generation fleet—including retirement of aging coal-fired generators as well as deployment of advanced technologies such as dry and hybrid cooling systems and CCS—will strongly affect future water demands.

2.1.1 Regional variability of water withdrawal and consumption

Water withdrawal and consumption for thermoelectric generation vary across regions of the United States. Figure 3 further describes the regional variation of the water withdrawal for thermoelectric power. As shown, the largest water withdrawal regions are dominated by a combination of coal and nuclear generation. Hydropower dominates in the Northwest and also makes up more than 10 percent of generation in Alaska and the Northeast. Comparisons between regions can yield interesting insights. The North Central and West regions have similar total generation and water withdrawal; however, the North Central region is dominated by coal while the West has a more diversified generation portfolio that relies heavily on natural gas.

The type of water withdrawn and consumed by thermoelectric generators can also vary across regions (Figure 4). Surface and groundwater categories in Figure 4 include fresh, brackish, and saline water combined. Discharge water is water that is discharged from another facility, such as treated wastewater effluent. Other/Mixed includes water sources that survey respondents did not classify as any of the other categories, and water that is a mixture of other categories. Figure 4 indicates that while water withdrawals in all eight regions are dominated by surface water, the Southeast withdraws a sizable fraction of discharge water. Water sources for consumption are somewhat more varied, with more than 10 percent of consumption by the West, Southwest/Central, and Southeast regions originating from groundwater and discharge water.

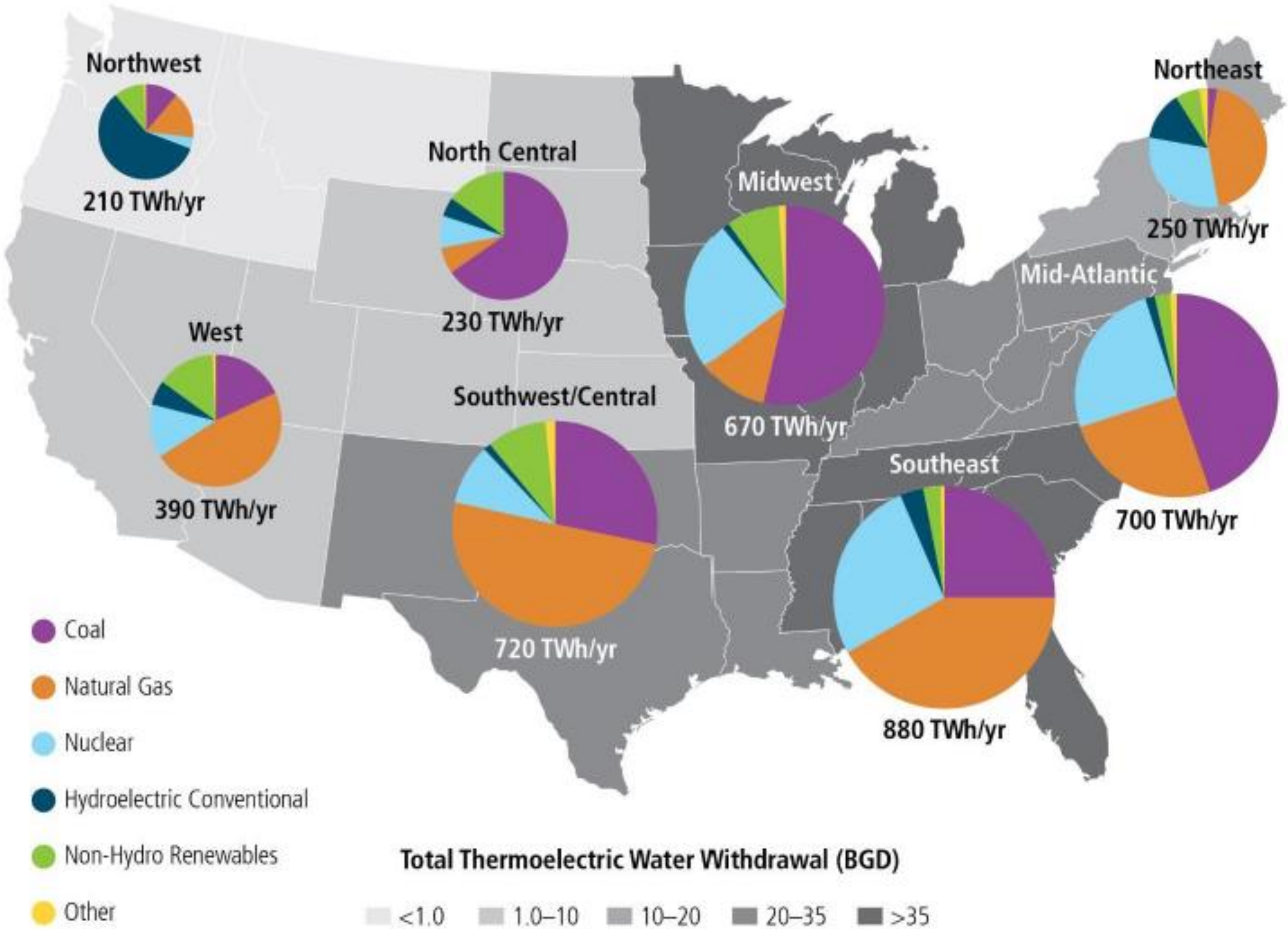
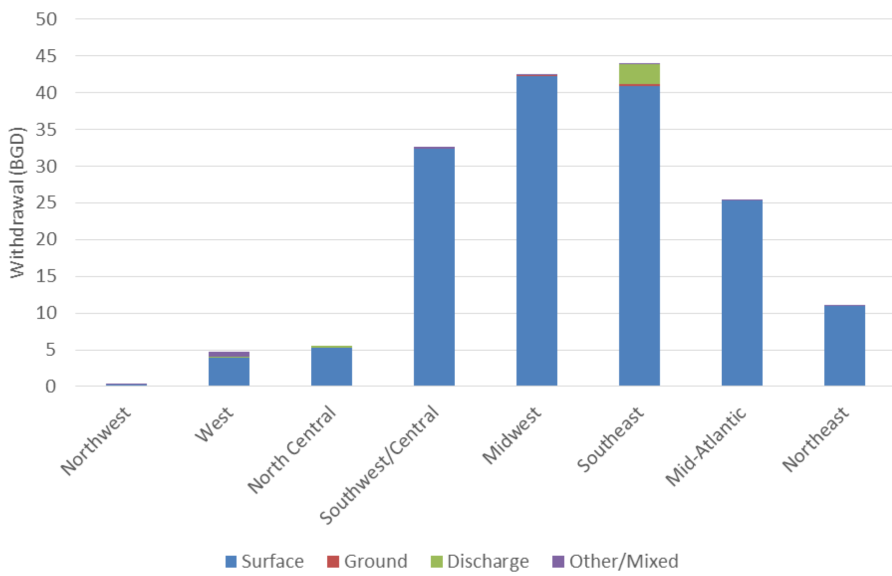


Figure 3. Water Withdrawal and Generation by Region in 2015

The largest water withdrawal regions are dominated by coal and/or nuclear generation. The area of each pie chart corresponds to total power generation in that region. "Other" includes petroleum, other fossil fuel gases, pumped storage, non-biogenic municipal solid waste, batteries, and hydrogen. The eight regions shown in the figure are notional, based upon contiguous groupings of states and their generation mixes, resources, and market structures. Data Source: EIA Form 923 (2015 data, published in 2016).



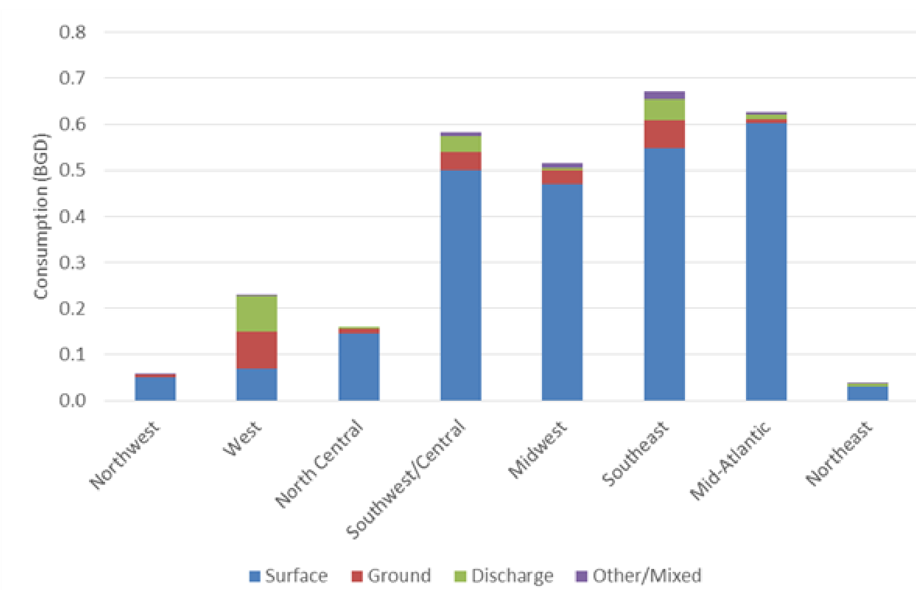


Figure 4. Total regional withdrawal and consumption by thermoelectric power plants by water source in 2015
Withdrawals in all regions[c] are dominated by surface water, but a sizeable fraction of withdrawals in the Southeast include discharge water. The majority of consumption in the West is discharge and groundwater, with smaller fractions of discharge and groundwater consumption in the other regions.

Data source: EIA thermoelectric cooling data (2015 data, published in 2016) derived from EIA Form 860 and EIA Form 923.

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[c] Regions are defined as follows: Northeast: Maine, New Hampshire, Vermont, Massachusetts, New York, Connecticut, Rhode Island; Mid-Atlantic: Pennsylvania, Ohio, West Virginia, Virginia, Kentucky, Maryland, New Jersey, Delaware, Washington DC; Southeast: Tennessee, North Carolina, Alabama, Mississippi, South Carolina, Georgia, Florida; Midwest: Minnesota, Wisconsin, Iowa, Illinois, Missouri, Indiana, Michigan; Southwest: New Mexico, Texas, Oklahoma, Arkansas, Louisiana; North Central: North Dakota, South Dakota, Kansas, Wyoming, Utah, Colorado, Nebraska; Northwest: Washington, Idaho, Montana, Oregon; West: California, Nebraska, Arizona. (Hawaii and Alaska are not included.)

2.1.2 Cooling system and generation technologies

The largest quantity of water use in thermoelectric generation is for condensing steam.[d] Power plants differ in the process used to cool and condense the steam. Most thermoelectric power plants use variations of two different wet cooling technologies: once-through and wet-recirculating cooling systems (Figure 5). Once-through cooling uses cooling water withdrawn from an external water source to condense steam in the condenser; the cooling water is then discharged back into the external water source with higher temperature. Wet-recirculating cooling systems, in contrast, re-use cooling water for multiple cycles, relying on evaporation in cooling towers to carry away heat and recovering water that does not evaporate for use in the next cooling cycle. Wet-recirculating cooling systems still require external water sources for make-up water to replace water that evaporates. Both types of cooling systems can be used in combination with a dedicated cooling pond or reservoir.[e]

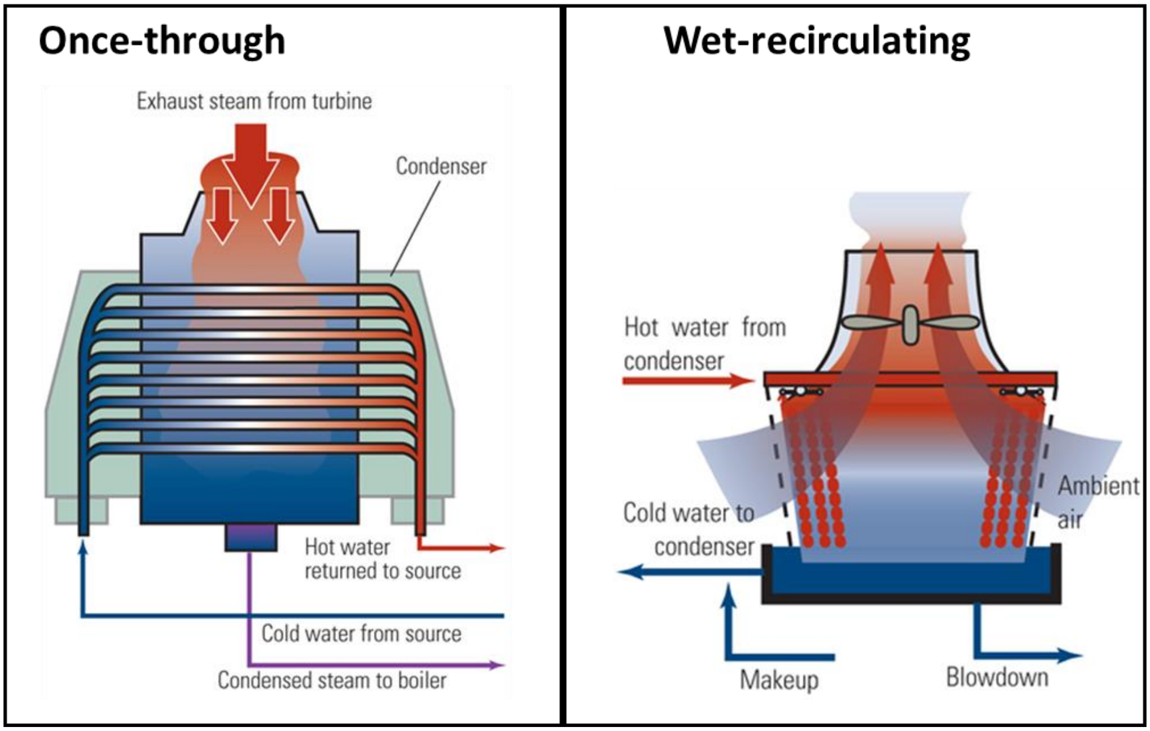

Figure 5. Once-through and wet-recirculating cooling systems.
Once-through cooling systems use cold water from an external source to condense steam in the condenser before discharging the cooling water (at warmer temperature) back into the external source. Wet-recirculating systems use cooling towers to dissipate heat via evaporation of hot water from the condenser, enabling un-evaporated water to be reused for another cycle. However, makeup water from an external source is required to replace evaporated cooling water in wet-recirculating systems.

Figure source: EPRI. Water Use for Power Generation. 2008.

[d] Water is also required for pollutant scrubbing processes, plant cleaning, and fuel processing, but these processes represent a small fraction of overall water use by thermoelectric generation.
[e] There can be some complexity in classifying once-through and wet-recirculating cooling systems, particularly when plants utilize various combinations of cooling towers and cooling ponds. In addition, terminology can vary. EIA generally classifies once-through cooling systems as "open-loop" and wet-recirculating cooling systems as "closed-loop." When referencing EIA data in this report, we define once-through as open-loop, and wet-recirculating as closed-loop.

Three key attributes of thermoelectric generators can significantly affect their water use: cooling system technology, generation technology, and operations. Figure 6 shows power generation, plant water withdrawal, and plant water consumption by cooling system technology for electricity generation in 2014, from EIA data.[f] Note that non-thermoelectric generation is also shown in the diagram for comparison purposes. Plants using once-through cooling delivered 21 percent of electricity supplies in the United States in 2015 and withdrew about 70 percent of the overall water withdrawn by power plants. Power plants using wet-recirculating systems supplied about 52 percent of the electricity generated in the United States in 2015 and withdrew 25 percent of the water withdrawn for electricity. Wet-recirculating systems consumed about 84 percent of the water consumed by electricity generation in 2015. Total water withdrawal by thermoelectric cooling totaled 167 billion gallons per day (BGD), and total water consumption by thermoelectric cooling totaled 2.9 BGD.[2] Note that total water volumes for withdrawal and consumption are very different magnitudes, but on the other hand, these two measures correspond to very different constraints, which can make it difficult to directly compare them. Consumption, as water that is taken out of the water cycle, is unavailable for any other local use after it is used for cooling, while withdrawn water can often be quickly returned to the water body it came from, albeit with higher temperature and other water quality changes. Depending on the system boundaries, withdrawal can also be a limiting constraint, as plant cooling intakes require both minimum water flow and sufficiently high water levels for operation.

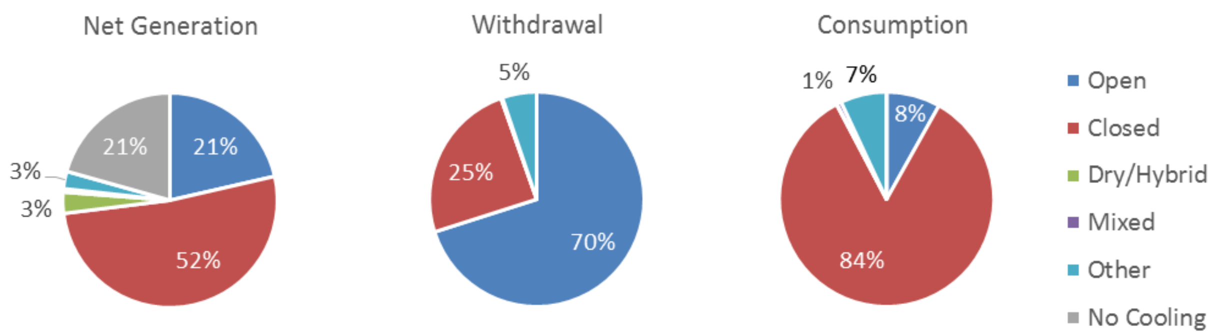

Figure 6. U.S. power generation, water withdrawal, and water consumption, by cooling type (2015).
In 2015, 21 percent of generation used once-through cooling and 52 percent of generation used wet-recirculating cooling. About 21 percent of the electricity generated—including hydropower, natural gas turbines, and wind turbines—did not require cooling. Water withdrawals for electricity generation totaled 167 billion gallons daily (BGD), the majority of which was withdrawn by once-through cooling. Water consumption totaled 2.9 BGD, with 84 percent of this amount consumed by wet-recirculating cooling.
Data source: EIA thermoelectric cooling data (2015 data, published in 2016) derived from EIA Form 860 and EIA Form 923.

A small fraction of thermoelectric generators use dry or hybrid cooling. Dry cooling uses convective heat transfer to air rather than evaporation as the cooling mechanism[3] (see Section 2.1.4), essentially eliminating water requirements for cooling. Hybrid systems use a combination of wet and dry mechanisms. About 21 percent of the electricity generated in 2015—including hydropower, natural gas turbines, and wind turbines—did not require cooling.

[f] In its Form 923, the U.S. Energy Information Administration (EIA) collects water diversion, withdrawal, discharge, and consumption data for thermoelectric cooling systems at plants with 100 megawatts (MW) or greater of generating capacity, which represents 99.2 percent of thermoelectric generation and 97.2 percent of thermoelectric capacity.

The type of generation technology also influences the amount of water withdrawn or consumed by the plant. Figure 7 and Figure 8 illustrate withdrawal and consumption values per unit of generation across a range of generation and cooling technologies. Variation in withdrawal as well as consumption demands across technologies can vary greatly. Tower-cooled concentrated solar power (CSP), though not widely deployed at present, has withdrawal and consumption demands that are in the same order of magnitude as tower-cooled nuclear, gas, and coal generation.[4]

In general, more efficient combustion platforms require less water per kilowatt-hour (kWh) of generation. For example, coal plants that are operated at supercritical temperature and pressure are more efficient than subcritical plants and require less cooling. The type of cycle used also has an effect on cooling demands. For example, natural gas combined cycle plants and integrated gasification combined cycle (IGCC) plants have lower water consumption per kWh of generation because the majority of the plants' output comes from combustion turbines that require minimal water compared to steam turbines.[5]

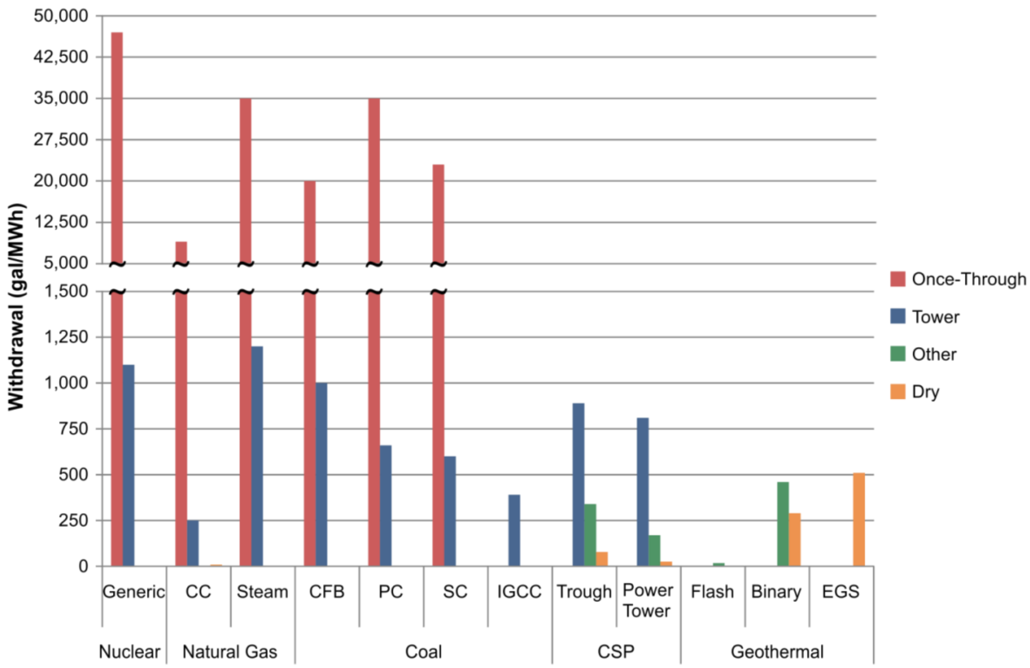

Figure 7. Water withdrawal factors for operation of various thermoelectric generation and cooling technologies.

Water withdrawal intensity factors are much larger for once-through cooling than for other cooling technologies, but these factors include significant spread, including nearly a factor-of-6 reduction in comparing nuclear to natural gas combined-cycle. (Note: the scales in the graphs above and below the axis split differ by a factor of 50.) Withdrawal factors for CSP tower cooling are in the same order of magnitude as nuclear, gas, and coal tower cooling. The withdrawal factor for dry cooling on gas combined-cycle plants is very small, while for CSP and geothermal, dry cooling withdrawal factors can be larger.

Figure from: The Energy-Water Nexus: Challenges and Opportunities (2014)

Data source: Meldrum et al. 2013

Abbreviations: CC: Combined Cycle; CFB: Circulating Fluidized Bed; PC: Pulverized Coal; SC: Supercritical Pulverized Coal; IGCC: Integrated Gasification Combined Cycle; CSP: Concentrating Solar Power; EGS: Enhanced Geothermal System.

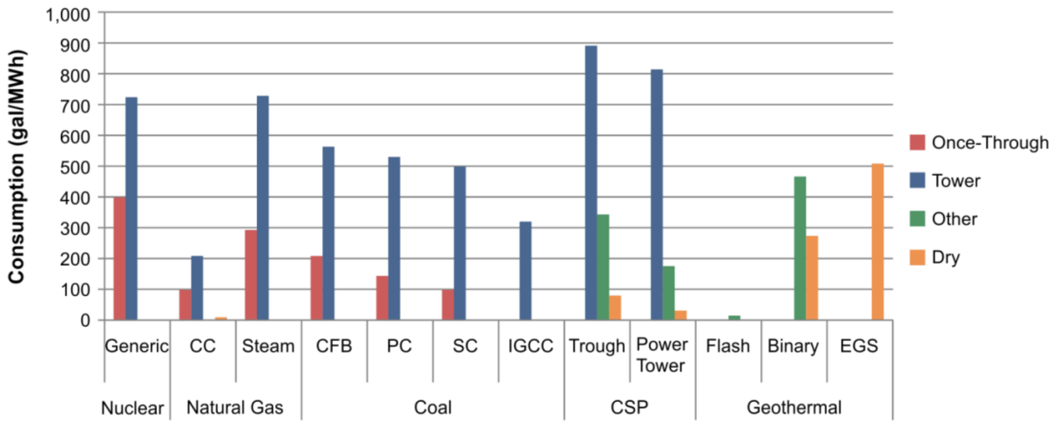

Figure 8. Water consumption factors for operation of various thermoelectric generation and cooling technologies.

Water consumption factors are in the same order of magnitude for tower cooling across generation technologies, with CSP, natural gas steam, and nuclear being highest, and natural gas combined-cycle being lowest. Once-through consumption factors are lower than tower cooling consumption factors within each technology. Consumption factors for dry cooling and other cooling categories span a wide range. Note that although EGS geothermal has highest consumption factor in the dry cooling category, most of this consumption is from components other than the cooling system.

Figure from: The Energy-Water Nexus: Challenges and Opportunities (2014)

Data source: Meldrum et al. 2013

Abbreviations: CC: Combined Cycle; CFB: Circulating Fluidized Bed; PC: Pulverized Coal; SC: Supercritical Pulverized Coal; IGCC: Integrated Gasification Combined Cycle; CSP: Concentrating Solar Power; EGS: Enhanced Geothermal System.

The dominant generation and cooling technologies vary with the age of the plant. As shown in Figure 9, conventional coal systems and natural gas steam turbine systems dominate the older generators while natural gas combined cycle generators account for the majority of the generators less than 25 years old.[g] These older generators are often less efficient at generating electricity and often use once-through cooling. These attributes can affect water withdrawal and consumption, leading to variation in the fleet's water demands by vintage year.

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[g] Note, however, that a sizable fraction of coal steam capacity is under 25 years old. Although many once-through coal steam plants may retire in coming decades, a significant number may continue to operate.

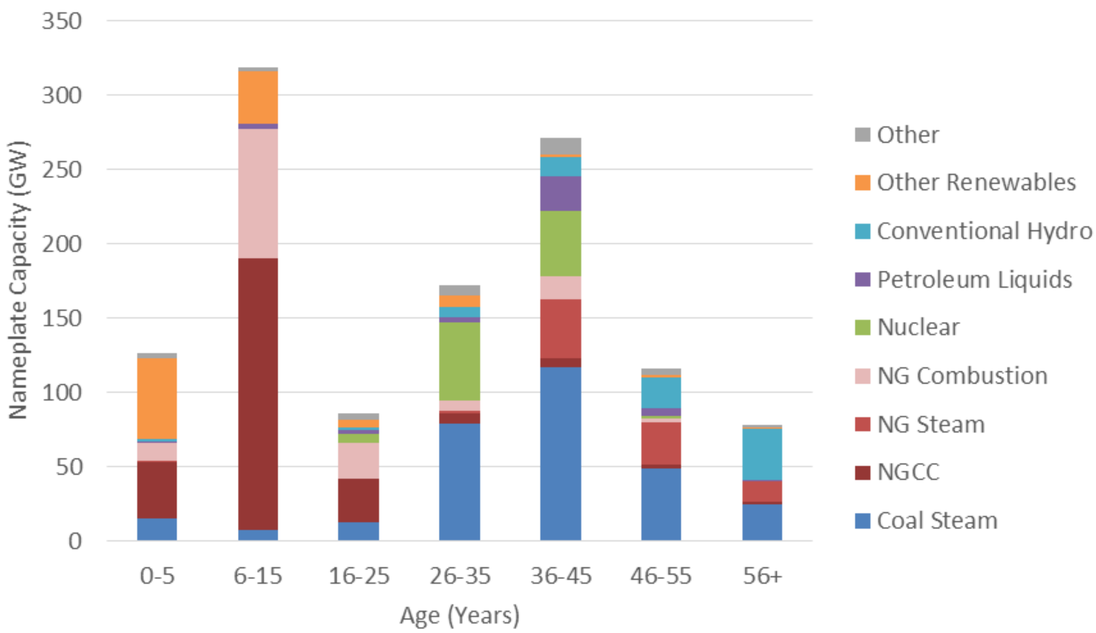

Figure 9. Current U.S. electricity generation capacity by age and technology type in 2015
Most new generators in the past 25 years have been natural gas-fired combined-cycle. The steam coal and natural gas steam fleets were built primarily 25-65 years ago. Non-hydropower renewables have come online primarily in the past 15 years, while nearly all hydropower came online more than 25 years ago.

Data Source: EIA Form 860 (2015 data, published in 2016).

There are emerging generation technologies that could further reduce water use. For example, DOE supports research and commercialization efforts for the use of supercritical carbon dioxide (sCO_2) in Brayton cycle energy conversion systems.[6] The fact that supercritical carbon dioxide as a working fluid exists in a single phase (unlike water, which must change between liquid and gas phases) means that generation efficiency can be increased significantly, thus requiring less water for cooling. Nuclear power, concentrated solar thermal, fossil fuel boilers, geothermal, and shipboard propulsion systems are all potential applications for sCO_2 cycles and could replace traditional steam Brayton and Rankine cycles. Challenges to be addressed include development of materials and components (e.g., valves, seals) that can withstand the high temperatures and pressures required for sCO_2 cycles.

2.1.3 Cooling system operations

In addition to cooling system and generation type, operations can also have an effect on water use. Figure 10 shows cooling system capacity factors versus generation capacity factors for five different generation types. On the vertical axis, plants that are dispatched primarily during times of peak electricity demand are considered peaking plants and will generally have lower generation capacity factors. Plants used for baseload electricity will generally have higher generation capacity factors. Plotting generation capacity factor versus cooling system capacity factor shows how often the cooling system is running compared with how often electricity is being generated. Petroleum liquids and natural gas steam plants, which tend to have lower generation capacity factors and are seen toward the bottom of Figure 10, make up a large portion of peaking plants. Many nuclear and coal steam plants, which tend to have higher generation capacity factors and are seen in the upper right hand corner of Figure 10, are used for baseload electricity. The dotted line illustrates the boundary at which a plant's cooling system capacity factor equals its generation capacity factor. Plants located close to the line are running their generation and cooling systems at roughly the same capacity factor. The further below the line a plant is, the more frequently that plant is running its cooling system while not generating electricity.

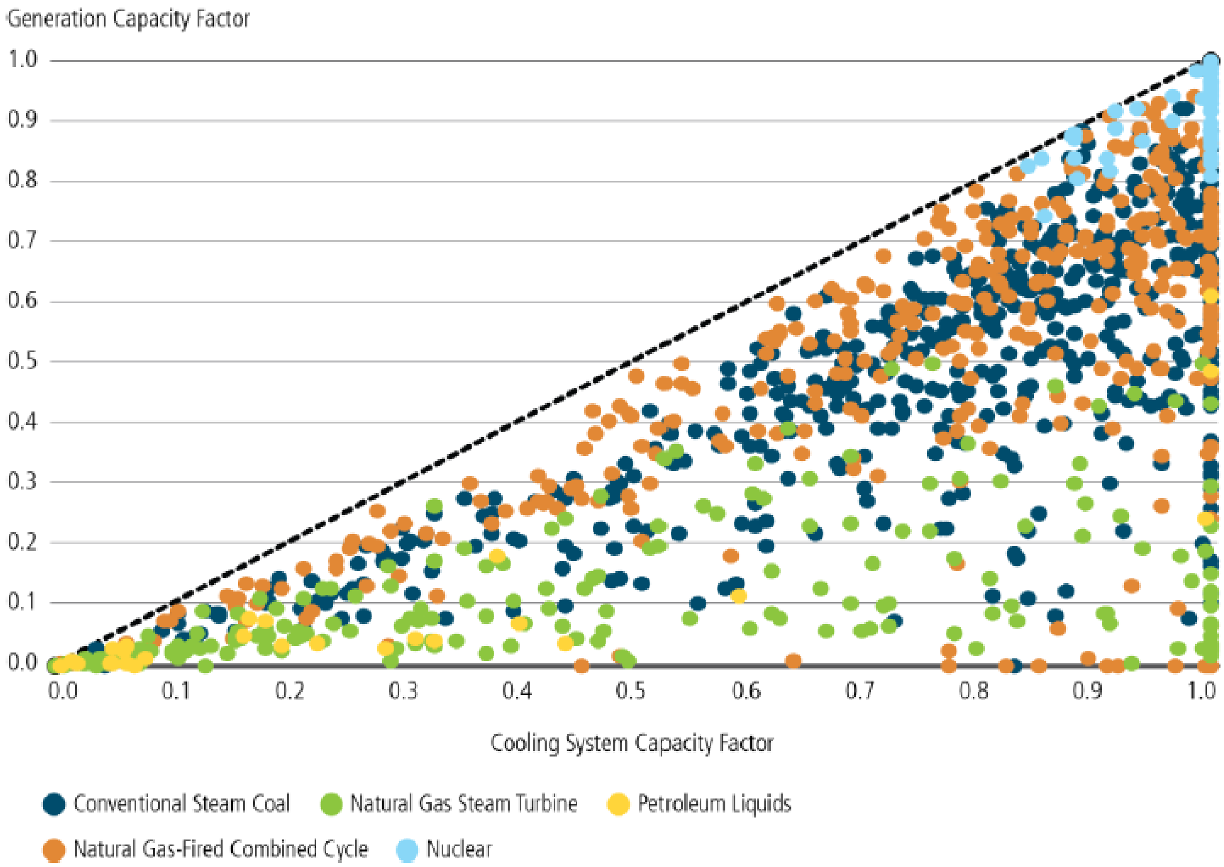

Figure 10. 2015 Cooling System Capacity Factors Vs. Generation Capacity Factors.
Electricity generators run their cooling systems with varying capacity factors relative to their generating capacity factors. Natural gas steam turbines (Rankine cycle plants)—many likely acting as peakers—run their cooling systems for a substantial amount of time when they are not generating, as do a number of NGCC plants. Plants on the dotted line run their cooling systems with the same capacity factor as their power generation capacity factor (i.e., only when they are generating). Plants that are dispatched primarily during times of peak electricity demand are considered peaking plants and will generally have lower power generation capacity factors. Plants used for baseload electricity will generally have higher power generation capacity factors.
Data source: EIA thermoelectric cooling data (2015 data, published in 2016) derived from EIA Form 860 and EIA Form 923.

Many natural gas steam turbines in particular (green dots in Figure 10) seem to run their cooling systems for a substantial fraction of the time when they are not generating. Most of these plants are likely operating as peaking plants. A number of these plants are operating in dry regions that are prone to drought. This behavior is not limited to natural gas steam plants, but is most noticeable in these plants.

2.1.4 Dry cooling

Dry cooling and hybrid wet/dry cooling systems, shown schematically in Figure 11, offer the possibility of 80 percent or better reductions in water withdrawals for coal-fired plants, as well as reduction in consumption. This can eliminate the need for cooling water discharge permits as well as the risk of plant derating or shutdown to comply with water discharge temperature limits (see Sections 6.2 and 7.2). In addition, plants with dry cooling do not need to be located near large sources of water, providing a significant increase in siting flexibility. However, these systems face significant adoption challenges. For example, existing dry (air-cooled) options have higher capital costs and require expanded physical footprints. In addition, current dry cooling technologies impose an efficiency penalty relative to once-through or wet-recirculating wet cooling because the temperature of air used for dry cooling is generally higher than that of the water used for once-through cooling or the wet-bulb temperature at which water begins to evaporate in wet-recirculating cooling. The higher temperature of the air used for cooling increases the back pressure on the generating turbine, reducing generation efficiency, particularly under high-temperature ambient conditions.[7] Dry cooling thus requires plants to generate less electricity on the hottest days, when demand tends to be highest. The energy penalty for current dry cooling technologies relative to once-through cooling ranges from 4.2 percent to 16 percent for a representative 400 MW coal-fired plant, depending on plant parameters and ambient conditions.[8]

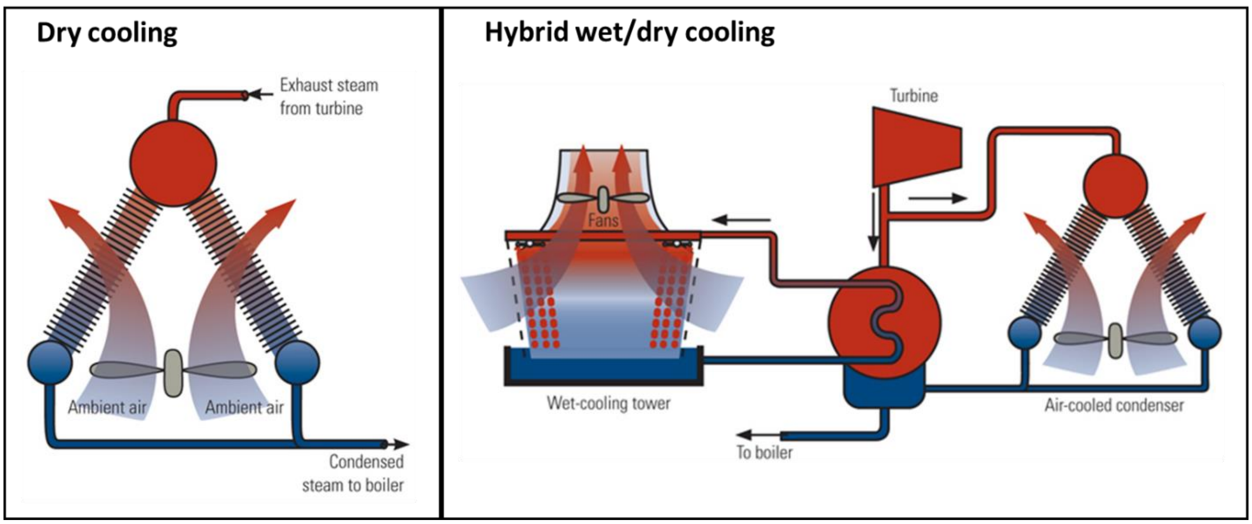

Figure 11. Dry cooling and hybrid wet/dry cooling systems.
Dry cooling systems use ambient air (rather than cooling water) to cool and condense steam from the condenser. Hybrid wet/dry cooling systems combine wet-recirculating systems with dry cooling systems to capture benefits of both systems.

Figure source: EPRI. Water Use for Power Generation. 2008.

Currently, dry or hybrid cooling systems cool about 130 TWh of net generation in the United States.[9] Most of the dry cooling systems currently online have been deployed in natural gas combined cycle plants since 2000. Additionally, according to the most recent data collected by EIA, 11 new dry cooling systems are expected to be operational by 2020.

According to some estimates, the lifetime cost of a dry cooling system could be as high as four to five times greater than a traditional water-based cooling system.[10] However, the tradeoff between capital costs and operating costs for dry cooling systems at different design points for different ambient conditions is complex. A power plant that is sizing a dry cooling system must balance the additional capital and maintenance costs of a larger system with the reduced ability for the system to sufficiently handle heat loads during especially warm or windy days. Without a detailed analysis for the proposed location that captures the variety of ambient conditions at a granular enough time scale, it is difficult to estimate the lifetime costs of a dry cooling system. These issues make it difficult to optimize the design of a dry cooling system; the industry tends to settle for summer average temperature as a design point. While this strategy may be effective for locations with consistent summer temperatures, it would be difficult for a system in a location with highly variable ambient conditions to keep up with the heat load on a particularly warm or windy day. During such conditions, the plant would incur heat rate penalties or, in extreme cases, capacity shortfalls.

Hybrid systems mitigate some of the problems associated specifically with dry cooling, particularly in dry climates where their wet system performance is not constrained by humidity, but they introduce additional layers of complexity, which translate into increased capital costs compared to traditional wet-cooling systems. An outstanding challenge is to develop dry and hybrid cooling technologies that are economically feasible for deployment, together with operational strategies to maximize the benefits they provide.

2.1.5 Trends and Outlook

As generation and cooling technologies have evolved over time, the amount of water withdrawn per kilowatt-hour has steadily declined since 1950 (Figure 12). Despite these decreases in water intensity, however, from 1950 to 1980 the total amount of water withdrawn across all thermoelectric plants nationally increased steadily and dramatically relative to irrigation, industry, and public use. Much of this increase was due to buildout of once-through cooling systems for the coal and nuclear fleet during this time period (Figure 9). Since about 1980, there has been a move from once-through to wet-recirculating cooling technologies, which has led to a leveling off of withdrawals. This move away from once-through cooling has been driven by policies such as the Clean Water Act that require permitting for facilities that discharge into water bodies, and also by improved generation and cooling system technologies. However, wet-recirculating technologies are generally associated with higher water consumption rates, as shown in Figure 7 and Figure 8.

Though long term trends are clear, there are data collection and reporting challenges that make it difficult to establish changes in water withdrawal data from year to year. For example, Figure 12 shows a dramatic decrease in withdrawals by thermoelectric plants between 2005 and 2010, but this decrease should be interpreted cautiously, as the process for estimating withdrawals is complex. Every five years, the U.S. Geologic Survey (USGS) publishes data on water use in the United States for all sectors. In order to estimate water withdrawals for the power sector, USGS aggregates data for each power plant, which state-level analysts develop from a variety of sources including historic survey responses from the U.S. Energy Information Administration (EIA), model-estimated water withdrawal, and state-level data sources, based on data availability and quality. Factors such as availability of new data sources can lead to significant changes in estimates between reported data sets.

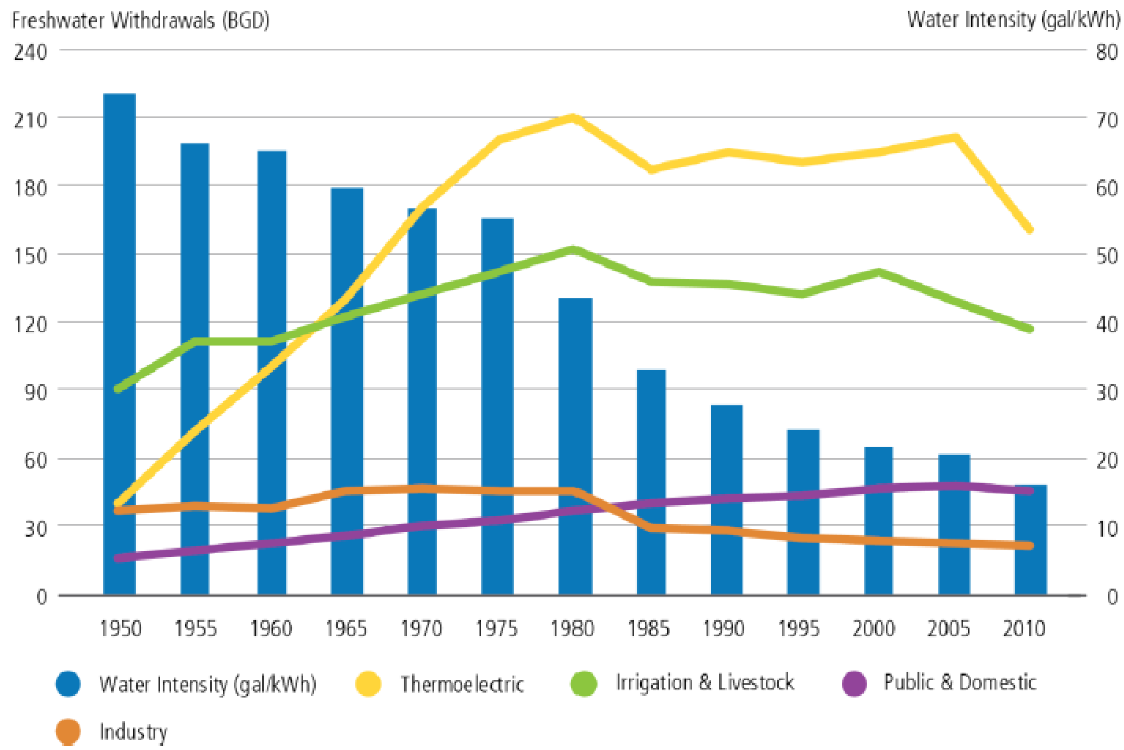

Figure 12. Water withdrawals for thermoelectric generation and other sectors.
While the water intensity of thermoelectric generation has decreased, total water withdrawn by thermoelectric generation increased significantly relative to other sectors from 1950-1980, but has leveled off in recent decades.

Data source: Maupin, M.A. et al., 2014, Estimated use of water in the United States in 2010: U.S. Geological Survey Circular 1405; and EIA. 2011. Annual Energy Review 2011.

Near-term trends and outlook for thermoelectric generation are available from EIA's planned retirements and proposed additions surveys. Figure 13 shows the fuel type for the capacity that is planning to retire or proposing to come online in the next five years. These figures are based on what electricity generators are reporting and are not projections. Most of the planned capacity retirements come from coal-fired power while new natural gas and renewable generation capacity is planned to be added. There is also some nuclear power planned to come online in the next three to five years.

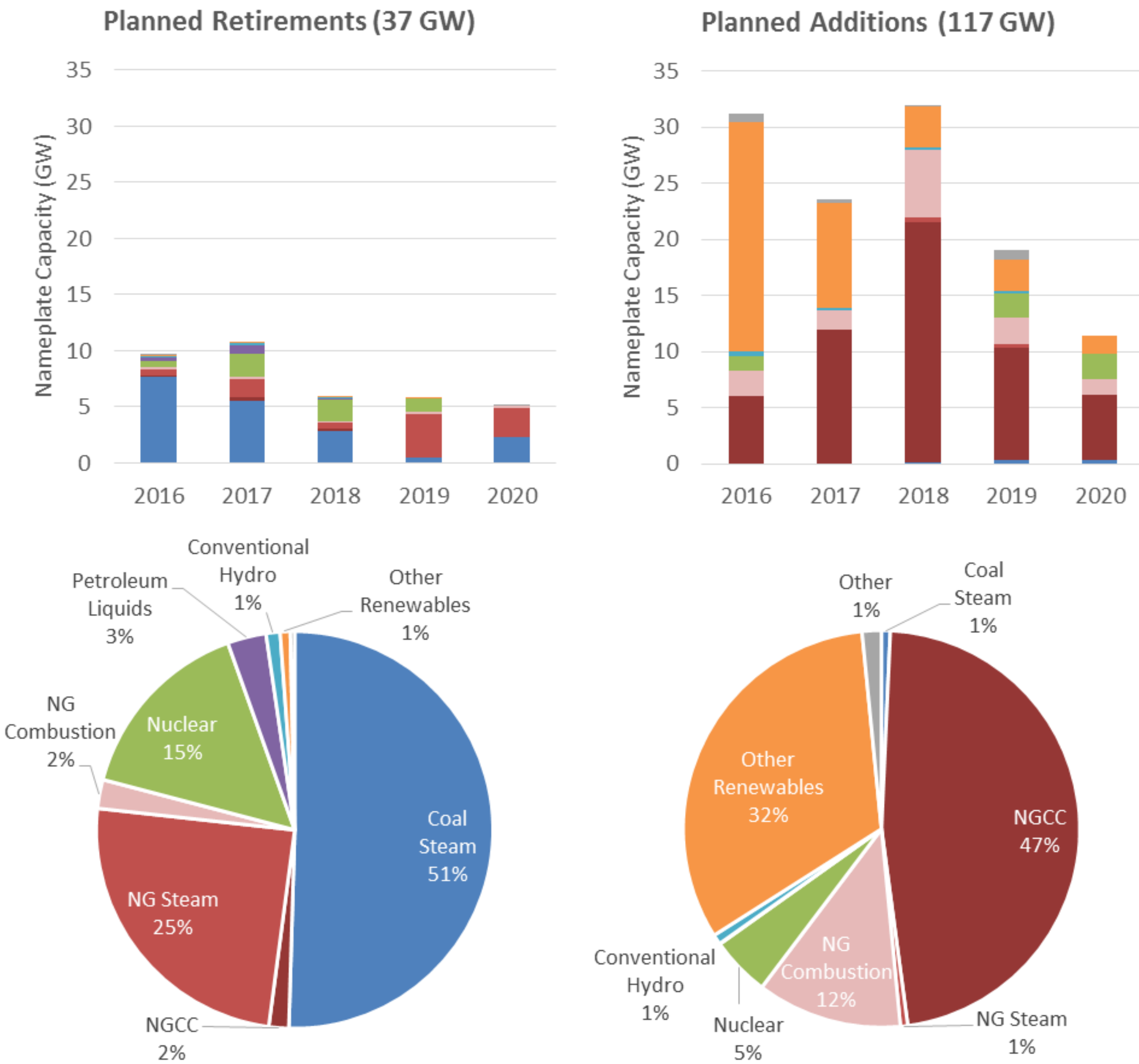

Figure 13. Planned retirements and additions of U.S. electricity generation capacity by fuel source (2016–2020).

Planned retirements are dominated by coal, while planned additions include large fractions of not only natural gas, but also renewables.

Data source: EIA Form 860 (2015 data, published in 2016)

While more than 90 percent of the capacity set to retire requires cooling (Figure 13), only about half of the planned additional capacity requires cooling (Figure 14).[h] Much of this additional capacity will come from natural gas combined cycle units, including retrofits to existing steam cycle generators in order to

[h] Each generator was categorized as either requiring or not requiring cooling based on its prime mover. The following prime movers were categorized as requiring cooling: steam turbine (including nuclear, natural gas, geothermal, and solar steam); natural gas combined cycle; and turbines used in a binary cycle (including those used for geothermal applications). All others were categorized as not requiring cooling. For a full list of prime movers, see http://www.eia.gov/survey/form/eia_860/form.pdf.

create combined cycle units. These units will still require cooling water for the steam cycle generators, but their overall water intensity is generally much lower than simple steam cycle systems.

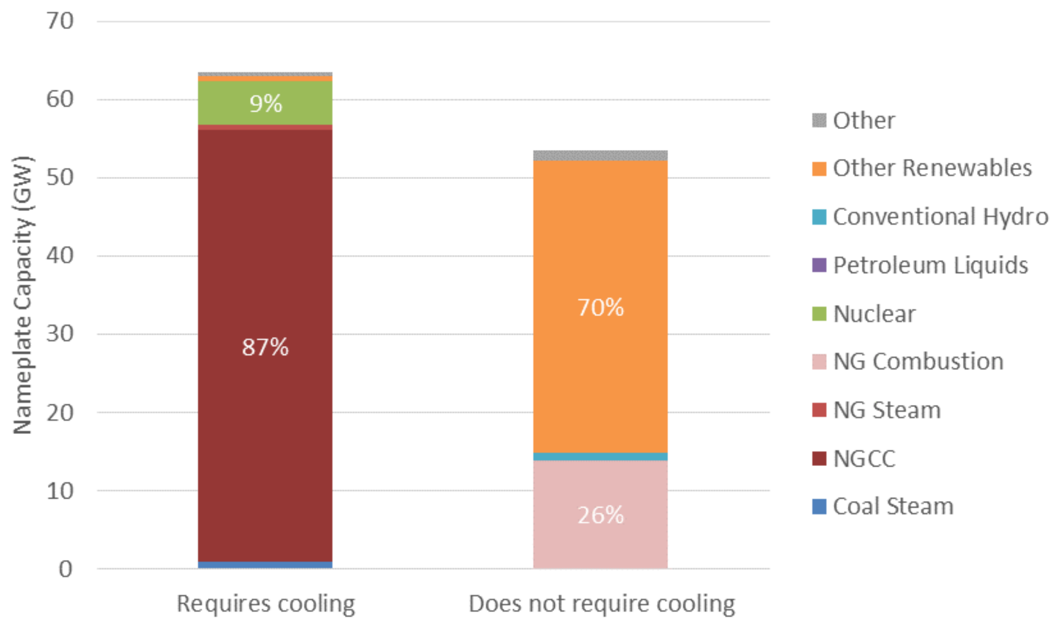

Figure 14. Planned additions of U.S. electricity generation capacity by cooling requirement and fuel source (2016–2020).

The planned additional capacity requiring no cooling is nearly equal to that requiring cooling, and this no-cooling portion is split between natural gas and renewables. Note that NGCC systems make up a large share of planned capacity additions, and these are classified as requiring cooling. However, because the combustion turbine component of the NGCC system requires far less water than the steam turbine component, the overall NGCC system tends to be relatively water efficient.

Data source: EIA Form 860 (2015 data, published in 2016)

Many of the generation units set to retire by 2020 use once-through cooling technologies, while many of the anticipated new generation units are expected to use recirculating cooling technologies (Figure 15). A number of plants are slated to use dry or hybrid cooling. The Eastern states will experience the most drastic changes in cooling practices because that is where the largest planned retirements and additions are scheduled to occur, and it is also where once-through cooling dominates in existing plants. In this region, many large coal-fired power plants using once-through cooling are expected to retire and be replaced by natural gas and nuclear plants using recirculating technologies. Shifting away from once-through cooling will reduce water withdrawals, but using recirculating cooling will generally increase water consumption.

Planned Retirements

Planned Additions

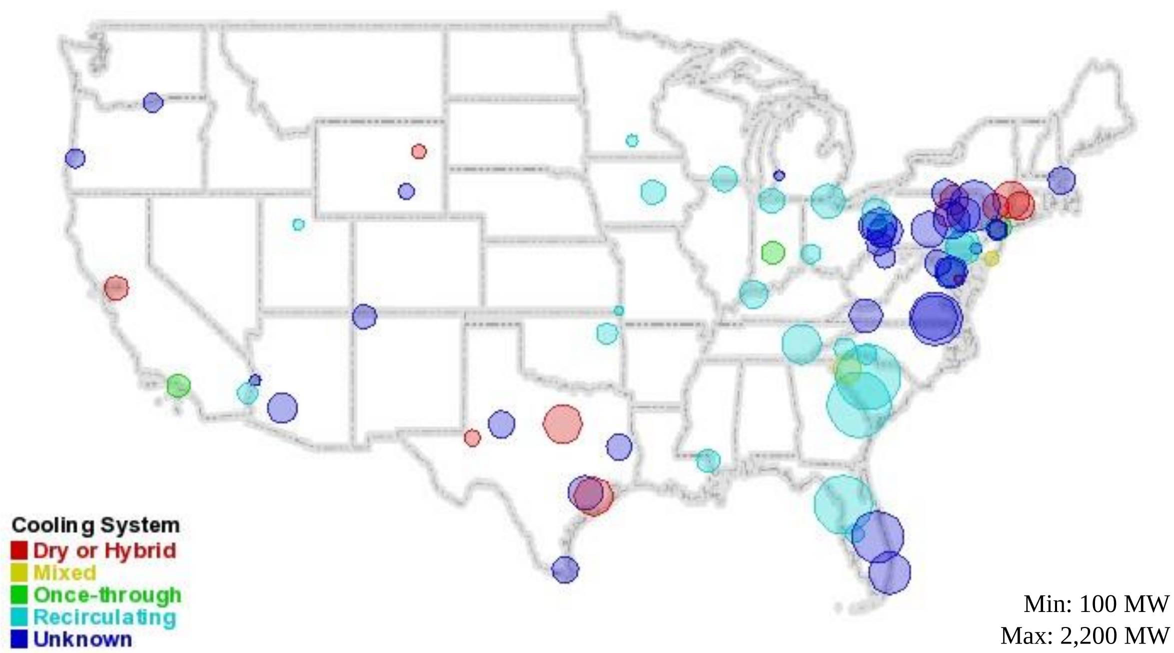

Figure 15. Planned retirements and additions of U.S. electricity generation capacity by cooling type (2016–2020).

Many planned retirements will occur in the Midwest and California, while additions appear clustered in the East. Size of dot indicates nameplate capacity. This figure only shows plants with at least 100 MW of planned thermoelectric capacity retirements or additions.

Data source: EIA Form 860 (2015 data, published in 2016)

Finally, the type and quality of water being used by the current fleet and proposed to be used by additional capacity can have water availability implications. Figure 16 compares the share of the number of cooling systems proposed for 2016-2020 to that of the current fleet, according to both cooling water source type (upper panel) and water type (lower panel). For source type, 72 percent of the current fleet uses surface water, while only 29 percent of proposed systems use surface water. Thirty-one percent of proposed systems are expected to use dry cooling, relative to only four percent of the current fleet. The share of plants using groundwater and wastewater treatment plant discharge is similar for the current fleet and the proposed systems. Comparing the source type data to the water type data (lower panel), we can see that most of the groundwater for proposed systems will be fresh groundwater. For water type, proposed systems are expected to include a much larger share of dry cooling and a much smaller share of freshwater use relative to the current fleet.

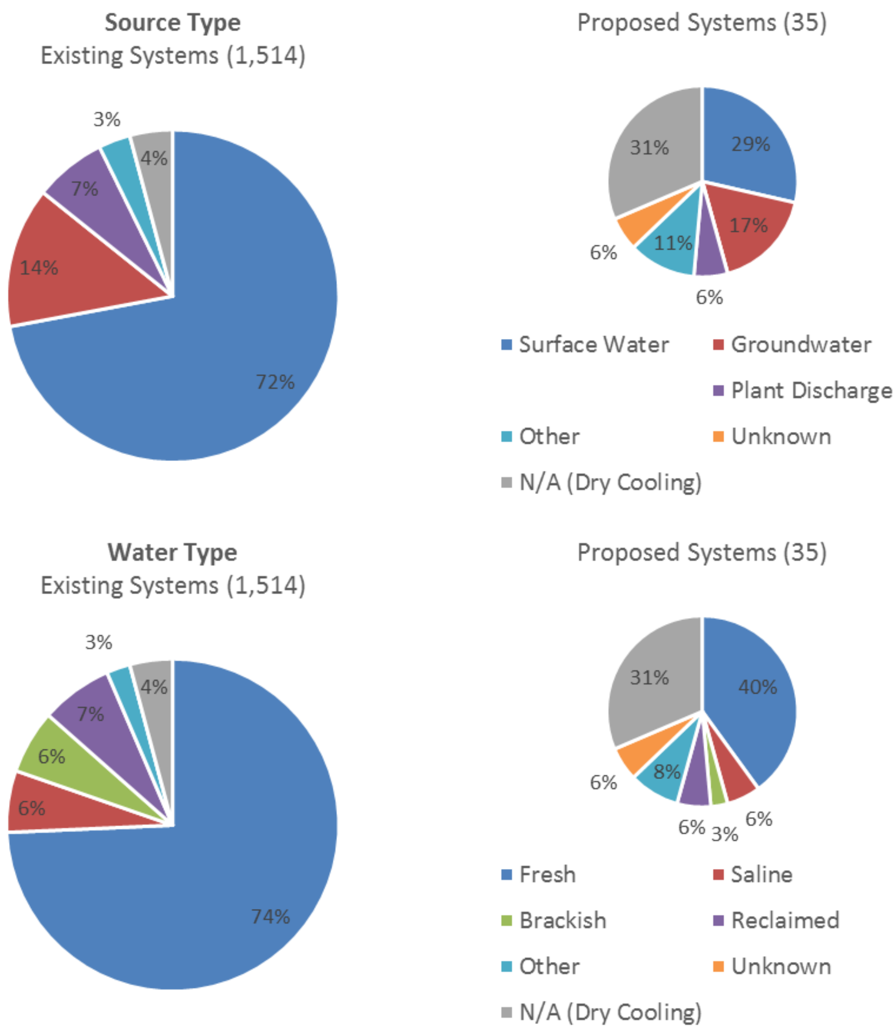

Figure 16. Number of existing and proposed (2016-2020) cooling systems by source type and water type. *Source type (upper panel) and water type (lower panel) are shown for existing cooling systems (left) and proposed cooling systems for 2016-2020 (right). The share of proposed systems that will use dry cooling is substantially larger than that of the current fleet.*

Data source: EIA Form 860 (2015 data, published in 2016)

2.2 Carbon Capture and Storage

In addition to water impacts from generation and cooling technologies, deployment of carbon capture and storage (CCS) can have a significant effect on water withdrawal and consumption. For example, a monoethanolamine carbon dioxide recovery unit increases water requirements both because its installation decreases the overall energy efficiency of the plant and because it has a number of cooling subprocesses that require water.[11] Figure 17 shows additional water withdrawal and consumption requirements expected for current CCS monoethanolamine technologies combined with various generation technologies with wet-recirculating cooling.[12]

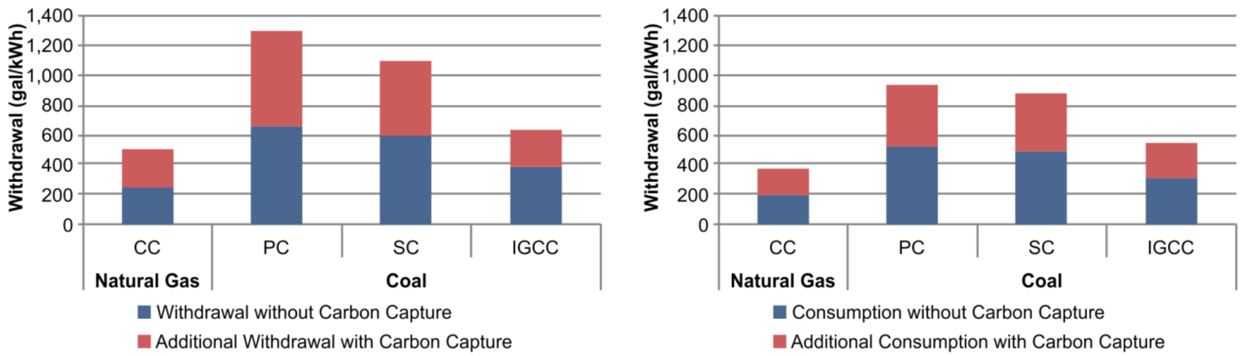

Figure 17. Additional water withdrawal and consumption requirements for monoethanolamine CCS. *Pulverized coal requires the most additional water withdrawal and consumption for monoethanolamine CCS. In all cases, these withdrawal and consumption figures are for recirculating cooling. Abbreviations: CC: Combined Cycle; PC: Pulverized Coal; SC: Supercritical Pulverized Coal; IGCC: Integrated Gasification Combined Cycle.*

Figure source: The Water-Energy Nexus: Challenges and Opportunities 2014
Data source: Meldrum et al. 2013

While monoethanolamine (MEA) in aqueous solutions is the current state of the art in post-combustion carbon capture, this technology currently imposes energy and water performance penalties and would increase the cost of electricity generation relative to comparable plants without capture.[13] The energy, water, and cost performance penalties associated with current MEA technologies for carbon capture are primarily attributable to the energy and water requirements for solvent regeneration.[14] [15] The post-combustion capture system requires water for flue gas cooling prior to solvent addition, plus cooling within the absorption and stripping process itself, as well as for the water knockout and final carbon dioxide compression steps, all of which add to overall water and cooling load requirements. Improved materials are key in developing second-generation and transformational systems for pre-combustion (applicable to IGCC coal plants), post-combustion (relevant to all fossil fuel plants, both future and existing), and oxy-combustion (an alternative to current coal and natural gas electricity generation strategies) capture.

There are three relevant classes of materials of interest in research and development related to CCS systems: solvents, sorbents, and membranes.[16] Desirable properties for these materials include increased ability for CO2 loading, reduced regenerative energy requirements, faster reaction kinetics, enhanced durability, and reduced costs. Numerous alternatives to MEA-based systems are under investigation, many of which have the potential to reduce both energy and water requirements.[17] Promising possibilities include advanced solvents and membranes,[18] calcium-looping strategies;[19] [20] metal-organic frameworks,[21] and microbial approaches.[22] Membranes, solid sorbents, and calcium-looping are examples of new technologies whose water requirements will be limited to cooling water for CO2 compression. DOE is currently testing many of these technologies at laboratory scale and in small pilot scales with industrial partners. Work remains at the pilot and demonstration scales to prove the technical and economic feasibility of alternatives to MEA processes that deliver energy, water, and cost savings compared to existing options.

2.3 Tradeoffs between Water Use and GHG Emissions

GHG emissions from and water use for electricity generation most often have a direct relationship. For coal-fired power plants, for example, modernizing technologies and operations can decrease both GHG emissions and water requirements. Existing policies aimed at reducing GHG emissions, such as the Clean Power Plan, are likely to accelerate the trend of decreasing water use. However, there are some cases where GHG emissions and water use have an inverse relationship. For example, depending on the technologies used, nuclear, CCS, CSP, and geothermal have potential to decrease GHG emissions but increase water use. Conversely, currently available dry or hybrid cooling technologies reduce or eliminate water withdrawal and consumption but can increase GHG emissions for fossil fueled plants due to reduced generation efficiency. Figure 18 shows tradeoffs between water consumption intensity and CO_2 emission intensity for a range of technologies.

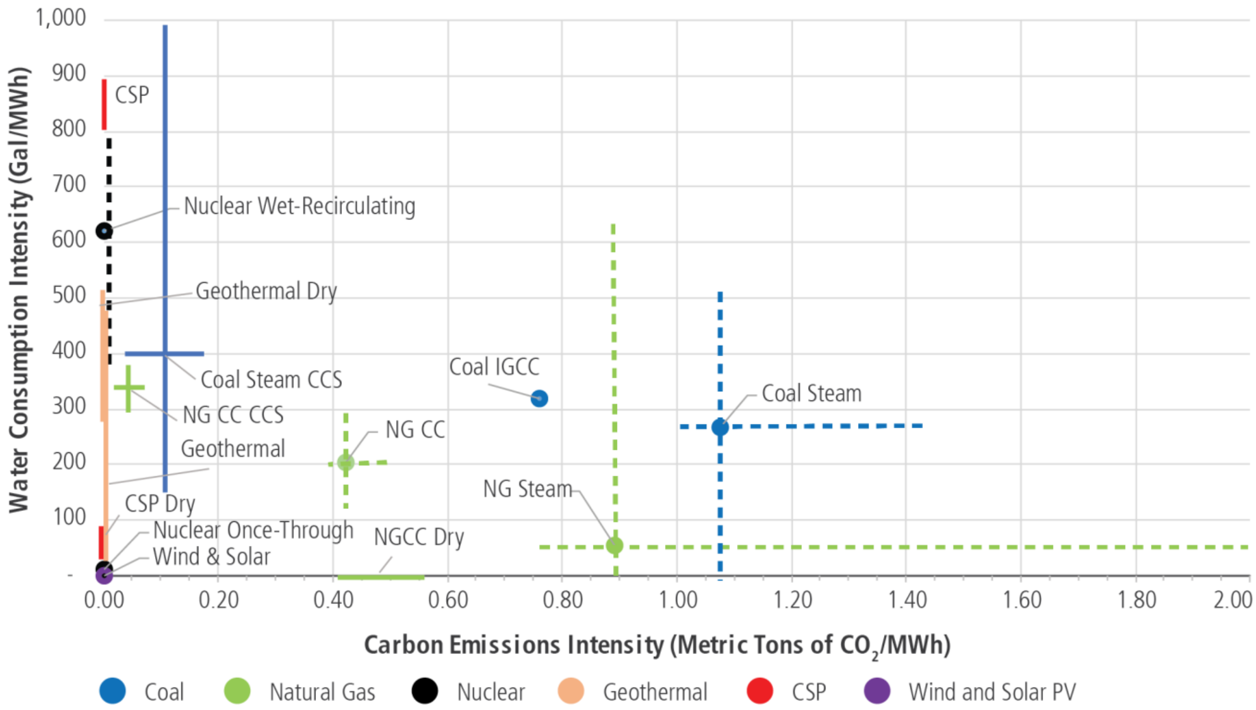

Figure 18. Water consumption intensity versus CO2 emission intensity for various technologies.

Some generation technologies (e.g., solar PV and wind) can have both low water and carbon intensities while other generation technologies present tradeoffs between water and carbon emissions. For example, low-carbon technologies, such as nuclear, geothermal, and CSP generation, along with carbon capture and storage (CCS), require large amounts of water. Conversely, dry cooling, which greatly reduces water requirements for thermoelectric cooling, often induces an efficiency penalty, which increases the carbon intensity of generation. Dotted lines represent ranges calculated from data, and solid lines represent ranges from literature values.
Figure source: EPSA
Data source: Thermoelectric cooling water data (2015 data, published in 2016) derived from EIA Form 923 and EIA Form 860. The Water-Energy Nexus: Challenges and Opportunities, (DOE, 2014). National Energy Technology Laboratory (NETL), "Cost and Performance Baseline for Fossil Energy Plants Vol 1a: Bituminous Coal (PC) and Natural gas to Electricity," (Pittsburgh, PA: NETL, 2015). Advanced Research Projects Agency-Energy (ARPA-E), "ARID Program Overview," (Washington, DC: ARPA-E, 2016).

Government support has sought to address some of these tradeoffs. Through the Advanced Research in Dry Cooling (ARID) program, ARPA-E has invested about $30 million to advance dry cooling technologies. The program aims to develop dry cooling technologies that do not consume any water, eliminate efficiency penalties, and do not increase the levelized cost of electricity cost by more than 5 percent. Reaching this target would allow for reduced water use for cooling without an additional efficiency penalty. In addition, DOE has supported designs for advanced nuclear reactors that use molten salt rather than water as a cooling fluid.

2.4 Summary and Conclusion

Thermoelectric generation requires significant water use for operation, as do associated technologies such as CCS. Advanced technologies have potential to decrease these water demands substantially. Increased deployment of dry and hybrid cooling technologies can reduce or eliminate cooling water demands. Further deployment of wet-recirculating systems can greatly reduce water withdrawal relative to once-through cooling, but can increase water consumption. Improved cooling system operations can also reduce water demands, as can more advanced CCS technologies.

A changing generation mix resulting from policy and technology drivers can reduce GHG emissions and water use, but some technology deployment scenarios such as high nuclear, CCS, and dry cooling can create tradeoffs among energy, water, and GHG goals that must be considered and balanced. These and other issues can be addressed in region-specific analytical tools to inform decisions such as water management, energy facility siting, and technology selection.

Chapter 3. Hydropower

U.S. hydropower[i] has the ability to provide both flexible, zero-GHG generation and a suite of ancillary services for the evolving modern electric grid, but policy constraints, high cost, and valuation challenges have in some cases limited its provision of these services. Hydropower is unique in that, more than other generation types, its siting and operations are tightly intertwined with competing non-energy goals such as providing ecosystem services, navigation, flood control, agriculture, and recreation. Such non-energy constraints can in some cases limit the ability of existing hydropower to provide flexibility and ancillary services even when it is technically capable of providing them. Ancillary services markets offer additional potential revenue streams for hydropower, but complexities in valuation and market rules can present challenges.

3.1 Key Characteristics of Hydropower

Hydropower comprises a significant share of electricity generation and depends on water to operate. Although the process of hydropower generation itself does not technically withdraw or consume water, hydropower requires suitable water to be available for electricity generation. Furthermore, the significant government ownership of dams used for hydropower can have operational as well as budgetary implications.

3.1.1 Hydropower Classification

Hydropower generation is often divided into two categories: conventional hydroelectric and hydroelectric pumped storage.[23] Most large conventional hydroelectric plants utilize dammed reservoirs in river systems to drive generating turbines; generating capacity increases linearly with the height of the reservoir ("hydraulic head") and the available flow. These types of plants are referred to as impoundment hydroelectric plants. Other conventional hydroelectric plants can be "run-of-river" plants, also known as diversion plants, which tend to be smaller in generating capacity and have no large storage reservoir, instead relying directly on natural river flow to drive generating turbines.

Hydroelectric pumped storage plants generate electricity in a similar fashion to impoundment hydroelectric plants, but they are in addition able to reverse their turbines to pump water upward into a storage reservoir, thereby storing electricity. Pumped storage plants can be either open-loop, meaning that they require connection to natural water flow to operate, or closed-loop, meaning that they can reuse water to operate without significant connection to natural water flow. Combinations of pumped storage and hydroelectric plants in the same location are also possible, and indeed, sufficiently large impoundment hydroelectric plants can serve a similar function to pumped storage by storing water and thus deferring generation until it is needed.

3.1.2 Hydropower Generating Capacity

Hydroelectricity in 2015 accounted for about 6 percent of total U.S. electricity generation.[24] Net summer capacity of conventional hydroelectric generation in the U.S. was 79.7 GW in 2015, accounting for 7.5 percent of total utility-scale capacity from all energy sources.[25] Net summer capacity for hydroelectric pumped storage was 22.6 GW, or 2.1 percent of total generating capacity.[26] Pumped storage can be alternately viewed as either generating capacity or electricity storage capacity. From the storage perspective, pumped storage accounts for about 98 percent of all utility-scale grid storage in the U.S., with the remaining 2 percent made up of batteries, compressed air, and flywheels.[27] A given hydroelectric

[i] The term "hydropower" in this report includes both conventional hydroelectric plants and hydroelectric pumped storage, which will be distinguished when necessary.

or pumped storage plant could include multiple generators; for example, the largest hydroelectric plant in the U.S. is the Grand Coulee Dam in Washington, which includes 33 generators for a total capacity of 7.1 GW. Lists of the ten largest-capacity conventional hydropower and pumped storage facilities are included in Table 1 and Table 2, respectively.

Table 1. Ten Largest Conventional Hydroelectric Facilities

Rank	Plant Name	State	Summer Capacity (MW)	Ownership
1	Grand Coulee	WA	6,765	BOR
2	Chief Joseph	WA	2,456	ACE
3	Robert Moses Niagara	NY	2,439	Nonfederal
4	John Day	OR	2,160	ACE
5	Hoover Dam	AZ, NV	2,079	BOR
6	The Dalles	OR	1,823	ACE
7	Glen Canyon Dam	AZ	1,312	BOR
8	Rocky Reach	WA	1,254	Nonfederal
9	Bonneville	OR	1,154	ACE
10	Boundary	WA	1,104	Nonfederal

Source: EIA Form 860 (2015 data, published in 2016) for Summer Capacity; 2016 National Hydropower Asset Assessment Program (NHAAP) database for Ownership.

Table 2. Ten Largest Hydroelectric Pumped Storage Facilities

Rank	Plant Name	State	Summer Capacity (MW)	Ownership
1	Bath County	VA	3,003	Nonfederal
2	Ludington	MI	1,964	Nonfederal
3	Raccoon Mountain	TN	1,616	TVA
4	Castaic	CA	1,575	Nonfederal
5	Bad Creek	SC	1,360	Nonfederal
6	Helms Pumped Storage	CA	1,212	Nonfederal
7	Blenheim Gilboa	NY	1,166	Nonfederal
8	Northfield Mountain	MA	1,146	Nonfederal
9	Muddy Run	PA	1,070	Nonfederal
10	Rocky Mountain Hydroelectric Plant	GA	1,035	Nonfederal

Source: EIA Form 860 (2015 data, published in 2016) for Summer Capacity; 2016 National Hydropower Asset Assessment Program (NHAAP) database for Ownership.

3.1.3 Government Ownership

Significant government ownership is a key distinguishing characteristic of hydropower. In 2014, 49 percent of hydroelectric capacity was owned by the federal government, with 24 percent owned by private entities, and the remaining 27 percent owned by public utilities, state agencies, and cooperatives.[28] Federal owners include the U.S. Army Corps of Engineers (ACE), the Bureau of Reclamation (BOR), and the Tennessee Valley Authority (TVA). Many of the largest conventional hydroelectric facilities are federally owned (Table 1), while many of the largest pumped storage facilities are nonfederal (Table 2).

Unlike other electricity generation, hydropower operations are often part of a larger waterway management operation that meets additional needs including navigation, flood control, irrigation, environmental mitigation, recreation, and water supply. For many federal dam projects in particular, these other purposes are higher in priority than electricity generation. The range and priority of authorized purposes affects the potential for hydropower generation on the dams.

The authorized purposes for ACE projects are determined by some combination of (1) legislation authorizing construction of the project, (2) legislation passed after the project is operational, and (3) legislation governing all ACE projects.[29] Projects are generally operated according to their authorized purposes.[j] While hydroelectric generation can be an authorized purpose of ACE projects, there is also an option for nonfederal hydropower projects, permitted by FERC, to utilize ACE reservoirs. Generally, ACE makes no changes to its operations due to the presence of nonfederal hydropower generation, as nonfederal hydropower at ACE reservoirs is treated as an incidental benefit, rather than an authorized purpose. A 1990 report by ACE details authorized purposes, including priority, as well as actual operations, of 541 ACE projects.[30] BOR allows similar "incidental" participation by nonfederal hydropower in its projects, with permitting handled either by FERC or BOR itself.[31]

Power produced at ACE and BOR facilities is marketed and sold by DOE's Power Marketing Administrations (PMAs). In some cases, PMAs must receive appropriations from Congress for modernization and general maintenance of federal facilities;[k] this situation has potential to limit funding available for upgrades to enable more flexible operation and ancillary services provision.[32] For the ACE facilities, for example, power was sold at cost for $3-4 billion of revenue in 2010, but only $230 million was appropriated back to the ACE for hydropower O&M and capital expenditures.[33] From a budget execution perspective, this places hydropower fourth in priority for the ACE, behind navigation, flood control, and environmental mitigation. In addition, of this $230 million, only $30 million was allocated in the budget line for major equipment replacement and upgrades.[34] The limited budget for equipment and upgrades across ACE facilities had led to declining performance in recent years.[35]

3.2 Regional and temporal variability

More than half of the total U.S. hydroelectric installed capacity is located in Washington, California, and Oregon, but most states have at least some hydroelectric capacity (Figure 19). Hydroelectric plants make up more than 30 percent of state-wide electricity generation capacity for Washington, Oregon, Idaho, Vermont, Montana, South Dakota, and Maine. Strong regional clusterings are apparent for both hydroelectric plants and pumped storage in California, the Pacific Northwest, the Southeast, and the Northeast. These regions are generally correlated with areas of relatively high historical water runoff. Most pumped storage is somewhat correlated with regions of high hydroelectric deployment, although pumped storage appears relatively more common in the east.

[j] However, in some cases changes to river conditions, economic conditions, or other factors can require changes to water control plans by ACE.

[k] The Bonneville Power Administration (BPA), unlike the other three PMAs, is self-financed and thus receives no federal appropriations. BPA covers its operating costs through power rates set to repay Treasury capital and interest. In addition, the 1992 National Energy Policy Act authorizes direct funding by BPA for the Corps of Engineers and Bureau of Reclamation for O&M and capital investments in the Federal Columbia River Power System (FCRPS).

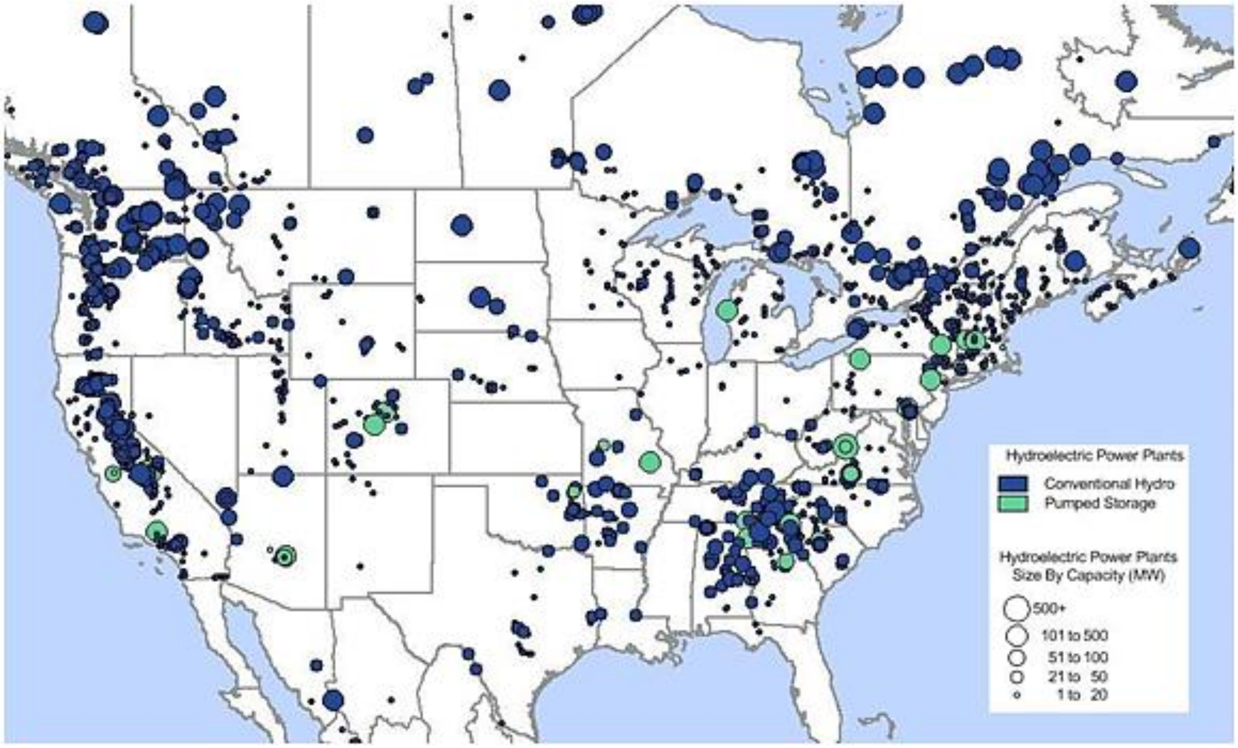

Figure 19. Location of hydropower in the U.S.
Strong regional clusterings are apparent in California, the Northwest, and the Southeast.
Data source: EIA. Hydroelectric power resources form regional clusters. Today in Energy. 2011.

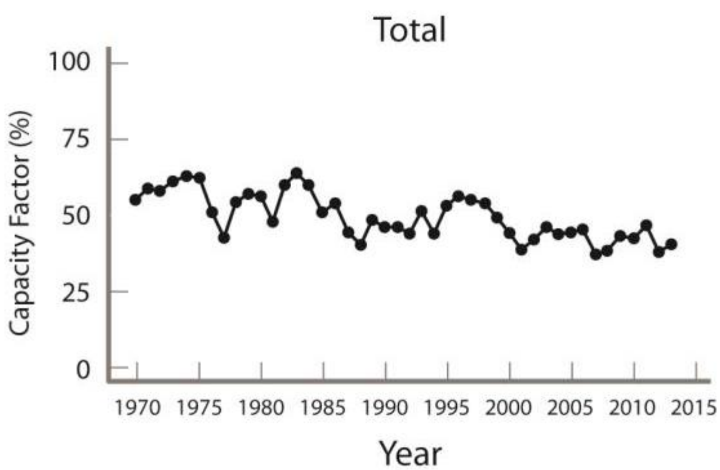

Figure 20. Long-run monthly hydropower capacity factor for plants built before 1970
Capacity factor varies by year, but a downward trend is apparent.
Data: EIA Form 920/921/923
Figure: 2014 Hydropower Market Report

Nationally, there has been a slow downward trend in hydropower capacity factor since the 1970's (Figure 20). The factors contributing to this downward trend include some combination of changes in operational management due to environmental regulations, changing availability of water under climate change, aging equipment, and shifting priorities of water uses in multipurpose projects.[36]

Due to hydropower's dependence on water availability, hydropower generating capacity can vary significantly over time. As shown in Figure 21, the northwest region generated the largest amount of electricity between 2002 and 2013. Each of the regions shown has at least some seasonal fluctuations (see Section 7.2.2), with the strongest in the NW.

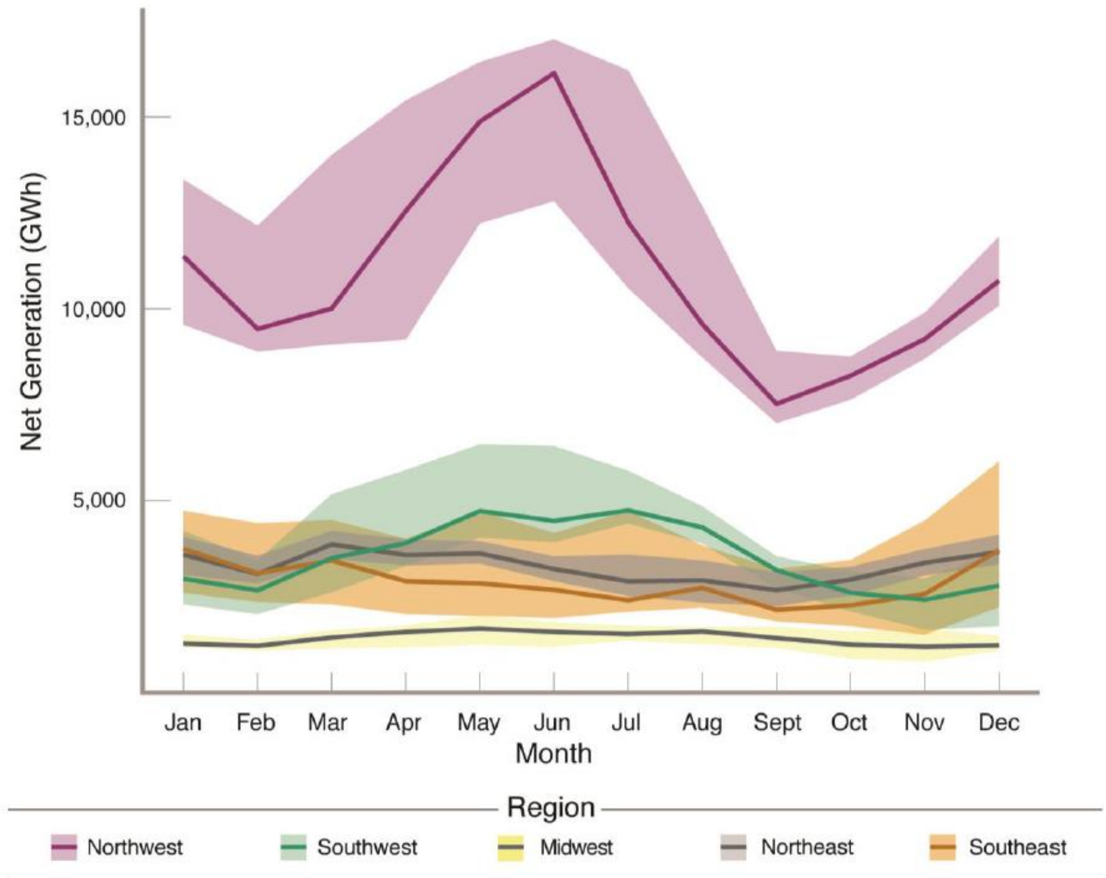

Figure 21. Monthly Hydropower Generation by Region (2002-2013)
The central lines depict the median generation level for each month in each region during 2002-2013. The surrounding bands enclose all but the 10 percent highest and 10 percent lowest observations. Regions are defined according to FERC hydropower region boundaries.[37]

Data Source: EIA Form 923
Figure from: DOE Hydropower Market Report 2014

3.3 Generation flexibility

Hydroelectric and pumped storage generation can provide flexibility to the grid in various ways, which is particularly relevant for balancing an increasing share of variable and non-dispatchable renewables. Although hydroelectric generation can simply serve as baseload generation, more flexible operation, depending on plant configuration and other factors, is widely utilized.[38] The terms of FERC-issued licenses for non-federal hydropower include required environmental measures and the operational mode for the facility. Operational modes described in Figure 22 span the range from zero/low flexibility to high flexibility.

Mode-of-Operation Class	Description/Purpose
Canal/Conduit	Uses water flow determined by the original purpose of the conveyance structure to generate electricity.
Run-of-River	Discharges from the project tailrace or dam, approximately, the sum of inflows to the project reservoir at any given time. Hydroelectric generation depends on natural incoming flows. Minimizes the fluctuation of the reservoir surface elevation and deviation from natural flow regimes.
Reregulating (Cascading Systems)	Stabilizes flow fluctuations from upstream peaking or storage release facilities and generates electricity. Often used to mitigate impacts to natural flow regimes from peaking reservoirs. Reduces impacts to natural flow regimes from upstream peaking plants.
Run-of-River/Peaking	Operates as run-of-river facility for periods of time or seasons (e.g., during fish spawning) and then operates as a peaking facility the remainder of time.
Intermediate Peaking	Stores limited amounts of water for occasional releases, or moderates the intensity of peaking for hydroelectric generation.
Run-of-River/Upstream Peaking (Cascading Systems)	Operates as run-of-river facility but harnesses the energy from upstream storage releases or peaking operations to generate electricity.
Peaking	Stores and releases water (high-flow releases) for hydroelectric generation. Typically large reservoir fluctuations because of seasonal drawdowns.
Source: McManamay and Bevelheimer (2013).	

Figure 22. Classification of hydropower operational modes
Modes of operation span the range from low or zero flexibility to high flexibility.
Data Source: McManamay and Bevelheimer 2013
Figure from: DOE Hydropower Market Report 2014

For federal hydropower, operations are determined by the ACE, BOR, or TVA. These agencies release operational information through various modes, such as through ACE's Water Control Manuals, BOR's centralized web portal, and TVA reservoir operation studies.[39] While federal hydropower is not constrained to operate in a FERC-regulated context, actual operational modes can generally be identified in a manner similar to those outlined in Figure 22.

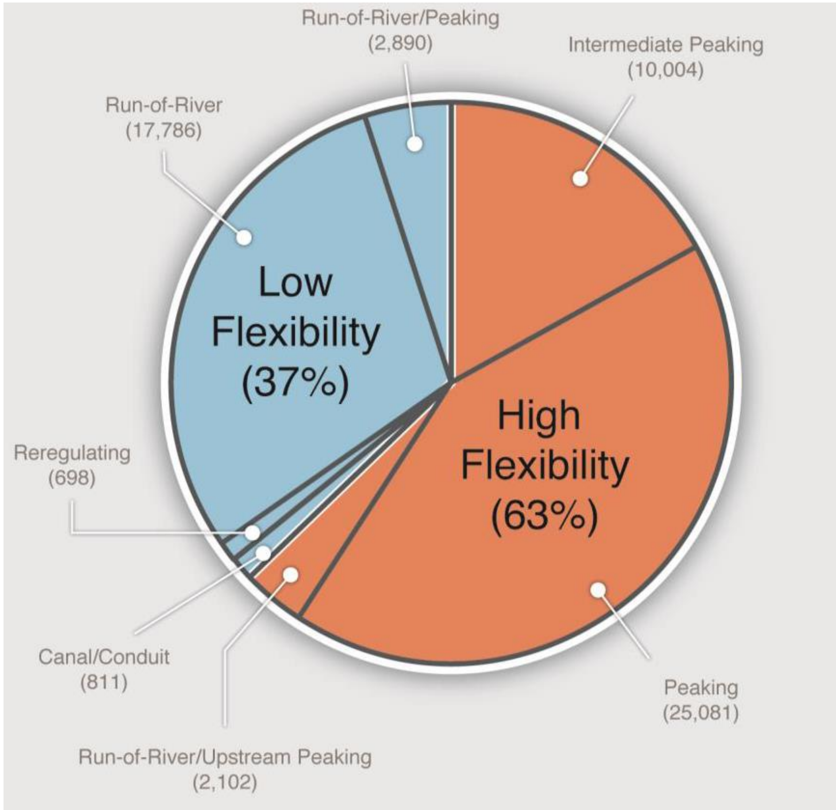

Figure 23. Distribution of operational modes in the U.S. hydroelectric generation fleet (numbers are MW capacity)

About 63 percent of hydropower capacity surveyed is high-flexibility generation. The surveyed sample represents about 75 percent of total capacity, with the remainder being primarily smaller and less flexible facilities. Data Source: DOE Hydropower Market Report 2014, released in 2015. Data is as of December 31, 2014. Figure from: DOE Hydropower Market Report 2014, released in 2015.

Figure 23 shows a mapping of about 75 percent of U.S. federal and non-federal hydropower capacity mapped to the seven categories of Figure 19. At least 35 GW of installed hydroelectric capacity as of December 31, 2014 constitutes "high flexibility" generation that is able to operate in peaking mode (Figure 23).

Median plant capacity in the peaking category is 30 MW, whereas run-of-river plants are typically smaller, with median capacity of 1 MW. Most of the ~23 percent of capacity which was not tracked comprises small plants, making it reasonable to assume that this fraction was primarily in the low-flexibility range.

Different regions have different mixes of low- and high-flexibility operation. Most of the run-of-river/upstream peaking category is found in the Northeast. The intermediate peaking category is found almost exclusively in the western regions. The two most common operational categories, peaking and run-of-river, are found in all regions.

Pumped storage allows maximal flexibility in operations, making it effectively a peaking resource. Pumped storage is often used to generate electricity by releasing water in the upper reservoir when electricity demand and prices are high (e.g., during the day). Turbines are then run in reverse to store electricity when demand and prices are low (e.g., at night). Often, plants will begin to release water and generate electricity once the sale price is high enough to cover their pumping losses. This strategy for smoothing out demand and generating revenue through arbitrage is known as “peak-shaving.”

The existing fleet of pumped storage plants was built primarily in the 1960s through the 1980s to complement nuclear and other thermoelectric baseload generation. However, pumped storage is well-suited to balance an increasing penetration of variable renewables, particularly with increasing retirements of older nuclear and thermoelectric plants. Closed-loop pumped storage plants are particularly suitable for flexible operations because they are less constrained by environmental regulations than open-loop plants.

3.4 Ancillary services

Both hydroelectric and pumped storage plants are technically capable of providing a variety of ancillary services, which may become increasingly valuable as variable generation grows.[40] In the Western Electricity Coordinating Council region, for example, hydropower is a major source of inertia and primary frequency response, but hydropower is not specifically compensated for either service.[41] Figure 24 gives definitions of ancillary services relevant to hydropower.

Grid Ancillary Services Relevant to Hydropower

Regulation and frequency response: *The ability of a resource or a system to respond to changes in system frequency, which must be maintained close to a constant level (60 Hertz).* NERC establishes control performance standards to ensure that each control area maintains reliability. This response can be provided by generators through three mechanisms:

- Inertia: A passive response, typically due to rotating masses in generators
- Primary frequency response or governor control: An active, unmanned response implemented through an electronic, digital, or mechanical device
- Frequency regulation: An active response to adjust an area's generation from a central location in order to maintain the area's interchange schedule and frequency

Hydropower generators can provide these regulation services. While hydropower turbines are able to respond to sudden changes in system frequency, the relatively large mass rotating in hydropower turbine generators and the dynamics of the water column in the penstock mean hydropower may have a lower response time than do gas or steam [75]. This larger inertia can, however, be an advantage in smaller or islanded power systems as it contributes to system stability [76].

Load-following and flexibility reserve: *The ability of the power system to balance variability existing in the load over longer timeframes than regulation and frequency response, from multiple minutes to several hours.* This function is typically accomplished by mid-merit (intermediate) and peaker units. Most U.S. hydropower units are able to and do effectively provide load following to an hourly schedule, as well as following ramps that occur within the hour time scale. This flexibility is not without impact, however. Increased variation in hydropower generation can impact riverbank erosion and aquatic life, as well as increase operating costs and decrease system lifetime. In order to determine optimal use of hydropower for load-following services, these impacts must be considered against the cost of providing load following from other types of generation.

Energy imbalance service: *The transmission operator provides energy to cover any mismatch in hourly energy between the transmission customer's energy supply and the demand that is served in the balancing authority area.*

Spinning reserve: *Online (connected to the grid) generation that is reserved to quickly respond to system events (such as the loss of a generator) by increasing or decreasing output.* Except when already running at full load, hydropower offers an excellent source of reserve because it has high ramping capability throughout its range.

Supplemental (non-spinning) reserve: *Offline generation that is capable of being connected within a specified period (usually 10 minutes) in response to an event in the system.* Offline hydropower generation is capable of synchronizing quickly, and can provide non-spinning reserve to the extent that sufficient water supply is available to the unit for generation.

Reactive power and voltage support: *The portion of electricity that establishes and sustains the electric and magnetic fields of AC equipment.* Insufficient provision of reactive power can lead to voltage collapses and system instability. All hydropower facilities are operated to follow a voltage schedule to ensure sufficient voltage support. Reactive power is typically a local issue. Because hydropower facilities are often located in remote areas, their ability to provide reactive power in such locations can be essential.

Black start (restoration) service: *The capability to start up in the absence of support from the transmission grid.* This capability is of value to restart sections of the grid after a blackout and can typically be provided by hydropower.

Figure 24. Grid ancillary services relevant to hydropower

This text box, from DOE's Hydropower Vision report, defines ancillary services relevant to hydropower.
Data Source: DOE Hydropower Vision 2016
Figure from: DOE Hydropower Vision 2016

More than 80 percent of hydropower capacity in the U.S. has sufficiently fast physical ramp rates and response time scales[1] needed to bid into spinning and non-spinning reserve markets.[42] Even run-of-river facilities can in some cases provide frequency regulation services.[43] In some cases multiple generators can

[1] For example, one bidding requirement is the ability to ramp from cold shutdown to full power within 10 minutes.

operate together as a system to provide all necessary ancillary services for a given region.[44] Pumped storage plants are also generally capable of providing all ancillary services in Figure 21 while in generating mode.

In general, the physical ability to deliver ancillary services depends on the response speed of the plant (Figure 25). For both hydroelectric and pumped storage plants, the response speed of generation depends on the total response speed of plant components, such as water discharge tunnels and other components[45]. Conventional reversible pumped storage generation, including most U.S. capacity, falls in the slower time scale range of seconds to minutes. For more advanced units, design has been optimized to provide faster start-up and ramping. Multiple generator units can also be combined to provide more advanced ancillary service options either unit alone; for example, a unit run in generating mode can be paired with a unit run in pumping mode to form an "asynchronous balanced" pair, which can both generate and absorb power as necessary for voltage support. Variable speed pump units provide the fastest response for regulation and allow the widest range of generation by being able to operate at a lower fraction of their total rated capacity. For pumped storage operating in pumping mode, energy is consumed rather than generated, but pumped storage plants equipped with variable speed generators can still provide frequency regulation and voltage support.

Although variable speed generators are widely deployed in pumped storage in Japan and throughout Europe, none have yet been deployed in the U.S., despite findings that existing plants in the U.S. could increase revenues by 61 percent by upgrading existing capacity through mechanical changes such as advanced turbines.[46] Europe's wider deployment of pumped storage (including variable speed generators) relative to the U.S. has been due to a number of factors, including more expensive natural gas, higher VER penetration, significant carbon trading, larger feed-in tariffs, and ancillary services payments.[47]

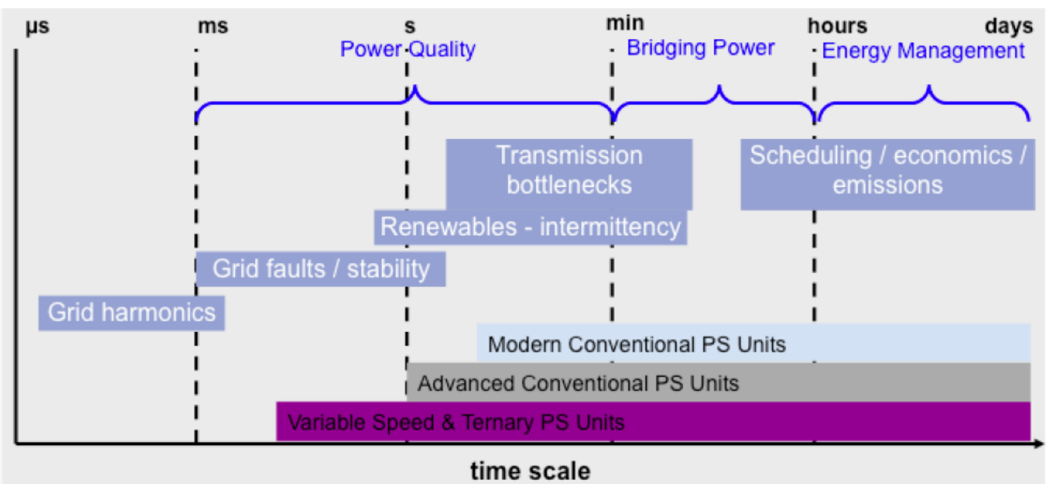

Figure 25. Frequency regulation time scale requirements, and capabilities provided by pumped storage
Advanced and variable-speed pumped storage are best suited to support variable renewables and provide other grid services.
Figure from: EPRI. Quantifying the Value of Hydropower in the Electric Grid: Final Report. 2013.

There is not currently a national-scale data set of hydropower's provision of ancillary services.[48] In the absence of data, potential ancillary services opportunities can be estimated through simulations and other region-level analyses. Estimates for the potential value of ancillary services range from 2 percent of revenue in the Northwest Power Pool, which includes abundant hydropower, to 20 percent of revenue in the Rocky Mountain Power Area.[49]

Ancillary services provided by hydropower are not always explicitly compensated by existing market structures. For example, hydropower is one of the main providers of inertia and primary frequency response in WECC, but it is not compensated for either service.[50] Recently, some market advances have been made that allow greater ancillary service participation. For example, FERC now requires ISOs to better compensate generators for frequency regulation services based on their response speed and flexibility to respond to a range of situations.[51] In addition, in June 2016, FERC issued Order No. 825 requiring all RTOs and ISOs to implement sub-hourly settlements, allowing more accurate alignment of the services provided with the prices paid for them. Market rules governing participation of flexible resources such as hydropower and pumped storage could be reviewed to determine if additional changes could allow these resources to participate more effectively.

Part of the challenge facing hydropower lies in the difficulty of optimizing generation given environmental and competing use constraints. Determining the best use of hydro resources through manual dispatch or market based bidding process can be difficult because the value of ancillary services can change quickly due to a number of factors including location, day, time, regulatory constraints, and interaction with other generators. Moreover, in the long-term, the best use of hydro resources may evolve as the generation mix changes.[52] Some ancillary services are explicitly or implicitly included in the national energy modeling system (NEMS), such as spinning reserve. However, the temporal and spatial resolution of NEMS severely limits its ability to capture this aspect of the market. Other models that are able to look at hourly dispatch at a nodal level may be more appropriate for analyzing potential hydropower contribution to this market. Improved methods and models for capturing ancillary service market dynamics have the potential to benefit hydropower operators and advance the modern electric grid.

3.5 Potential Resources

There is significant additional potential hydropower resource in the U.S. DOE's 2012 report entitled "An Assessment of Energy Potential at Non-powered Dams in the United States" identified over 12 GW of potential capacity in over 50,000 existing unpowered dams, principally in the Ohio, Mississippi, Alabama, and Arkansas River basins (Figure 26).[53] DOE's 2014 report entitled "New Stream-reach Development: A Comprehensive Assessment of Hydropower Energy Potential in the United States" identified over 65 GW of potential capacity at previously undeveloped stream-reaches[m] in the United States.[54] Much of this potential capacity includes small hydropower projects (<10 MW), which may also be able to serve as distributed generation.[55] On the pumped storage side, a number of facilities, representing up to 39 GW of capacity, are currently seeking licenses from FERC. Figure 27 overlays pumped storage license applications with wind and solar penetration, showing some correlation, particularly in the West.

[m] This estimate excludes federally protected lands such as national parks, national wild and scenic rivers, and wilderness areas.

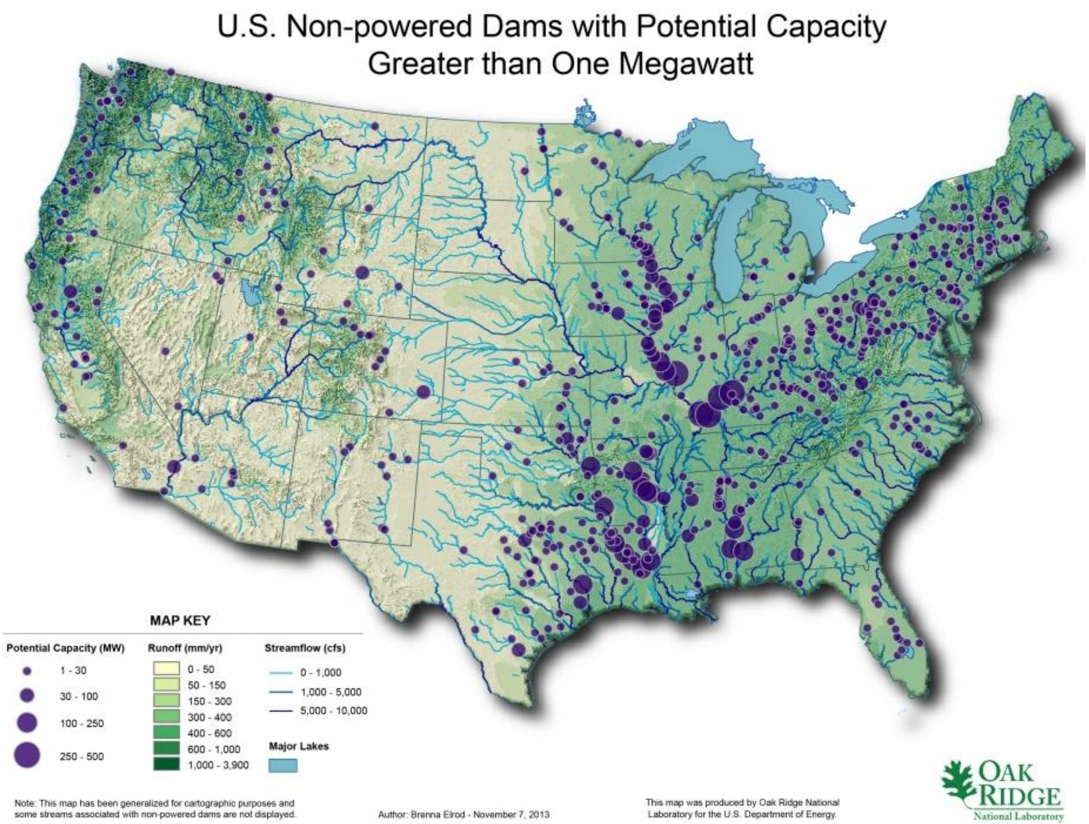

Figure 26. Hydropower development potential for existing non-powered dams

Significant hydropower development potential exists, particularly along the Mississippi and other river systems in the Midwest and the South.

Figure from: DOE 2012

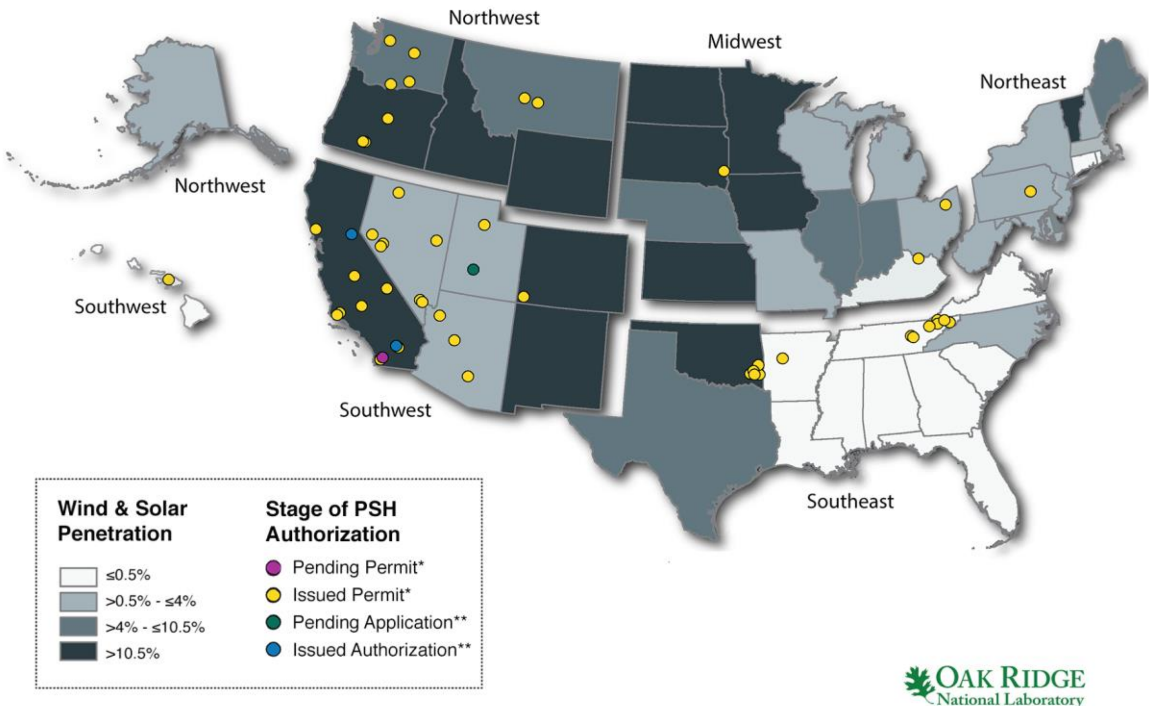

Figure 27. Pumped hydropower storage application status and wind and solar penetration.
Most pumped storage permits are located in the West, and in some cases overlap with areas of high wind and solar penetration. Pending Permit and Issued Permit categories refer to permits for an initial feasibility study. These categories have high attrition rates. Pending Application refers to an applicant that has applied for a license to operate. Issued Authorization means that the applicant has received a license to operate. Note, however, that holding a license does not guarantee construction of a plant.
Figure from: DOE Hydropower Market Report 2014

As discussed in Section 3.3 and 3.4, there has been renewed interest in recent years in using pumped storage to balance variable renewables. FERC permit and license applications for new pumped storage facilities have trended toward configurations that can enable greater flexibility and ancillary services provision. Of the 51 projects in the development pipeline as of December 2014 (including pending permits, issued permits, pending applications, and issued authorizations), 33 are closed-loop.[56] Closed-loop plants are more capital-intensive than open-loop plants, but they may be more capable of providing flexible generation and ancillary services because they are separated from natural water bodies and thus face fewer environmental constraints in their operations. In addition, 9 of these 51 projects list adjustable-speed turbines as the planned technology, which can enable frequency regulation and provision of other ancillary services. While a designation of planned turbine technology on a preliminary permit is very tentative, nevertheless these applications demonstrate interest in more flexible operation.[57]

For pumped storage plants in particular, the decision to develop new projects or add capacity to existing projects will continue to be strongly site-specific. Only particular geographies are appropriate for siting, such as areas that include a high reservoir that is naturally separate from a lower reservoir. Appropriate geographies must also be feasible to develop based on environmental and other land- and water-use considerations.

3.6 Summary and Conclusion

The current hydropower fleet is capable of providing significant grid flexibility and ancillary services to balance variable energy resources, but it may be discouraged from doing so due to low budgets for upgrading technology at federal facilities, regulatory constraints on nonfederal facilities, and limited market valuation of ancillary services. Hydropower's heavy government ownership together with the multipurpose nature of many large federal dams can create challenges associated with modernizing the federal hydropower fleet, but on the other hand, many hydropower opportunities fall within the federal domain. Adding hydropower capacity to existing dams, upgrading equipment for greater flexibility, and siting new pumped storage facilities are potential opportunities for improving hydropower's contributions to the modern electricity system.

Chapter 4. Electricity for Water Systems

This chapter describes electricity use by the water sector, including water and wastewater conveyance, treatment, and distribution. Energy demands can vary significantly across different types of water and wastewater treatment technologies, as can opportunities for energy efficiency and energy recovery. However, relative to data on water requirements for electricity generation, data on electricity consumption by the water sector is very sparse. Improved data collection could illuminate opportunities for improved energy performance of water systems.

4.1 Electricity Consumption

In addition to flows of water for electricity systems, the energy-water nexus Sankey diagram (Figure 2) also shows significant flows of electricity used for water systems. Unfortunately, there is very little measurement-based data on electricity consumption in water and wastewater systems. In addition, there are an estimated 52,000 municipal water treatment systems within the United States with an unknown number of different configurations with different energy intensities, many of which depend strongly on regional and local constraints.[58] This makes it challenging to extrapolate from literature values to energy use at regional and national scales. Research in this area often must rely on formula-based estimates or decades-old information that does not necessarily reflect current reality for changing systems. The best national estimate of electricity use for long-distance water conveyance, municipal water treatment, and water distribution (but excluding end-uses such as home water heating) is between 3 and 3.5 percent of the total U.S. electricity consumption.[59] For comparison, residential and commercial lighting in 2014 accounted for 11 percent of total U.S. electricity consumption.[60] To provide a sense of the range of energy intensities across the water sector, Table 3 summarizes key statistics for California.

Table 3. Energy Intensity of Water Treatment and Pumping in California (kWh/MG)

	Low	High	Notes	Reference
Treatment				
Drinking Water Treatment	100	16000	High: Desalination	61
Wastewater Treatment and Distribution	1100	4600		62
Pumping				
Water Supply/Conveyance	0	14000	High: Interbasin transfer (State Water Project); Low: Gravity fed	63
Primary Drinking Water Distribution	700	1200		64
Recycled Water Distribution	400	1200		65
Groundwater for Agriculture	500	1500	High: CO River Basin Low: North CA Coast	66

Source: The Water-Energy Nexus: Challenges and Opportunities (2014)

Factors that influence the energy demands of water provisioning and treatment throughout the municipal and agricultural water sectors vary significantly (Table 4). The conventional municipal supply cycle includes water conveyance from the source, water treatment, distribution to end use, conveyance to wastewater treatment, and distribution back to surface or groundwater sources. Supply side energy drivers include the type of water source, volume of water, and water quality. Additionally, conveyance energy drivers most notably include distance and elevation of pumping needs as well as the conveyance system efficiency factors for pumps, motors, and types of conduit. The electricity demands for water treatment are heavily influenced by the quality of water and the treatment plant configuration. Important energy drivers for water distribution include the terrain and the system losses or leaks, which can be difficult to locate and quantify. Wastewater treatment energy requirements are influenced by the level of treatment and ultimate use or discharge requirements of the water.

In addition to the drivers shown in Table 4, wastewater treatment also has the potential to provide net-positive energy generation. Wastewater contains a significant amount of chemical energy that can be recovered through technologies such as anaerobic digestion, in some cases even offsetting the energy required for treatment and enabling net-positive electricity generation. Low-grade thermal energy present in wastewater can also be utilized, for example through district heating or cooling schemes.

Table 4. Energy Drivers in the Municipal and Agricultural Water Sectors

<table>
<tr><th>Segment of the Municipal or Agricultural Water Sector</th><th>Sub-Segment</th><th>Primary Energy Drivers</th></tr>
<tr><td rowspan="4">Supply</td><td>Surface Water</td><td>Volume of water, source water quality</td></tr>
<tr><td>Groundwater</td><td>Volume of water pumped, depth of well, pump, & motor efficiency</td></tr>
<tr><td>Desalination, Brackish & Seawater</td><td>Source water quality, volume & quantity of water treated, technology used</td></tr>
<tr><td>Recycled Water</td><td>Wastewater discharge standard & level of additional treatment needed to convert wastewater effluent into usable supplies</td></tr>
<tr><td rowspan="3">Conveyance</td><td>Pipelines</td><td rowspan="3">Volume of water being conveyed over what distance and elevations, Conveyance system efficiency: conditions, vintage & efficiency of pumps & motors; type of conduit (pipeline vs. open channel, lined vs. unlined); rate of water leaks, seepage & evaporation)</td></tr>
<tr><td>Aqueducts</td></tr>
<tr><td>Irrigation Canals</td></tr>
<tr><td rowspan="4">Water Treatment</td><td>Filtration</td><td rowspan="4">Treatment plant configurations, the number of times water is treated, the type of water disinfection technologies used, water quality standards</td></tr>
<tr><td>Reverse Osmosis</td></tr>
<tr><td>Ozone</td></tr>
<tr><td>Ultraviolet</td></tr>
<tr><td rowspan="4">Distribution</td><td>Flat</td><td rowspan="4">Pumping energy determined by volume, system size & pressure, topography of distribution network, system age, distribution system water losses (leaks)</td></tr>
<tr><td>Moderate</td></tr>
<tr><td>Hilly</td></tr>
<tr><td>Variable</td></tr>
<tr><td rowspan="3">Wastewater Treatment</td><td>Primary</td><td rowspan="3">Plant capacity, level of treatment, treatment technologies used, wastewater influent quality, discharge requirements</td></tr>
<tr><td>Secondary</td></tr>
<tr><td>Tertiary</td></tr>
</table>

Source: Adapted from Bennett, B., L. Park and R. Wilkinson. "Embedded Energy in Water Studies: Statewide and Regional Water Energy Relationship." California Public Utilities Commission. 2010.

4.2 Water and wastewater treatment

Water and wastewater treatment processes consume significant amounts of energy.[67] [68] Even freshwater sources rarely meet drinking water standards under the Safe Drinking Water Act without some form of treatment. According to some estimates, national energy demand for water and wastewater treatment increased by more than 30 percent between 1996 and 2013.[69] These increases are due primarily to increases in population (about 17 percent) and more stringent water quality regulations. Irrigation for agriculture, inputs for aquaculture, supplies for livestock watering, and cooling sources for power plants can also require treatment. These uses have different water quality needs, which may correspond to different energy requirements for treatment.[70]

Energy intensity of treatment also depends on the source of the water. Generally, treatment of water that is either high in salinity—such as seawater, or produced water from some oil and gas operations—or contains large amounts of organic material—such as municipal wastewater—has relatively high energy requirements.[71] Thus, as more nontraditional[n] types of water are used, the associated energy requirements will generally increase. Desalination can be one hundred times as energy-intensive as treatment of fresh water (Table 3).[72]

4.2.1 Municipal treatment for drinking water

Conventional municipal water treatment for producing drinking water comprises about one percent of national energy consumption.[73] Although it represents only a small fraction of the total U.S. energy requirements, electricity for water treatment can represent the largest single energy usage and expense for a given municipality.[74] [75] In addition, the share of electricity required by water systems can have significant regional variation.

Traditional drinking water treatment in the United States consists of four steps which include coagulation, sedimentation, filtration, and disinfection. After treatment, water is pumped into a storage reservoir such as a water tower where gravity can keep distribution lines pressurized before end use. Advanced treatment options such as UV or ozone disinfection and membrane filtration are also being added to treatment processes throughout the United States.

4.2.2 Desalination

Seawater and brackish water resources are widespread, and desalination has been practiced at commercial scales for decades. Thermal methods such as multistage flash and multiple effect distillation are still widely utilized in areas where energy is plentiful and fresh water is scarce, such as the Middle East.[76] However, these technologies are energy-intensive. Reverse osmosis (RO) and nanofiltration (NF) have emerged as the predominant technologies used in desalination operations in the United States, as they are significantly less energy-intensive than traditional thermal techniques. Seawater reverse osmosis plants generally consume between 3 and 4 kWh/m^3 of water.[77] [78] This has decreased significantly over the last 40 years due to advances in technology, particularly through higher-permeability membranes, energy recovery devices, and more efficient pumps. However, both capital and energy costs are still high, and thus opportunities for improvement remain. In addition, brine discharge from desalination can cause environmental impacts such as increased salinity of coastal waters, which may require more sophisticated brine management strategies to mitigate.

Co-location of desalination plants with thermoelectric plants can provide an opportunity to reduce costs and mitigate impacts of brine disposal. For example, the Carlsbad desalination plant, which began

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[n] "Nontraditional" water refers generally to water sources other than surface freshwater, such as municipal wastewater, brackish groundwater, seawater, produced water, etc.

operating in 2015 in Carlsbad, California, uses cooling water from the Encina Power Plant for its intake supply.[79] Two gallons of intake seawater are required for each gallon of potable water produced by the Carlsbad plant; the remainder is concentrated brine that is diluted 5:1 with the post-condenser cooling water from the Encina Power Plant before discharge. Co-location strategies such as this for electricity generation and desalination can also reduce operational and permitting costs by allowing seawater intake and discharge points to be shared.

Further opportunities exist for coupling desalination (or other wastewater treatment) with waste heat from thermoelectric generating plants. For example, in the case of a forward osmosis/membrane distillation combination, a properly scaled desalination operation could meet the vast majority of its energy needs via unwanted steam from a thermoelectric plant. Additionally, productive use of waste heat decreases power plant cooling requirements.

Brackish groundwater is also an important resource in water-scarce regions. Depending on initial salinity, brine management requirements, and other factors, brackish groundwater may require less energy to desalinate than seawater. Additionally, produced waters from oil and gas, geothermal electricity generation, and potentially CCS operations have a range of salinities. Beneficial use of these waters presents a significant opportunity that will be made more attractive with cost and energy-efficient desalination solutions. Finally, the heat, pressure, and salinity available in produced waters from energy operations constitute potential energy resources that could be used either to generate electricity or reduce the costs of in-situ desalination.

4.2.3 Wastewater treatment and energy recovery

Wastewater treatment requires significant energy, but in some cases the chemical and thermal energy embedded in wastewater can be extracted to offset the energy needed for treatment.

Wastewater treatment is typically described in three stages: primary, secondary, and tertiary. Primary treatment, also referred to as mechanical treatment, includes initial screens and sedimentation to remove solids. Primary treatment is typically the least energy-intensive step, consuming about 0.02-0.37 kWh/m^3 in developed countries.[80] Secondary treatment involves the breakdown of dissolved organic matter not removed in primary treatment by microbes, potentially including a range of biological processes, filters, and settling tanks. Secondary treatment is more energy-intense than primary treatment, ranging from 0.30-2.1 kWh/m^3 in developed countries.[81] Tertiary treatment refers to any additional treatment beyond secondary treatment, which can include additional chemical treatment, and ranges in energy intensity from 0.40-3.8 kWh/m^3 in developed countries.[82]

Although the vast majority of treated wastewater is discharged directly back into the environment, there is increased interest in reuse of the wastewater with additional treatment. There are numerous technologies used for the additional (tertiary) treatment of wastewater in the United States, and these technologies can be highly energy-intensive. Case studies throughout the literature have shown a wide variety of energy intensities (kWh/MG) for this additional wastewater treatment (Table 5). In all of these studies, the source water prior to tertiary treatment had already undergone primary and secondary treatment. Unfortunately, these remain simply estimates because they are derived from energy requirements for the entire facility; it is therefore difficult to separate the energy demands for each element of the treatment configuration. Energy use for wastewater tertiary treatment may also vary depending on the end use of the recycled wastewater.

Table 5. Energy Intensity of Water Treatment

Key: Reverse Osmosis (RO), Micro Filtration (MF), Ultraviolet treatment (UV)

Technologies Used	Energy Intensity (kWh/MG)	End Use	Data Source
Conventional Tertiary Treatment			
Anthracite coal bed filtration, demineralization, chlorination	982	Irrigation, industrial use	83
Flocculation, direct filtration, UV/advanced oxidation	1500	Irrigation, industrial use	84
Clarification, media filtration, chlorination	1619	Irrigation, industrial, and commercial use	85
Anthracite coal bed filtration, UV	1703	Irrigation, industrial use	86
Rapid mix, flocculation, media filtration, and UV	1800	Irrigation	87
Membrane Treatment			
Coagulation, flocculation, clarification, UF, RO, UV/advanced oxidation	3220	Agriculture, industrial use	88
MF, RO, UV/advanced oxidation	3680	Groundwater recharge	89
MF, RO, UV/advanced oxidation	3926	Seawater intrusion barrier	90
UF, RO, UV	4050	Industrial use	91
MF, RO	4674	Industrial use	92
MF, RO	8300	High-quality industrial use	93

Source: Cooley, H. and R. Wilkinson. "Implications of Future Water Supply Sources for Energy Demands." WateReuse Research Foundation (2012).

In addition to opportunities related to reusing treated wastewater, municipal wastewater also contains 5 to 10 times as much chemical and thermal energy as is currently required to treat this water to meet discharge standards.[94] While only a portion of the potential is recoverable in practice, it is feasible for wastewater treatment plants to become net producers of energy.[95] Fuel cells are one recovery option, as are other strategies for recovering energy from biosolids such as anaerobic digestion.[96] There are also possibilities of extracting both nutrients and valuable inorganic materials such as metals from various waste streams. Biomass energy recovery for many wastewater facilities has the potential to generate electricity through the collection of biogas generated from the anaerobic digester. The EPA estimates that for each million gallons per day of wastewater flow, a typical anaerobic digester can produce 26 kilowatts of electricity capacity and 2.4 million BTU per day of thermal energy.[97] Barriers to wider deployment of energy recovery technologies, however, have included high capital cost of anaerobic digesters as well as low natural gas prices in the U.S.[98]

4.3 Water Conveyance

There are more than two million miles of water distribution pipelines in the United States in 2006.[99] These pipelines utilize significant amounts of energy to operate the various pumps needed to transport and pressurize water conveyance. This estimate includes the infrastructure from the source of water to the end use but does not include the plumbing pipes within buildings. Additionally, this estimate does not include the water conveyance infrastructure that carries water to agricultural and industrial sites outside of the conventional municipal water treatment system.

Pumping for water conveyance also has a range of possible energy intensities, depending on the configuration. The quantity of energy required for pumping primarily relates to elevation change. As shown in Table 3, interbasin transfer can be an order of magnitude higher in energy intensity than local distribution or groundwater pumping.

Energy efficiency in water conveyance has potential to be improved through development of standards. For example, DOE has regulatory authority over pumps, including commercial and industrial water pumps. In 2016, DOE finalized new energy conservation standards for pumps with compliance required starting in 2020.[o] These standards could result in significant energy savings through minimum efficiency standards. Moreover, requirements for compliance with these standards could have the ancillary benefit of enhanced data collection on energy use by pumps.

4.4 Summary and Conclusion

Water conveyance, treatment, and distribution consume significant amounts of electricity. Opportunities exist for improved energy efficiency in the water sector, as well as for energy recovery from wastewater. Data on energy use by various processes and in various regions, however, is not collected in a centralized way. Enhanced data collection on energy use by the water sector could enable identification of key energy efficiency and energy recovery opportunities.

[o] 10 C.F.R. 429, 10 C.F.R. 431. The Energy Policy and Conservation Act of 1975 (EPCA), as amended, sets forth a variety of provisions designed to improve energy efficiency. Part C of Title III establishes the "Energy Conservation Program for Certain Industrial Equipment." The covered equipment includes pumps.

Chapter 5. Energy-Water Data

Data collection, quality, resolution, and usability are critical issues in the energy-water space. Energy-water data has relevance to both water-for-energy and energy-for-water technologies and systems. Integrating and improving analytic capacity spanning diverse data domains at a range of spatial and temporal scales is important for analysis at the energy-water nexus, and in a broader context, to improve understanding of U.S. energy resilience and opportunities for increased energy efficiency and flexibility. This chapter describes data, techniques, practices, and systems that have the potential to support advanced analyses and inform better decisions relevant to energy and water.

5.1 Sensing and Metering

In the energy-for-water space, many systems suffer from a lack of comprehensive and reliable measurement-based data. The development of relatively low-cost networks of widely distributed sensors with attendant summarization and analytic capacities would provide a basis for further analysis, modeling, and decision support. Depending on the application, these capabilities could improve operations of wastewater treatment and desalination plants as well as benefit residential end-users of energy and water. While smart meters are increasingly deployed in electrical grids, monitoring of water infrastructure lags significantly.[100] Networks of remote, automated leak detection could help in prioritizing repairs to aging water infrastructure, with concomitant energy savings, particularly in locales with high embedded energy costs of water,[101] [102] such as Southern California and the Southwest. Additionally, more sophisticated process sensing would aid in enrolling drinking and wastewater treatment systems in automated demand response programs, which, in addition to supporting flexible operations, often facilitate energy efficiency gains as well.[103]

5.2 Energy and Water Use Surveys

Surveys are in many cases the best tool available for periodic collection of aggregate data related to energy and water. Even where sensor networks are in place, as is the case for energy and water metering, the data is not always publicly available or lacks the resolution desirable for certain analysis needs. Although self-reported information has its limitations,[104] EIA relies heavily on this method, with full awareness of the necessity for disciplined quality control techniques.

EIA uses existing large surveys such as the Form 860 and Form 923 to collect detailed information on water use and other characteristics of cooling systems at electric power plants. EIA also quadrennially collects residential energy use information via its Residential Energy Consumption Survey (RECS), most recently in 2009. EIA gathers and publishes information on energy use in commercial buildings in its Commercial Buildings Energy Consumption Survey (CBECS), including for water heating.[p] EIA does not, however, collect energy use data from the water supply and treatment sectors (see also Section 5.4).

EIA collects a limited amount of residential water use data as part of its RECS energy surveys. The current RECS includes a few questions on aspects of residential water usage, but does not collect total water consumption data from residential consumers or water suppliers. According to EIA's website, EIA does not have statutory authority to collect water data from water suppliers.[105] While expanding RECS to survey residential water consumption would require additional effort, detailed information about home water usage could be used to develop benchmarks for water performance that would inform DOE appliance standards and would also be valuable to EPA's WaterSense program.

[p] Relevant survey data for RECS 2013 and CBECS 2012 are not yet released to the public as of December 2016.

The CBECS 2007 collection included water consumption data for commercial buildings for the first time. Data published from CBECS 2007 include tabulation of the ability of commercial buildings to provide water consumption data, by building type and region, but do not include the actual water consumption data.[106] The CBECS 2007 water consumption survey questions were experimental, but EIA plans to release water consumption data again for the CBECS 2012 collection.

While the U.S. Geological Survey (USGS) compiles a nationwide summary of water uses every five years, it has not included water consumption since 1995. Although the recently release 2010 report includes information from a new power plant consumption model, water consumption is not directly surveyed. Urban water consumption is reported by many water utilities. However, agriculture and self-supplied users are usually not reported. In addition, there is no national clearinghouse for this data.

5.3 Federal Energy-Water Data Sets

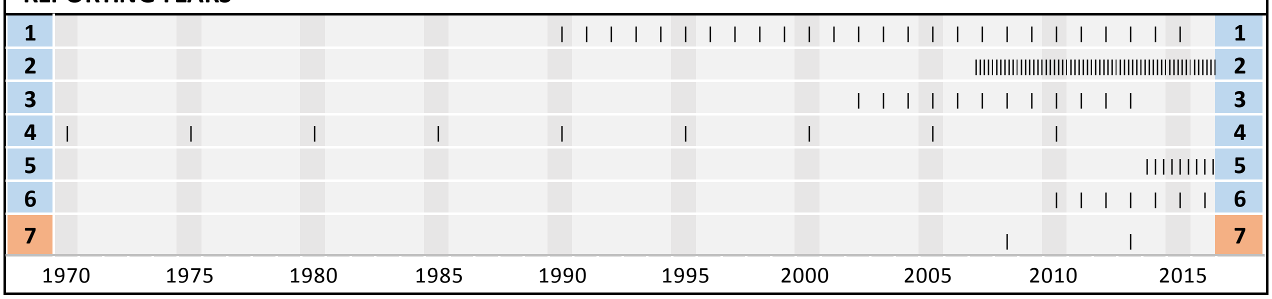
Data in the energy-water space is collected, stored, and utilized by the federal government, state and local government, utilities, industry, academia, nonprofits, and other sectors. Responsibility for a significant fraction of national-level energy-water data falls within the mission space of federal government agencies, including DOE, EPA, DOI, ACE, USDA, and others. While additional data needs exist throughout the energy-water nexus, available federal data on water for electricity systems is in general more detailed than data on electricity for water systems. Table 6 lays out illustrative examples of federal energy-water data sets currently available, including their key characteristics, spatial coverage, data collection method, and temporal resolution. Spatial coverage varies across data sets, as does temporal resolution in terms of reporting years, making analysis and integration of multiple data sets potentially challenging. Although Table 6 is not comprehensive, the dearth of energy-for-water data sources relative to water-for-energy data sources is broadly representative of federal energy-water data.

Table 6. Examples of Federal Energy-Water Data Sources

WATER FOR ENERGY   ENERGY FOR WATER

#	DATABASE	AGENCY	KEY ENERGY-WATER INFORMATION	COVERAGE: Unit	Site	County	State	METHOD
1	**EIA Form 860**	EIA	▪ Generation and cooling system equipment for existing and planned generators	●			●	Survey
2	**EIA Form 923**	EIA	▪ Generation, fuel use, and cooling system operations	●			●	Survey
3	**National Hydropower Asset Assessment Program (NHAAP)**	DOE	▪ Inventory of US hydropower resources ▪ Hydropower resource potential		●		●	Compiled database, Model
4	**Water Use Data**	DOI	▪ Water withdrawal by major economic sector			●	●	Compiled database
5	**FERC Issued Licenses, Exemptions, and Conduit Determination**	FERC	▪ FERC license/exemption orders and amendments for hydropower projects		●		●	Compiled database
6	**ECHO Database: Enforcement and Compliance History Online**	EPA	▪ Environmental violations (e.g. temperature) ▪ Inspection dates and findings ▪ Enforcement actions and penalties		●		●	Compiled database
7	**Farm and Ranch Irrigation Survey**	USDA	▪ On-farm energy expenses for pumping irrigation water by water source and type of Energy				●	Survey

REPORTING YEARS



5.4 Data Gaps

A principal data gap in the energy-water nexus is collection of energy usage data for the water sector by EIA. Energy usage in delivering water services represents a significant portion of U.S. electricity consumption and may present major opportunities for both efficiency and renewable generation, but EIA does not currently collect this data in its surveys. CBECS includes energy use for commercial buildings, but it does not include energy use by municipal water utilities, which provide 85 percent of the water services in the United States.

Freshwater resource data is somewhat more readily available, but includes significant gaps. Information on fresh surface waters in the United States—including measured water elevation and flow at streamgages, as well as other attributes—is collected by USGS through its Water Data for the Nation dataset. However, water temperature is measured by only a fraction of streamgages, making analysis and measurement-based model validation difficult. Fresh groundwater is fairly well characterized in terms of location and quality, particularly where it is in active use as a source for municipal, agricultural, or other human uses.

Improved characterization of subsurface resources is also important for the beneficial use of nontraditional waters. While some work has been done,[107] additional specificity is needed in order to assess economic viability in specific locations for particular nontraditional water uses. The USGS is conducting a survey of brackish groundwater resources, which is projected to be completed in 2017.[108]

5.5 Data Quality and Harmonization

In addition to challenges related to data measurement and collection, a critical challenge is to ensure that data is of sufficiently quality and can be harmonized and accurately compared across disparate data sets. Within the federal government, a large amount of energy-water data is collected and published by EIA and USGS. The U.S. Government Accountability Office has highlighted opportunities for better coordination between EIA and USGS.[109] While data quality and harmonization efforts by both agencies have improved in recent years, significant challenges remain to ensuring that this energy-water data can support advanced analyses and decision support tools at relevant spatial and temporal scales.

First, each agency employs different methodologies in collecting water withdrawal data from thermoelectric generators. EIA uses surveys to solicit responses from each thermoelectric generation facility about their water withdrawal in a “top-down” approach. While EIA data quality depends on the quality of survey responses and the way they are interpreted by survey respondents (plus revisions and quality control conducted in-house by EIA), the survey format is designed to ensure consistency and comparability among different generators. USGS employs a more “bottom-up” approach to withdrawal data collection. In the USGS method, state-level analysts aggregate data from a variety of sources including model-estimated water withdrawal, state-level databases, and current and historical EIA data. The state-level analysts aggregate these data according to their own procedures to obtain total withdrawal numbers, which are then compiled by USGS. Year-to-year changes in state-level data sources, staff, and methodology can significantly affect the overall USGS withdrawal data. These differences in methodology between EIA and USGS can therefore make it difficult to harmonize data and analyze trends over time.

In addition to varying methodologies, EIA and USGS can also define once-through cooling, recirculating cooling, cooling ponds, and other critical terms differently, and this can make comparison of data sets challenging. For example, USGS measures withdrawal in terms of diversion from a natural water body, while EIA measures flow through the power plant’s condenser. Depending on the topologies of the water body and/or the generation facility, these measures could differ significantly. In addition, some data being collected can be incompletely defined. EIA, for example, collects cooling water intake depths for thermoelectric generators in terms of their distance below the water surface. However, no external reference is given to indicate the elevation of the water relative to sea level, a high-water mark, the average water level, or any other reference that would allow comparison among different cooling intakes for purposes of drought vulnerability analyses, for example. Efforts to sharpen and standardize definitions for data being collected could improve analytical usefulness of both EIA and USGS data.

EIA and USGS also collect data of differing spatial and temporal resolution, which can complicate comparisons and analyses that require both data sets. While EIA provides water withdrawal for thermoelectric cooling data at the level of individual plants, USGS provides this data primarily at the state level. While the total national water withdrawal estimates for EIA and USGS have converged somewhat in recent years, disparity remains at the regional and state levels. In the temporal domain, USGS collects water withdrawal data every five years, with an approximately five-year delay before publication. EIA, however, collects monthly water withdrawal data. Harmonization of these differing spatial and temporal scales is important for analysis that utilizes both data sources.

Beyond EIA and USGS, many other federal agencies are partners in the collection, maintenance, and use of energy-water data, including NASA, USDA, NOAA, and others. There is an opportunity for these diverse data layers across the federal government to be better harmonized and integrated to enable advanced analytics and decision support within government and for external stakeholders.

5.6 Summary and Conclusion

Data limitations can hinder analysis in the energy-water nexus. Analysis of various aspects of the energy-water nexus suffer from a lack of data of sufficient quality, usability, and spatial and temporal resolution. For example, while EIA collects commercial and industrial energy use data through its surveys, it does not collect energy use data for municipal water and wastewater treatment and conveyance, which makes analysis of energy use and savings opportunities challenging. Enhanced and more widely distributed remote sensing, smart metering, networks of real-time sensors, improved survey methods, and attendant summarization and analytic capabilities would provide a basis for improved analysis, modeling, and decision support. Harmonization of data sets, particularly among federal agencies, is a critical need for improving confidence in the data and allowing advanced analyses of regional variability and trends over time. In particular, the diversity of federal data sets could benefit from improved integration to enable novel analysis by a variety of users.

Chapter 6. Water Policies Impacting Electricity Generation and End Use

Although energy and water flows are often physically interconnected, the energy and water policy landscape is highly fragmented in the U.S., making it difficult for decision-makers in industry and government to effectively balance energy and water goals. This chapter will outline several key policy categories in the energy-water nexus: the water rights framework, water regulations affecting thermoelectric generation, policies affecting hydropower, and finance mechanisms for energy and water infrastructure. Other important policy drivers outside the scope of this chapter include river operation requirements enforced by ACE, BOR, and TVA; and state-level integrated energy-water policies.

6.1 Water Rights Framework

The United States' framework for water management is based on a wide range of legal directives. The U.S. Constitution, federal and state legislation, judicial decisions, and common law distribute authority over water among federal, tribal[q], state, and local governments. International treaties involving neighboring country governments also come into play. While the federal government is authorized to develop and manage waters for commercial navigation, flood control, and other purposes, states otherwise have primary authority for water rights allocation and permitting.

6.1.1 Surface Water Allocation Policies

States have a strong role in overseeing water rights and allocation permitting. State-level water rights and permitting inform the decision-making of any significant water user. Because water issues vary greatly by region, water resource policies—even policy frameworks—can vary greatly from state to state, or even within states.[110] With respect to surface water, states generally follow some variation of two governance doctrines—the prior appropriation doctrine and the riparian doctrine. Groundwater governance is slightly more complex and is discussed in Section 5.1.2.

[q] Along with federal lands, Indian lands are typically entitled to water rights based on federal law. These water rights, commonly referred to as "federal reserved water rights," are based on the premise that when Indian and federal reservations were established, enough water was reserved to fulfill the purpose of such reservations. In the case of Indian tribes, this means sufficient water to fulfill the purpose of Indian reservations as homelands for the tribes. Federal reserved water rights also differ from state-based water rights in other ways, including priority dates, quantification of rights, and types of use. While many tribes have either fully adjudicated or settled their water rights claims, most tribes in the West still have very large, and un-quantified, rights to water—including surface and groundwater—for their reservations (Newton, N. J. and R. Anderson. 2004. Cohen's Handbook of Federal Indian Law 2005 Edition. LexisNexis Publisher).

Legal Framework in the West	Western States
Pure prior appropriation (9)	Alaska, Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, Utah, and Wyoming
Prior appropriation, formerly riparian (6)	Kansas, North Dakota, South Dakota, Oregon, Texas, and Washington
Mixed riparian-appropriation (3)	California, Nebraska, and Oklahoma
Legal Framework in the East	**Eastern States**
Pure riparian (8)	New Hampshire, Vermont, Rhode Island, West Virginia, Ohio, Tennessee, Missouri, and Louisiana
Regulated riparian (21)	Alabama, Arkansas, Connecticut, Delaware, Florida, Georgia, Illinois, Indiana, Iowa, Kentucky, Maryland, Massachusetts, Michigan, Minnesota, Mississippi, New Jersey, New York, North Carolina, Pennsylvania, Rhode Island, South Carolina, Virginia, and Wisconsin

Table 7. Framework for Surface Water Law
Data Source: Gleick and Christian-Smith 2012

Figure Source: The Water-Energy Nexus: Challenges and Opportunities

Prior Appropriation Doctrine

The vast majority of the states in the arid West follow the prior appropriation doctrine, under which water allocation is made on a first-come, first-serve basis and not linked to land ownership.[111] Because of relative water scarcity, water rights are linked to a specific basin and many states prohibit transfers between basins. Furthermore, users must prove that their rights are being exercised and put to a beneficial use or the rights can be deemed abandoned and terminated. In times of water shortage, those who most recently obtained a legal right to use the water must yield to more senior right holders, although if any of the latter's rights have not been exercised and put to a beneficial use, such a right could be deemed forfeited. Water rights may be transferred through various mechanisms, but transfers must often receive approval from state regulators.

Riparian Doctrine

The riparian doctrine, also called the "common law" doctrine, is tied to land ownership and mostly recognized in Eastern states where water is relatively abundant. Owners of land bordering waterways have a right to use water that flows past the land for any reasonable purpose. In addition, all landowners have an equal right to use the water because no one possesses a greater right through prior use. Water rights may not be bought or sold, and when water runs short, users have to "share the shortage in proportion to their rights".[112] About half of the Eastern states have also adopted what is called regulated riparianism, or water-use permits for non-riparian landowners to acquire water rights for a limited period of "reasonable" use.[113]

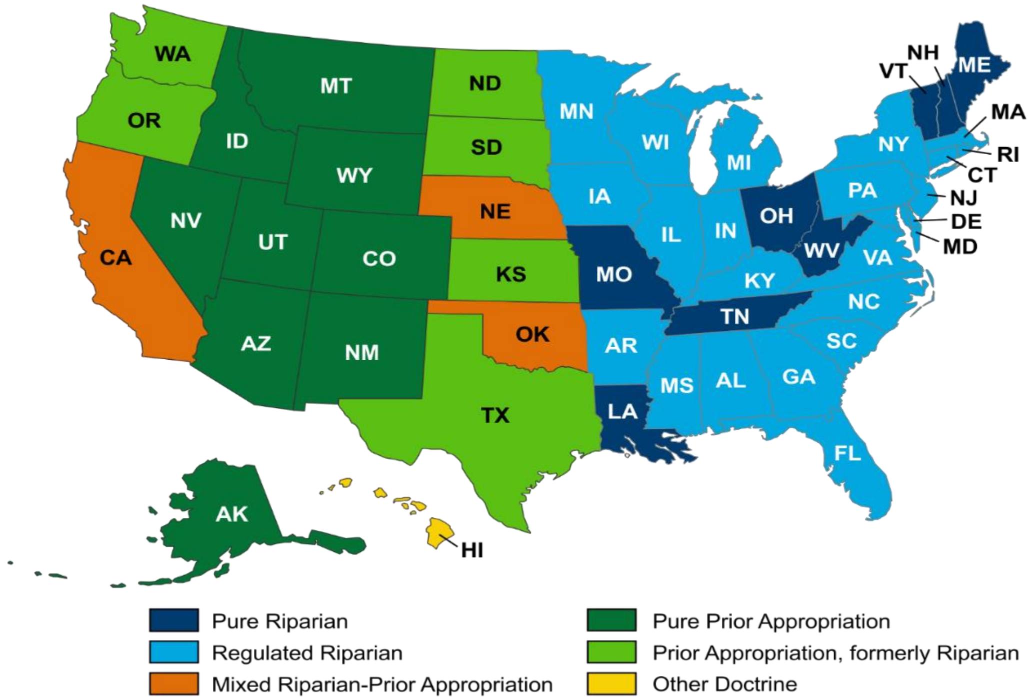


Figure 28. Water governance policies in the United States, by state.
Most western states are governed prior appropriation, while eastern states are governed by riparian frameworks.

Data source: Gleick and Christian-Smith 2012

Figure source: The Water-Energy Nexus: Challenges and Opportunities

6.1.2 Groundwater Allocation Policies

Groundwater rights and laws are extremely complex in the United States because several overarching doctrines come into play, including absolute ownership, reasonable use, correlative rights, and prior appropriation.[114] The absolute ownership doctrine, most evident in Indiana, Maine, and Texas, does not limit the amount of groundwater withdrawn by the overlying landowner even if the withdrawal could harm existing uses. The reasonable use doctrine, in contrast, prohibits waste and limits water usage to overlying land unless it can be transported without harming other overlying owners.[115] Neither absolute ownership nor the reasonable use doctrine considers the total demand on the aquifer or the impact of groundwater overdraft.

Approaches that consider aggregate water demand and the impact on groundwater do exist, including Section 858 of the *Restatement of Torts*, which states that a groundwater user can only withdraw water if it is done without (1) unreasonably affecting other users by lowering the water table or pressure, (2) exceeding his or her share of the total annual supply, or (3) affecting surface water supplies.[116] Section 858 or a variation of it is applied in Michigan, Ohio, Wisconsin, Arkansas, Florida, Nebraska, New Jersey, and Missouri.[117]

In reality, however, applying any of the legal frameworks to control total demand has been challenging due to a lack of reporting and monitoring of groundwater use. Increasingly, states are practicing some level of tracking and oversight. For example, New Mexico has a statewide water management system based on basin-wide adjudications. Nebraska regulates groundwater pumping through natural resource districts, while in Kansas local residents form groundwater management districts and apply their own standards to prevent overdraft. However, some regions do still suffer from groundwater overdraft.[118]

Relatively more stringent surface water regulations can lead to more groundwater use and vice versa. Lower surface water availability coupled with more stringent policies regarding surface water withdrawals has contributed to a higher percentage of groundwater, effluent, and recycled water use for cooling in Western states. However, in recent years, some of these states have instituted more stringent groundwater policies for thermoelectric cooling. Arizona, which sets no limit on water used by thermoelectric power plants, nevertheless requires larger thermoelectric power plants (plants of 100 MW capacity or more) to apply for a groundwater permit in active groundwater management areas.[119] Some of these states have also denied groundwater permits to power plants to protect groundwater resources.[120][121]

6.1.3 Thermoelectric cooling and water rights

Water use by thermoelectric cooling shows significant correlation with state-level water rights frameworks. Power plants in areas governed by riparian water rights frameworks have had fewer issues finding and using surface water for cooling, mainly due to relative water abundance. Once-through cooling, which requires higher water withdrawal but also enables greater generation efficiency, is more prevalent in these areas. Although a riparian water rights framework may have encouraged once-through cooling, other factors are arguably at least as important, such as the fact that most large population centers were located in the East in the mid-20th century, and many large power plants built to serve these population centers during this time used once-through cooling because it was the principal technology available.

As shown in Figure 29, median power plant withdrawal intensity in riparian states is higher than for plants in prior appropriation states.[r] Median consumption intensity has the opposite characteristic, with greater median consumption intensity in prior appropriation states. This is likely due to the larger share of recirculating and other high-consumption cooling systems in more arid states, which are more likely to be governed by prior appropriation.

[r] This is based on use of both fresh and non-fresh water sources.

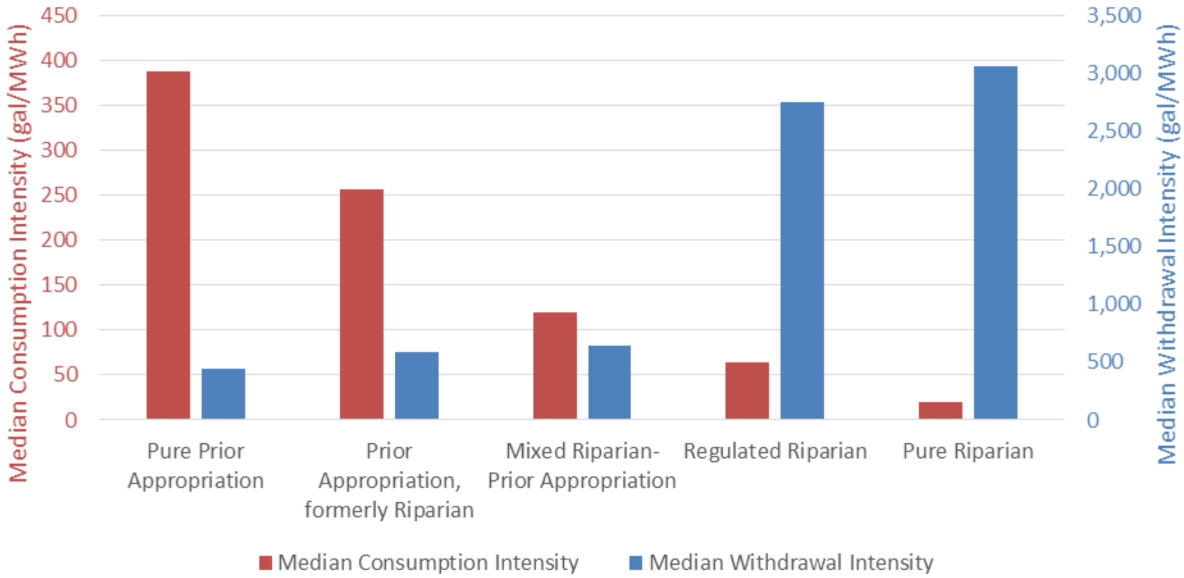


Figure 29. Median water withdrawal and consumption intensities at power plants by water governance policy (2015).

Riparian frameworks correlate with large water withdrawal intensity, while prior appropriation correlates with significantly reduced withdrawal intensity but increased consumption intensity.

Data source: EIA thermoelectric cooling data (2015 data, published in 2016) derived from EIA Form 860 and EIA Form 923; Gleick and Christian-Smith (2012)[s]

6.2 Water Policies Affecting Electricity Generation

The U.S. power sector includes the generation, transmission, distribution, and regulation of electricity for industrial, commercial, public, and residential users. In recent years, it has undergone changes driven by the abundant natural gas supply and push for renewable power generation, among other factors. Such drivers, together with U.S. policy incentives for renewable energy, could complicate the decisions many coal-fired units make related to aging infrastructure and water availability. Plant owners face myriad challenges, including recent and anticipated environmental regulations; these, among other factors, are informing plant owners' decisions about whether to retrofit or retire their units.

A few federal laws are particularly important in guiding national water management, such as the Clean Water Act (CWA), the Water Resources Development Act, the Safe Drinking Water Act, the Reclamation Act, the Federal Power Act, the National Environmental Policy Act, and the Endangered Species Act. Section 6.2.1, below, will focus primarily on regulations under the Clean Water Act.

Federal oversight and administration of water management guidelines is shared across approximately 30 agencies in 10 different departments.[122] Similarly, federal funding for water is split across many agencies, with no single agency ultimately responsible for the impact of multiple contributors (e.g.,

[s] The type of water governance information is from Gleick and Christian-Smith (2012). "Riparian" includes pure riparian and regulated riparian states. "Prior Appropriation" includes states that have been prior appropriation doctrine implementers all along (pure prior appropriation states) or currently prior appropriation states that are formerly riparian states (prior appropriation, formerly riparian states). "Hybrid" or "Other" includes states that implement both prior appropriation and riparian doctrines and states like Hawaii that has a completely different doctrine than other states.

agriculture, development, and energy) to water management. Highly fragmented authority in managing the country's water has presented challenges in improving water quality in many parts of the country.[123]

6.2.1 Thermoelectric cooling regulations

EPA regulates water discharges from power plants under the Clean Water Act. Water temperature is one relevant property of discharged water that is included under this authority. Hotter water holds less dissolved oxygen, potentially harming fish and other aquatic life. EPA or its state-level designee regulates water temperature through effluent temperature limits set by the National Pollutant Discharge Elimination System (NPDES) program authorized by Section 402 of the CWA.[t] Power plants that withdraw water and then release it back into the environment at an elevated temperature must comply with temperature limits under the NPDES program.[124] At higher temperatures of intake water, power plants may reduce electricity production, or use temporary or permanent "helper towers" to meet the discharge temperature limit or risk paying fines.[125] Section 316(a) of the CWA provides a mechanism for facilities to seek additional relief from thermal limits based on water quality or technology-based standards.

Regulatory limits for water temperature are not uniform, but are specific to each plant. For example, the specific thermal operation limits of three TVA nuclear power plants are summarized in Table 8. These heat release limits are specified in each plant's NPDES permits that are in general reviewed and re-issued every five years. The main regulators are the state water agencies. To remain in compliance, each nuclear power plant is required to submit the monthly discharge monitoring report (DMR) summarizing all monitoring variables requested in the NPDES permit. In case of large deviation from the permitted limit, the licensee could be requested to de-rate or shut down the generating units until such a situation is resolved.

Table 8. Summary of NPDES effluent temperature limits for three TVA nuclear power plants

Plants	Permit #	Parameter	Permit Limit
Browns Ferry (BFN)	AL0022080	Downstream temperature (daily average)	90 °F
		Downstream temperature (daily maximum)	93 °F
		River temperature between upstream and downstream	10 °F
Sequoyah (SQN)	TN0026450	Downstream temperature (daily average)	30.5 °C
		River temperature between upstream and downstream	3 °C (summer) 5 °C (winter)
		Downstream temperature rate of change	2 °C / hour
Watts Bar (WBN)	TN0020168	Downstream temperature (daily average)	30.5 °C
		River temperature between upstream and downstream	3 °C
		Downstream temperature rate of change	2 °C / hour

Several new federal rules related to water and thermoelectric power plants have recently been finalized, including the steam electric plant effluent discharge guideline and the CWA 316(b) cooling water intake rule.

[t] Section 316(a) of the CWA allows a thermal discharger to seek effluent temperature permit variances by demonstrating that less stringent thermal effluent limitations would still protect aquatic life (Veil 1993).

EPA in September 2015 finalized a rule revising the effluent limitations guidelines for the Steam Electric Power Generating category. The rule sets the first federal limits on the levels of toxic metals in flue gas desulfurization wastewater that can be discharged from power plants, based on technology improvements in the steam electric power industry over the last three decades. The rule is projected to reduce the amount of toxic metals, nutrients, and other pollutants that steam electric power plants are allowed to discharge. Annual compliance costs for the final rule are estimated at $480 million, while estimated benefits associated with the rule are $451 to $566 million.[126]

EPA also finalized the existing facility cooling water intake rule under CWA section 316(b) in August 2014. The rule seeks to prevent adverse environmental impact from impingement of fish and shellfish on cooling water intake screens or entrainment of their eggs and larvae through a power plant's cooling system, where they may be killed by heat, physical stress, or chemicals. EPA states that this rule covers roughly 544 existing power plants that are designed to withdraw at least 2 million gallons per day of cooling water. The rule requires the covered facilities to choose one of seven options to reduce impingement mortality to fish and other aquatic organisms, such as using advanced fish-friendly screen technologies cooling intake structures, and also requires the permitting authority to make a case by case determination for reducing entrainment mortality. One option that power plants covered by the rule can use for compliance is wet-recirculating cooling (also known as "closed-loop" cooling), which eliminates most of the adverse environmental impacts. EPA also requires new units at existing facilities to install wet-recirculating cooling or its equivalent. As a result, the thermoelectric generation fleet is expected to continue its shift from once-through to wet-recirculating (and/or dry) cooling systems.

6.2.2 Hydropower policies

While all electricity generation is subject to environmental and siting constraints in one form or another, hydropower projects face particularly complex and multifaceted constraints. Many hydropower projects are components of multipurpose dams that must balance electricity generation with requirements to manage water for environmental mitigation, navigation, flood control, agriculture, recreation, and other non-energy services. Key legislation in the 1970s such as the Endangered Species Act and the Clean Water Act imposed environmental constraints on hydropower operations. The Electric Consumers Protection Act in 1986 required FERC to give equal consideration to both power and non-power factors during the licensing process, in some cases reducing flexibility of current installed capacity or reducing attractiveness for new development.[127] Adding new capacity to existing projects and changing operational strategies must likewise balance these constraints. Figure 30 shows relevant policy milestones and cumulative capacity for hydropower.

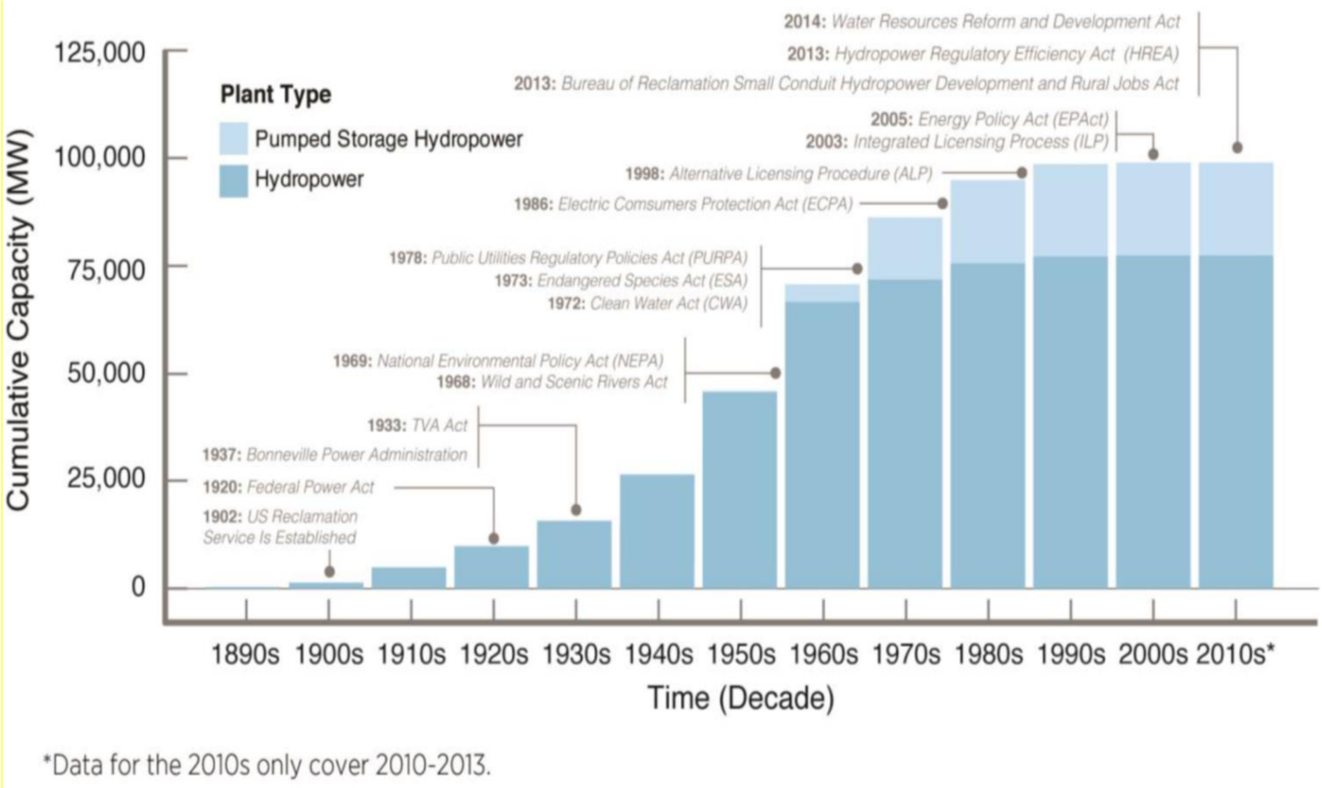


Figure 30. Hydropower installation timeline and major legislative and institutional milestones
Most hydropower buildout occurred in the mid-20th century, while pumped storage occurred in the later 20th century. Policies are included in the timeline for reference.

Source: DOE Hydropower Market Report 2014

In recent decades, the federal and state-level policies and incentives have limited development of new or expanded hydroelectric and pumped storage capacity relative to other renewables.[128] The investment tax credit and the production tax credit established by the Energy Policy Act of 1992, as amended, both provide significant subsidies to non-hydropower renewables relative to hydropower. For solar generation, for example, the investment tax credit amounts to 10 percent of the initial investment in the facility and was increased in 2016 for some solar projects and residential producers. The investment tax credits, however, do not apply to large-scale hydroelectric facilities. For wind, the production tax credit allows a $0.023 credit for each kilowatt-hour of wind generation during the first 10 years of operation. In contrast, some hydroelectric facilities receive a $0.011 production credit, which is essentially only half of the credit that wind generators can receive. In addition, state-level renewable portfolio standards and renewable energy credit programs have commonly only allowed full credit for hydropower that meets criteria such as small capacity or recent vintage.

6.3 Finance for Energy and Water Infrastructure

Public-sector financing and public-private partnerships play an instrumental role in catalyzing deployment of technologies that enhance resilience; flexibility; energy and water efficiency; and reduce vulnerabilities in energy and water infrastructure. Examples of such opportunities span both energy and water infrastructure. Financing can enable reduced reliance on freshwater and diversify water sources, such as through deployment of dry or hybrid cooling systems for thermoelectric generation, or desalination plants. Financing can also enable reduced electricity demand or net electricity generation from water systems, such as through water infrastructure demand response capabilities, or energy recovery technologies in wastewater treatment plants.

Many of these projects take years to complete and require sustained financing, which can involve a number of conventional and unconventional funding mechanisms as well as project sponsors and partners. For example, the Southeast Geysers Effluent Project to inject municipal wastewater to replenish depleted reservoirs, which was the cheapest and environmentally preferable solution for both the generator and wastewater treatment facility, required sustained federal support from DOE, BLM, EPA, ACE, and the Department of Commerce. One of the more unique financing mechanisms utilized in this project was an agreement with BLM to reduce its share of future royalty payments in exchange for industry paying more of the upfront capital costs, which was offset by the greater power output and longer anticipated project lifetime.

Federal financing for water and wastewater infrastructure projects largely falls under the jurisdiction of the EPA through capitalization grants to the Clean Water State Revolving Fund (CWSRF) and the Drinking Water State Revolving Fund (DWSRF), where the CWSRF has a 10 percent set aside (i.e., no less than 10 percent) for "green projects" including energy efficiency. From 1988 through 2014, the CWSRF provided over $105 billion in assistance to 34,902 communities, with a return of $2.80 for every federal dollar invested.[129] In 2014, the Water Resources Reform and Development Act established an additional financing mechanism managed by the EPA for water and wastewater infrastructure called the Water Infrastructure Finance and Innovation Act Program. As of 2016, Congress has only appropriated start-up funding of $2.2 million for this program. Additional appropriations could allow the EPA to begin providing low interest loans for larger projects.

Municipal public financing for energy and water infrastructure is an emerging trend. Two large categories of municipal financing strategies are green bonds and Sustainable Responsible Investing (SRI). Green bonds are bonds that are issued to finance projects that meet certain specified criteria, such as energy efficiency, LEED certification, or climate change mitigation. SRI investing is a broader investment philosophy that considers environmental, governance, and societal impacts criteria in addition to investment returns. Massachusetts, New York, New Jersey, and California have all begun to issue green bonds for projects which can include clean water infrastructure. DC Water, the regional water utility serving 2.2 million customers in the Washington DC metro area, has secured both green bonds and SRI financing in recent years.

The private sector can also add value to energy and water infrastructure projects by improving energy performance. Established forms of financing that can be used for water and wastewater infrastructure projects include Energy Savings Performance Contracts (ESPCs). These contracts are agreements between energy services companies (ESCOs) and utilities or owners in which the ESCO provides scope development, design, and construction of efficiency improvements. The resulting energy and water efficiency improvements can result in significant cost savings, which are guaranteed upfront by the ESCO. After the contract ends, any additional savings accrue to the utility or owner.

While tax-exempt municipal bonds and green bonds are available for a number of potential energy and water infrastructure projects, most financing programs have generally applied to a subset of projects that improve efficiency, resiliency, or flexibility of either energy or water systems, and few have considered both systems. For instance, eligibility criteria for DOE loan guarantees often specify GHG reductions or energy efficiency, but might not consider projects that use waste heat for water treatment or dry cooling for thermoelectric generation. Improved integration of energy and water finance mechanisms could unlock additional opportunities.

6.4 Summary and Conclusion

The energy and water policy landscape is highly fragmented. Policy interconnections between electricity and water systems are complex and often are not well documented. Because energy and water flows are often physically interconnected, policy and regulations designed separately for energy or water systems can make it difficult to productively balance energy and water goals. Opportunities exist to better integrate energy and water policies, and to pursue finance mechanisms that improve performance of both energy and water infrastructure.

Chapter 7. Implications of Future Climate Change

The impacts of climate change are key constraints on future energy and water systems. Changing water availability due to changing climate can increase risks to long-lived electricity assets such as thermoelectric and hydropower plants. Climate change impacts on these assets can be complex, as both thermoelectric generation and hydropower require sufficient flows of water as well as water that is of sufficiently low temperature to avoid environmental impacts upon discharge or release. High-resolution data, modeling, and analysis are required to assess climate change impacts on connected energy and water systems.

7.1 Trends relating to the provisioning of water

Increasing temperatures, shifts in precipitation patterns, and more intense floods and droughts have potential to create unplanned variability in the amount and timing of water available for electricity generation. In most future scenarios, summer precipitation is expected to decrease in most states. However, northern states should see an increase in precipitation during winter and spring (Figure 31). Such changes in timing of precipitation have the potential to significantly affect scheduling and operations of electricity generation that requires water.

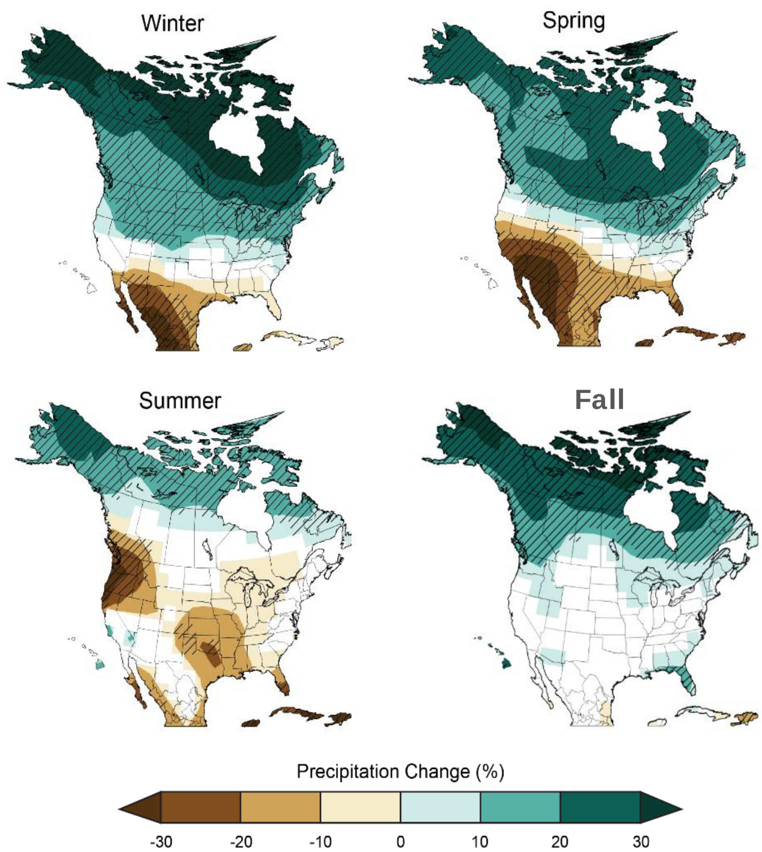


Figure 31. Projected future changes in precipitation by 2080–2099.

Projected precipitation changes show seasonal reductions in the southwest as well as the northwest. Data is relative to average seasonal precipitation in 1961–1979 under the A2 emission scenario and simulated by 15 climate models; hatched areas indicate highest confidence in the projected change.

Source: USGCRP 2014

A related consideration is the fact that more precipitation is expected to fall as rain rather than snow.[130] This, combined with increasing average temperatures, will likely cause runoff to begin earlier in the spring, which could affect when water is available for hydropower and other energy activities.[131] Snowpack is an important reservoir for water required in hydroelectric generation and areas of the Southwest, especially inland California, have experienced much lower levels of snowpack in recent years (Figure 32).

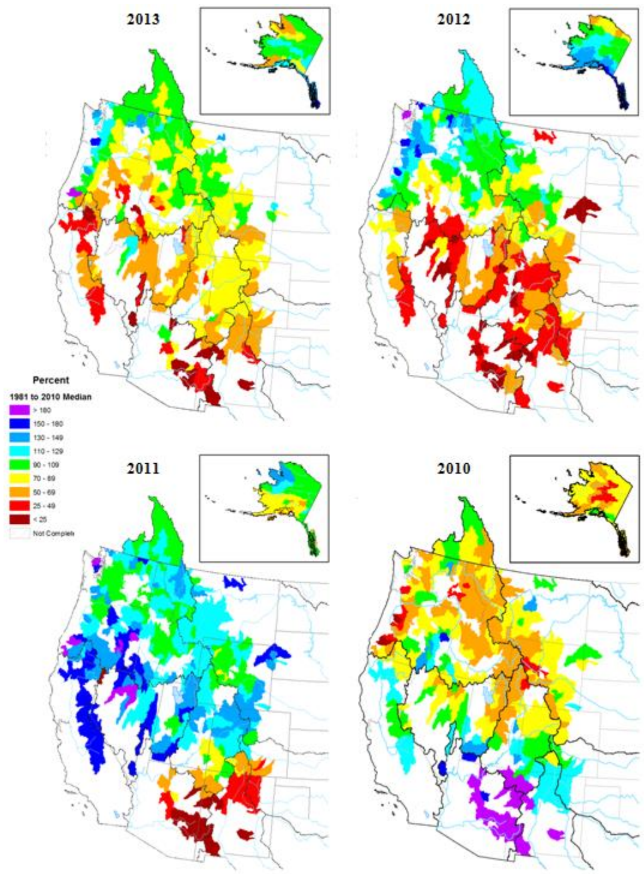


Figure 32. April snowpack from 2010–2013 as a percent of historical median (1981–2010).
Snowpack has varied significantly in recent years, from well above to well below historical medians.

Source: NRCS 2013

Along with timing and availability implications, decreasing snowpack also means less cold water is entering rivers from mountain runoff, which increases water temperatures and creates water quality issues, especially in the hot summer months when air temperature and electricity demand are highest. These water temperature concerns can affect operations of hydropower as well as thermoelectric generation. Higher air temperatures are also contributing to this water scarcity problem by increasing evaporation rates for surface waters.

Higher average temperatures and less precipitation will require producer adaptability in many areas of the energy sector. However, this could be increasingly difficult because of the inherent variability in the water supply. Changes in regional precipitation patterns and more frequent and severe drought and floods will make it more difficult to predict when and where water will be available. This is especially problematic when attempting to choose sites for future water-intensive energy activities such as thermoelectric power plants.

Figure 33 shows annual precipitation in the United States from 2006-2012. In 2007, the Southeast experienced relatively low levels of precipitation, but that was quickly followed by a year of relatively high levels of precipitation in 2009. The Southwest region of the United States saw similar fluctuations in precipitation. On average, the Southwest receives less precipitation than other areas of the country, but it experienced especially low levels of precipitation in 2011 and 2012.[132]

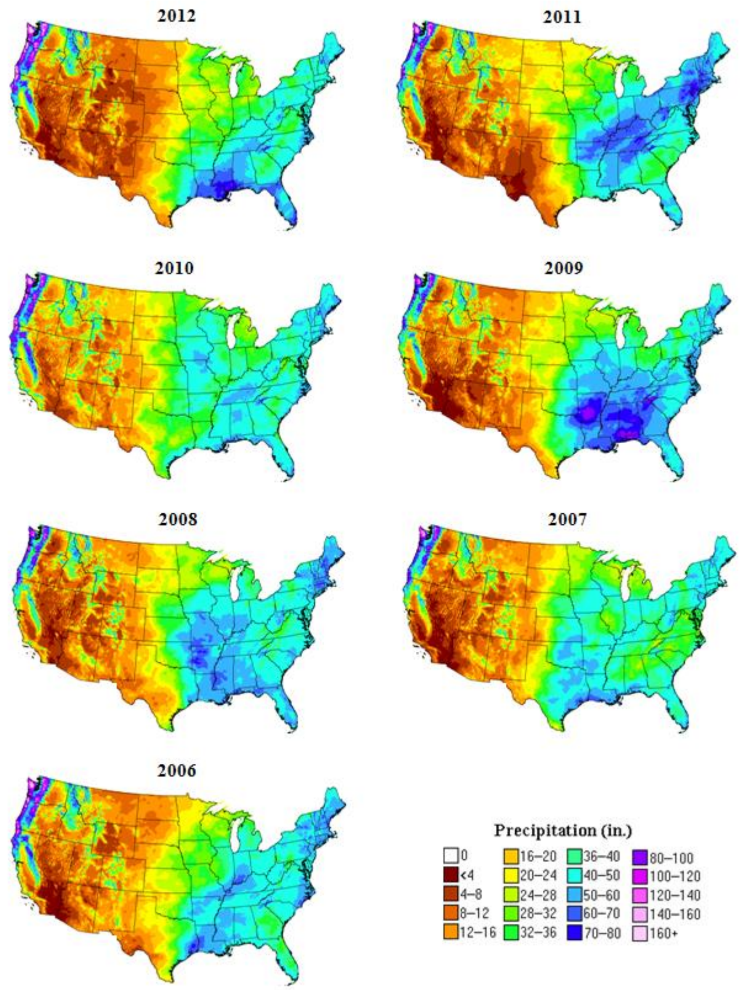


Figure 33. Annual average precipitation, 2006–2012.
Average precipitation varies from year to year, but is significantly less in western states.

Source: PRISM Climate Group 2013

The energy system must also be capable of handling rapid fluctuations in water availability due to extreme weather events such as droughts and floods. For example, too much water due to floods, storm surges, and sea-level rise can damage infrastructure and inundate energy facilities. Such was the case in Colorado in September 2013 when flooding damaged electric power substations.

Finally, population growth and migration patterns may further stress regions that are vulnerable to climate change. According to the U.S. Census Bureau, the projected percent change in population by region of the

United States varies significantly. The South and the West are both expected to see over 40 percent population growth by 2030, relative to 2000.[133] The Northeast and Midwest are expected to see less than 10 percent growth by 2030, relative to 2000.[134] Competing energy and water needs may become more serious in regions such as the South and West where large projected population growth overlaps with projected water constraints under climate change.

7.2 Trends related to electricity generation

Adverse events such as droughts and heat waves have had significant impacts on electricity generation in recent years. Thermoelectric generation is particularly vulnerable to exceeding cooling water discharge temperature limits during droughts or heat waves, in some cases requiring plant derating or shutdown. Hydropower is vulnerable to earlier snowmelt shifting the timing of water available for generation. Climate change may further intensify these impacts.

7.2.1 Thermoelectric Cooling

For thermoelectric generation, water temperature can pose problems in addition to water availability. As discussed in Chapter 5, EPA regulates water discharge temperature from power plants under the authority of the Clean Water Act. Since 2004, water stress has led to at least a dozen power plants to temporarily reduce their power output or shut down entirely, and prompted at least eight states to deny new plant proposals.[135] During prolonged heat in the summer of 2010, for example, water temperatures in the Tennessee River hit 90°F, forcing the Browns Ferry nuclear power plant to significantly reduce the power output from its three reactors for nearly five consecutive weeks—all while cities in the region were experiencing high power demands for air conditioning. Similar events occurred when intense heat and drought in 2012 caused many operational problems for thermoelectric power plants throughout the Midwest United States. Figure 34 shows U.S.-wide violations of average monthly discharge temperature limits between January 2008 and December 2011.

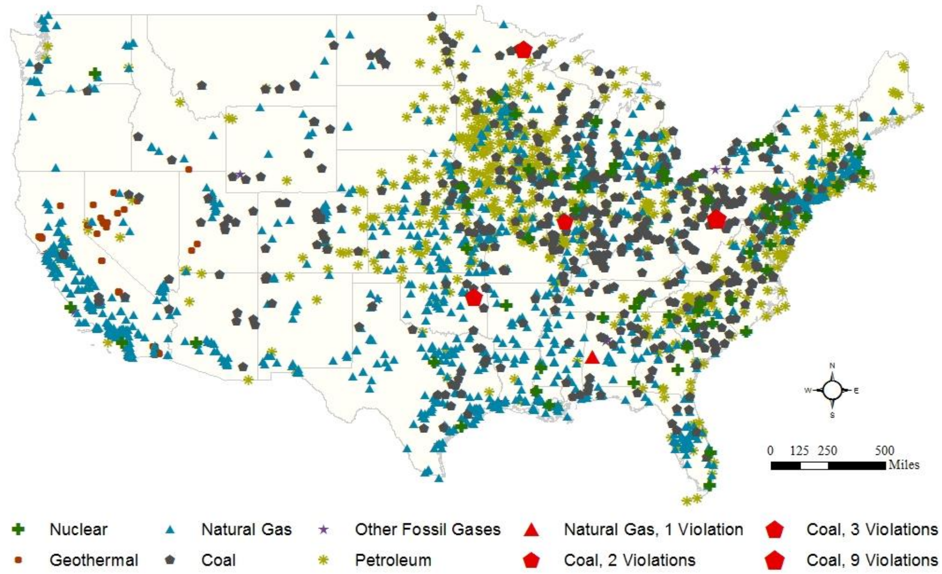


Figure 34. Thermoelectric power plants in the United States, indicating average monthly discharge temperature violations between January 2008 and December 2011.
Discharge violations occur rarely, but more often in the east and the Midwest rather than the west.

Data source: EPA ECHO Database: CWA Effluent Report

Figure Source: The Water-Energy Nexus: Challenges and Opportunities

Several recent papers discuss potential vulnerabilities of electricity generation under climate change. In a recent study on the vulnerability of US and European electricity supply to climate change, van Vliet et al. predict that water scarcity, lower summer river flows, and higher river water temperatures due to global warming could lead to a -4.4 to -16 percent decrease in power plant capacity by 2060.[136] Bartos and Chester project that by mid-century, climate change may reduce average U.S. summertime generating capacity by 1.027 GW, with potentially disruptive impacts occurring in California and the desert Southwest.[137] Vulnerable facilities account for 46 percent of existing capacity in the Western Electricity Coordinating Council (WECC) region and, among individual facilities, impacts range from a -4 percent increase in capacity to a -14 percent decrease in capacity.

7.2.2 Hydropower

The future role of hydropower depends primarily on how climate change will impact the availability and variability of the water resources used for hydroelectricity generation. A 2013 DOE report entitled "Effects of Climate Change on Federal Hydropower" concerning the effects of climate change on federal hydropower projects a 2 percent reduction in hydroelectric generation due to changes in the timing and total amount of water from runoff.[138] Increased frequency and intensity of extreme weather events (e.g., droughts and floods) also pose significant operational challenges, particularly in systems with limited reservoir storage or operational flexibility.

Weather and climate impacts on hydropower vary by region. California experienced a marked decrease in hydropower generation through 2015 (Figure 35), due primarily to recent drought,[139] but generation has increased in 2016. Hydropower generation in New York, on the other hand, has remained essentially stable and shown an upward trend in recent summers. In the Pacific Northwest, Oregon and Washington have seen significant decreases in summer hydropower generation, particularly in 2015. The Northwest experienced higher than normal temperatures in winter 2014-15, causing higher rainfall but decreased snowfall, and hence less snowpack, during winter months. This caused higher hydropower generation in winter but lower generation throughout spring and summer as usual snowmelt flows were unavailable.[140]

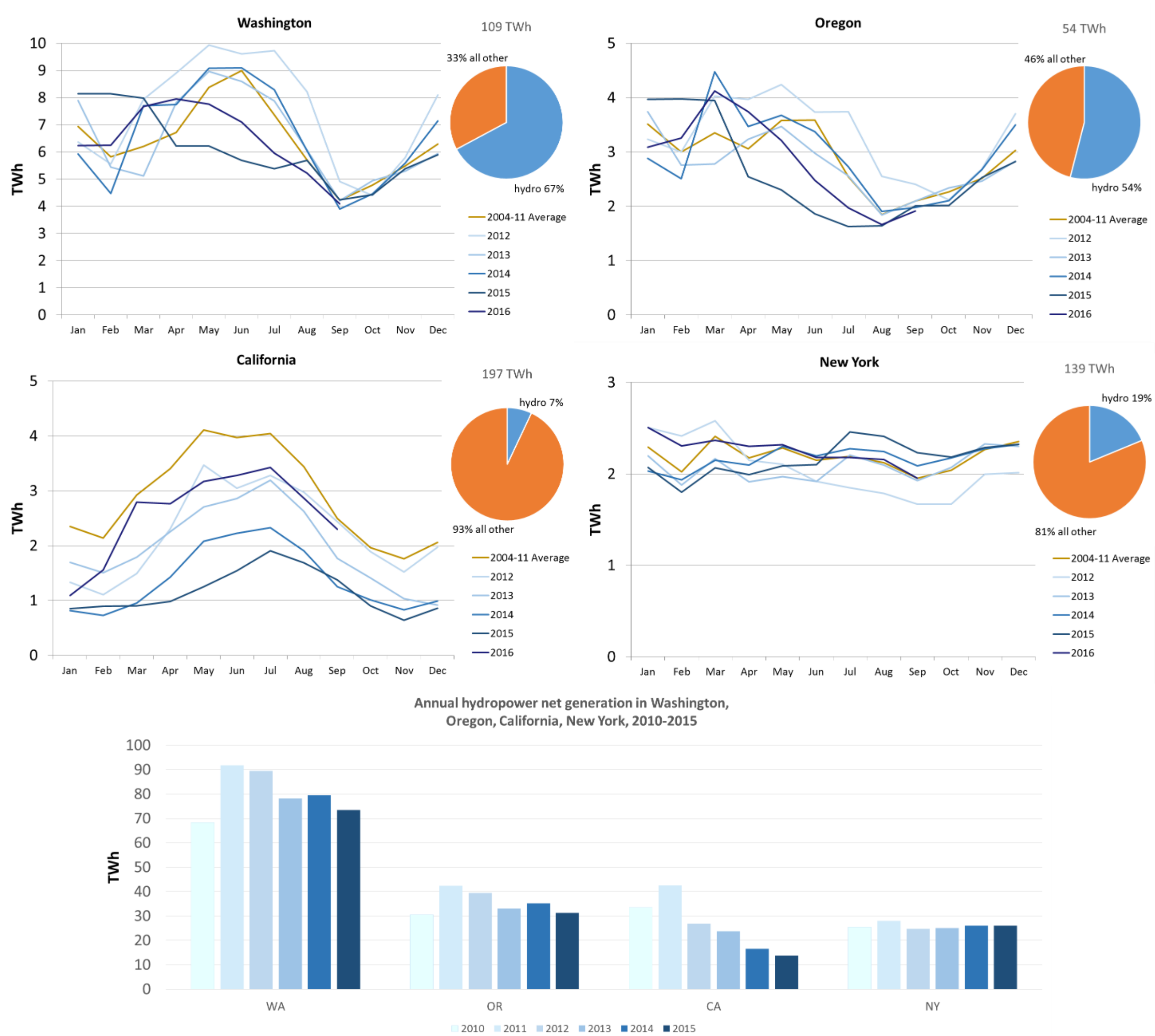


Figure 35. Hydropower generation trends in the four largest hydropower states

Hydropower generation trends are shown in the top four hydropower-generating states. The top four panels show monthly hydropower net generation in 2012 through 2016 and the 2004-11 average each states. Pie charts show the hydropower share of total generation in each state. The bottom panel shows the annual hydropower net generation in the states from 2010-2015.

Data source: EIA. Electric Power Monthly, Tables 1.3.A and 1.10A, November 2016 and previous months.

7.3 Summary and Conclusion

Climate change impacts such as higher temperatures, shifting precipitation patterns, and more frequent extreme events may intensify water stress on the electricity system in some areas of the United States. Relevant water stresses include both water availability and water quality (particularly temperature), and affect hydropower as well as thermoelectric generation. Solutions involving enhanced operational flexibility may be required to address climate change impacts.

Chapter 8. Findings

Energy-Water Baseline Findings

Key System Attributes

- ***Electricity and water systems are physically interconnected***
    - The national level hybrid Sankey diagram shows interconnected energy and water flows.

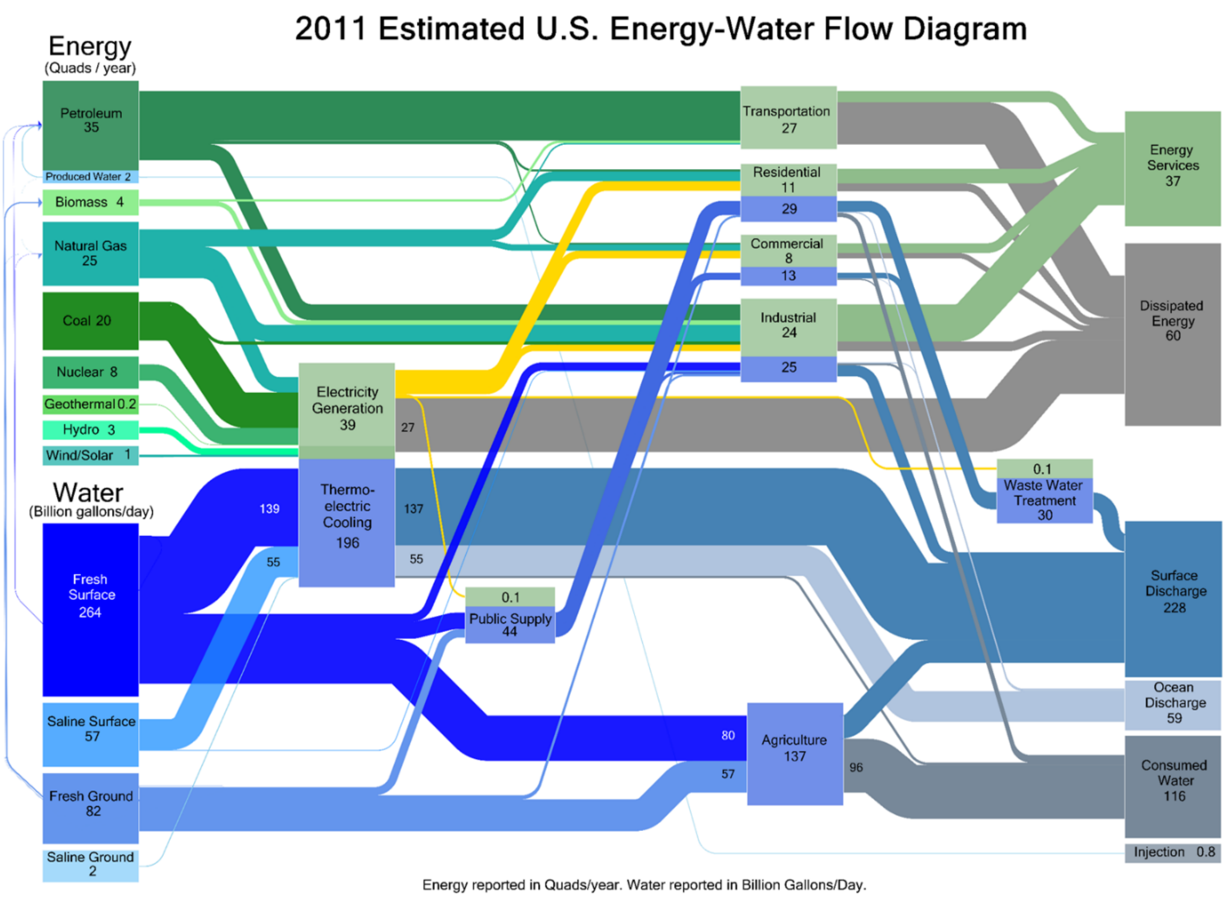


Figure 36. Hybrid Sankey diagram of 2011 U.S. interconnected water and energy flows.
Significant fractions of surface freshwater withdrawals are for thermoelectric cooling and for agriculture, but agriculture consumes more water than thermoelectric cooling consumes. Most electricity is generated for residential, commercial, and industrial use, but significant fractions are used for public water supply and wastewater treatment. The Sankey diagram aids in visualizing these complex data streams and interconnections as a first step toward further analysis.
Source: The Water-Energy Nexus: Challenges and Opportunities (2014)

- ***Thermoelectric cooling is the largest withdrawer of fresh and saline water nationally***

    - Water plays a critical role in the generation of electricity and the production of fuels. Large quantities of freshwater withdrawals in the United States are used for cooling thermoelectric power plants. Agriculture, for comparison, accounts for a significant but smaller share of freshwater withdrawals.[141] In 2010, thermoelectric cooling withdrew 167 billion gallons of fresh plus saline water per day (BGD) in the United States.[142]

    - Although thermoelectric cooling remains the largest water withdrawer, irrigation remains the largest water consumer in the United States. Thermoelectric cooling accounts for a much smaller fraction of consumed water, about 2.9 BGD.[143]

    - With the retirement of many older coal and nuclear plants that use once-through cooling, national thermoelectric water withdrawal rates are currently decreasing. However, thermoelectric water consumption is increasing due to increased use of recirculating cooling systems, which withdraw far less water but consume more water than once-through cooling systems. In addition, not all once-through coal and nuclear plants are retiring; many may continue to operate for decades.

- ***Thermoelectric operational practice may increase water use***

    - Many natural gas steam turbines in particular (green dots in Figure 37) run their cooling systems for a substantial fraction of the time when they are not generating. Most of these plants are likely operating as peaking plants. A number of these plants are operating in dry regions that are prone to drought. This behavior is not limited to natural gas steam plants, but is most noticeable in these plants.

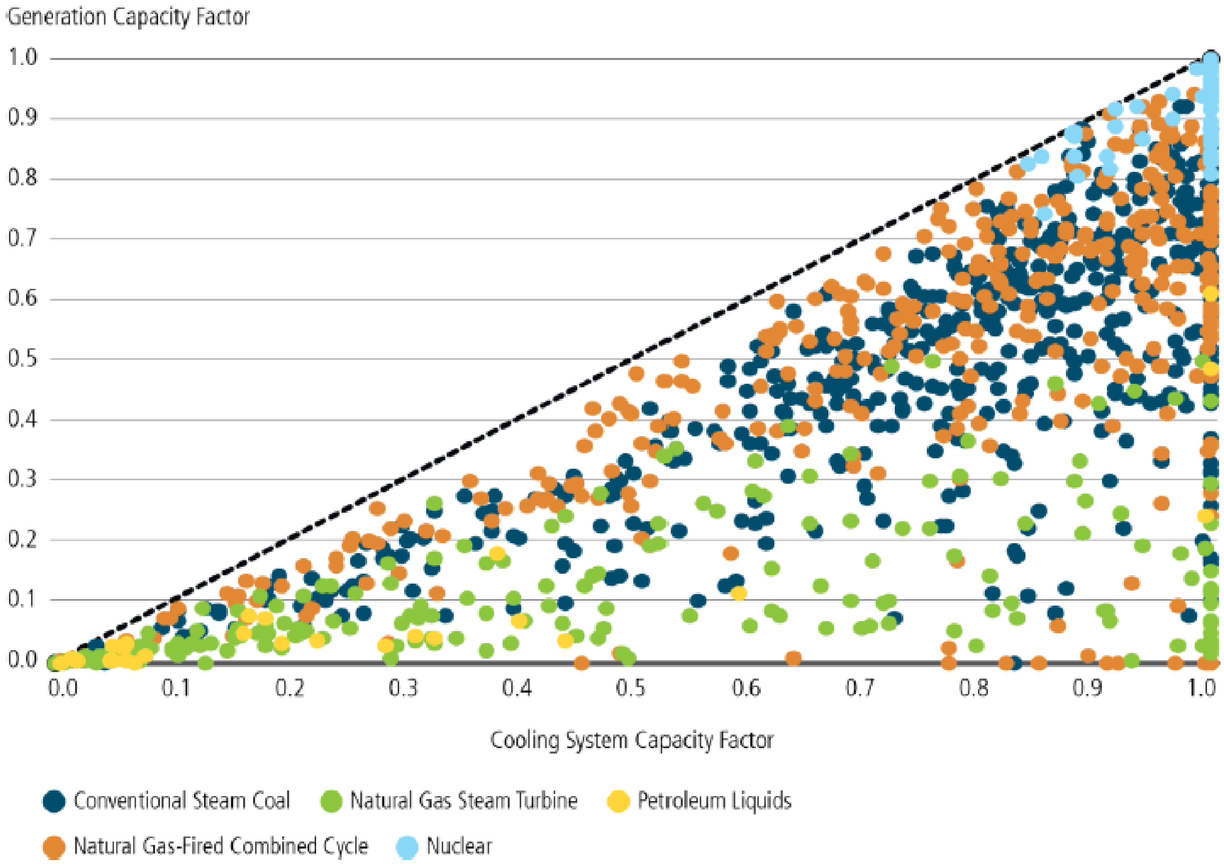


Figure 37. 2014 Cooling System Capacity Factors Vs. Generation Capacity Factors.
Electricity generators run their cooling systems with varying capacity factors relative to their generating capacity factors. Natural gas steam turbines (Rankine cycle plants)—many likely acting as peakers—evidently run their cooling systems for a substantial amount of time when they are not generating, as do a number of natural gas combined cycle plants. Plants on the dotted line will run their cooling systems with the same capacity factor as their generation capacity factor, i.e. only when they are generating.
Data source: EIA thermoelectric cooling data (2015 data, published in 2016) derived from EIA Form 860 and EIA Form 923.

- ***Water treatment and pumping use significant electricity***

  - Just as water is needed to supply energy, energy is required for treatment and delivery of water for human use. Irrigation pumping, water conveyance, and municipal water treatment and distribution account for 3 to 3.5 percent of the total U.S. electricity consumption.[144] For comparison, residential and commercial lighting in 2014 accounted for 11 percent of total U.S. electricity consumption.[145]

- ***Energy-water relationships vary regionally***

  - Once-through cooling, which requires higher water withdrawal but also enables greater generation efficiency, is more prevalent in the relatively water-rich eastern U.S. In addition, many of the large generators in the East are older, coal-fired plants that tend to use once-through cooling but are increasingly retiring. Newer thermoelectric plants, such as those more common in the West, tend to use recirculating cooling. Figure 38 below shows quantitatively that regions of high water withdrawal for thermoelectric generation (dominated for all regions by surface water withdrawal) correlate with significant coal-fired and nuclear generation. The western U.S. has a lower water withdrawal that correlates with more diverse generation portfolios and smaller overall shares of coal and nuclear.

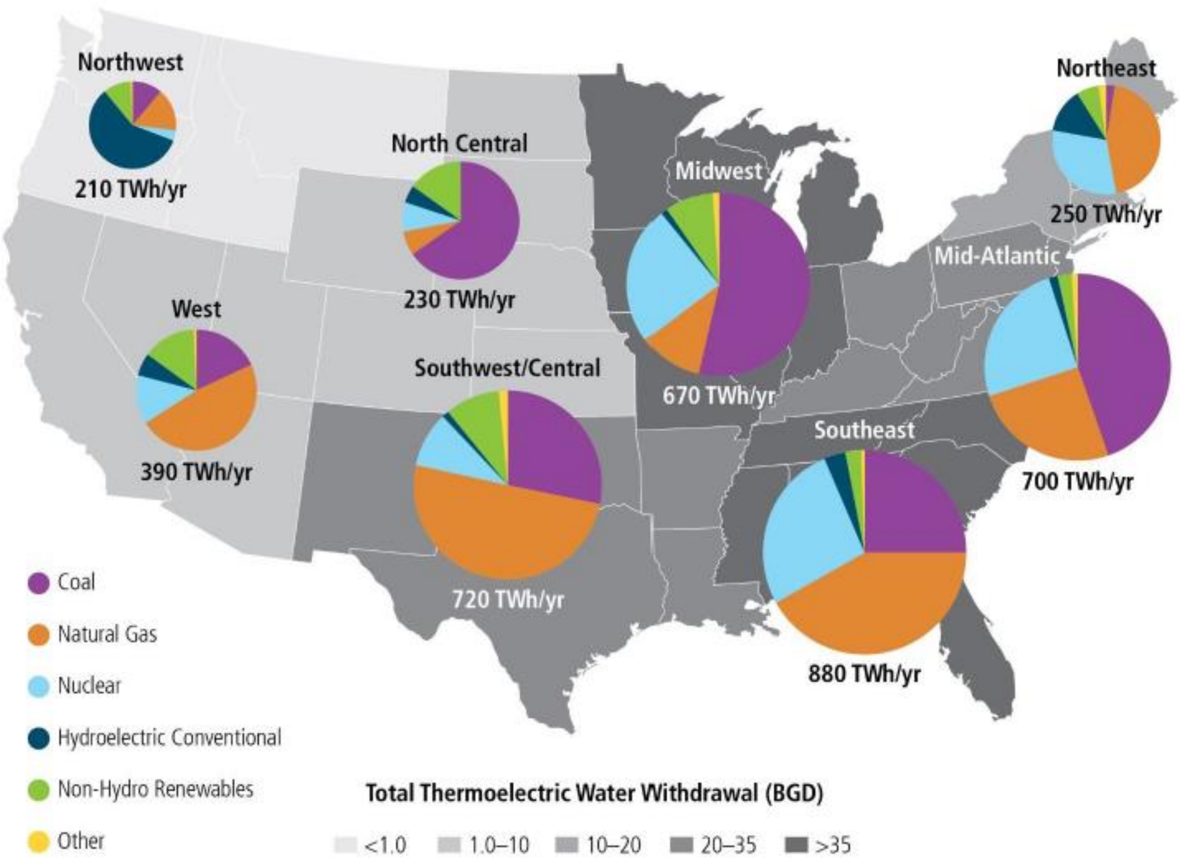


Figure 38. Water Withdrawal and Generation by Region in 2015

The largest water withdrawal regions are dominated by coal and/or nuclear generation. The area of each pie chart corresponds to total power generation in that region. "Other" includes petroleum, other fossil fuel gases, pumped storage, non-biogenic municipal solid waste, batteries, and hydrogen. The eight regions shown in the figure are notional, based upon contiguous groupings of states and their generation mixes, resources, and market structures. Data Source: EIA Form 923 (2015 data, published in 2016).

- ***Proportion of hydropower capacity owned by the government brings operational and capital investment implications***

  - Many large hydropower plants are government-owned. As of 2014, federal agencies including the U.S. Army Corps of Engineers, the Bureau of Reclamation, and the Tennessee Valley Authority own approximately half of the current installed hydropower capacity.[146] Many of the largest conventional hydroelectric facilities are federally owned, while many of the largest pumped storage facilities are nonfederal.

- Of the federal hydropower owners, only TVA actually sells the power produced at its facilities. Power produced at ACE and BOR facilities is marketed and sold by DOE's Power Marketing Administrations (PMAs). In some cases, PMAs must receive appropriations from Congress for modernization and general maintenance of federal facilities;[u] this situation has potential to limit funding available for upgrades to enable more flexible operation and ancillary services provision.[147]

➢ ***Energy and water policy landscape is highly fragmented***

- The energy-water decision landscape is highly complex and fragmented. This is a result of multiple factors, including the distribution of jurisdictional responsibility among federal, state, and local law-makers; inherent differences in resource abundance and historical resource development across the nation; and a diverse set of actors and interests.

- State-level water rights and permitting inform the decisionmaking of any significant water user. Because water issues vary greatly by region, water resource policies—even policy frameworks—can vary greatly from state to state.[148] With respect to surface water, states generally follow some variation of two governance doctrines—the prior appropriation doctrine and the riparian doctrine. Under the prior appropriation doctrine, water allocation is made on a first-come, first-serve basis and not linked to land ownership; during times of shortage, more senior rights holders may use available water before more junior rights holders.[149] Under the riparian doctrine, also called the "common law" doctrine, owners of land bordering waterways have a right to use water that flows past the land for any reasonable purpose. Figure 39, below, displays water rights doctrines by state.

[u] The Bonneville Power Administration (BPA), unlike the other three PMAs, is self-financed and thus receives no federal appropriations. BPA covers its operating costs through power rates set to repay Treasury capital and interest. In addition, the 1992 National Energy Policy Act authorizes direct funding by BPA for the Corps of Engineers and Bureau of Reclamation for O&M and capital investments in the Federal Columbia River Power System (FCRPS).

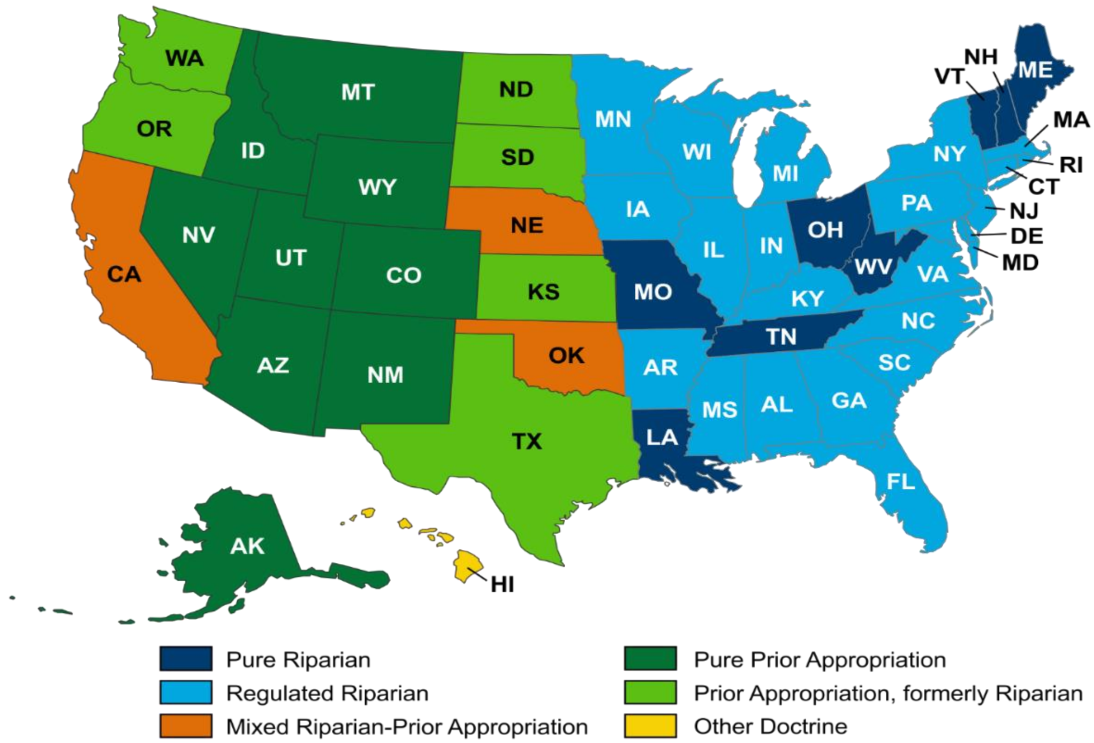


Figure 39. Water governance policies in the United States, by state.
Most western states are governed prior appropriation, while eastern states are governed by riparian frameworks.
Data source: Gleick and Christian-Smith 2012
Figure source: The Water-Energy Nexus: Challenges and Opportunities

- Power plants in states with riparian water rights have had fewer issues finding and using surface water for cooling, mainly due to relative water abundance. As a result, once-through cooling, which requires higher water withdrawal but also enables greater generation efficiency, is more prevalent in these areas. As shown in Figure 40, median power plant withdrawal intensity in riparian states is higher than for plants in prior appropriation states.[v] Median consumption intensity has the opposite trend, with greater median consumption intensity in prior appropriation states. This is likely due to the larger share of wet-recirculating and other high-consumption cooling systems in more arid states, which are more likely to be governed by prior appropriation.

[v] This is based on use of both fresh and non-fresh water sources.

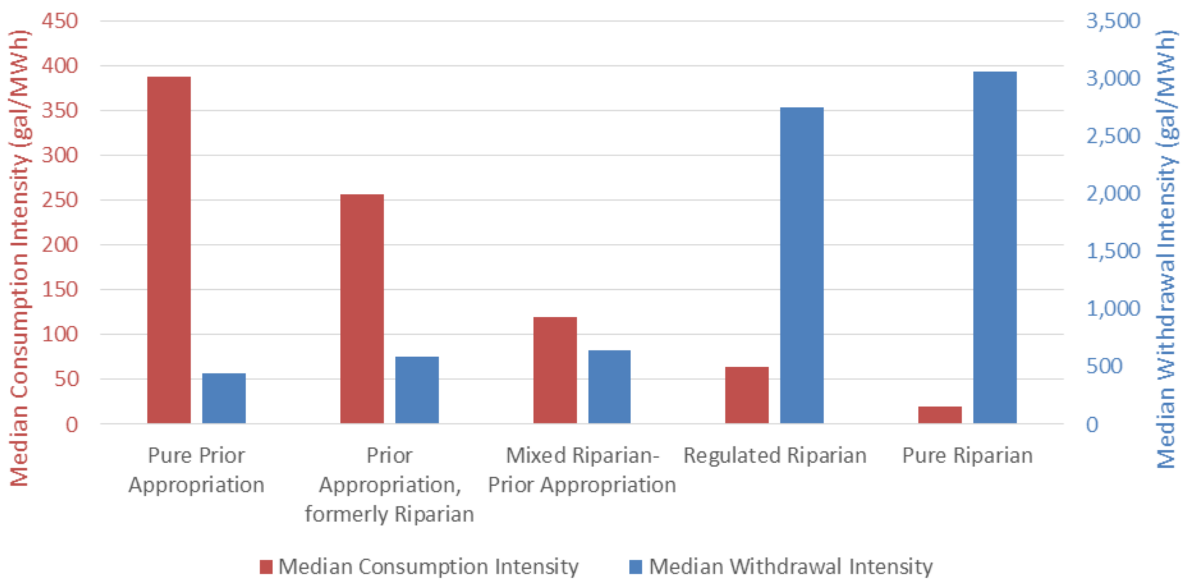


Figure 40. Median water withdrawal and consumption intensities at power plants by water governance policy (2014).

Riparian frameworks correlate with large water withdrawal intensity, while prior appropriation correlates with significantly reduced withdrawal intensity but increased consumption intensity.

Data source: EIA thermoelectric cooling data (2015 data, published in 2016) derived from EIA Form 860 and EIA Form 923; Gleick and Christian-Smith (2012)[w]

Key Changes and Drivers

➢ ***Change in electricity generation fuel mix over time has water use implications***

- The variation in possible future scenarios for electricity generation will significantly impact the energy-water nexus, as both generation technology type and cooling system type can strongly affect water withdrawal and consumption rates by thermoelectric generators.

- Many of the generation units set to retire by 2020 use once-through cooling technologies, while many of the anticipated new generation units are expected to use recirculating cooling technologies (Figure 41). This trend is likely to cause decreased water withdrawal but increased water consumption. Note that planned renewable additions account for 70 percent of planned additions, and the vast majority of these renewables require no cooling.

[w] The type of water governance information is from Gleick and Christian-Smith (2012). "Riparian" includes pure riparian and regulated riparian states. "Prior Appropriation" includes states that have been prior appropriation doctrine implementers all along (pure prior appropriation states) or currently prior appropriation states that are formerly riparian states (prior appropriation, formerly riparian states). "Hybrid" or "Other" includes states that implement both prior appropriation and riparian doctrines and states like Hawaii that has a completely different doctrine than other states.

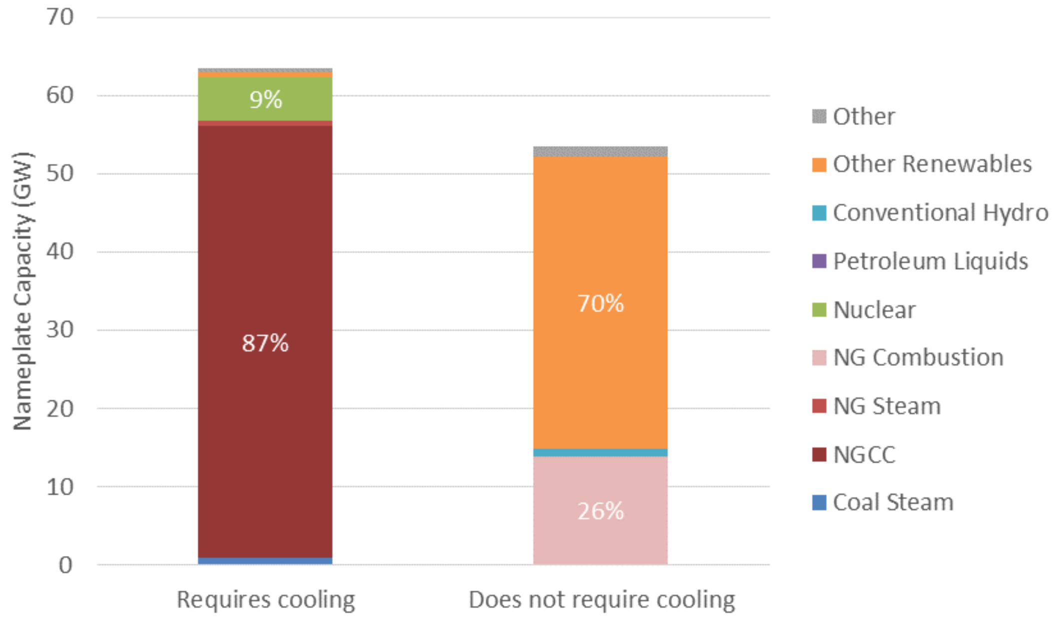


Figure 41. Planned additions of U.S. electricity generation capacity by cooling requirement and fuel source (2016–2020).

The planned additional capacity requiring no cooling is nearly equal to that requiring cooling, and this no-cooling portion is split between natural gas and renewables. Note that NGCC systems make up a large share of planned capacity additions, and these are classified as requiring cooling. However, because the combustion turbine component of the NGCC system requires far less water than the steam turbine component, the overall NGCC system tends to be relatively water efficient.

Data source: EIA Form 860 (2015 data, published in 2016)

- The source type and water type of water proposed to be used for new capacity additions is changing relative to the source type and water type used by the current fleet (Figure 42). For source type, 72 percent of the current fleet uses surface water, while only 29 percent of proposed systems use surface water. Thirty-one percent of proposed systems are expected to use dry cooling, relative to only four percent of the current fleet. The share of plants using groundwater and wastewater treatment plant discharge is similar for the current fleet and the proposed systems. Comparing the source type data to the water type data (lower panel), we can see that most of the groundwater for proposed systems will be fresh groundwater. For water type, proposed systems are expected to include a much larger share of dry cooling and a much smaller share of freshwater use relative to the current fleet.

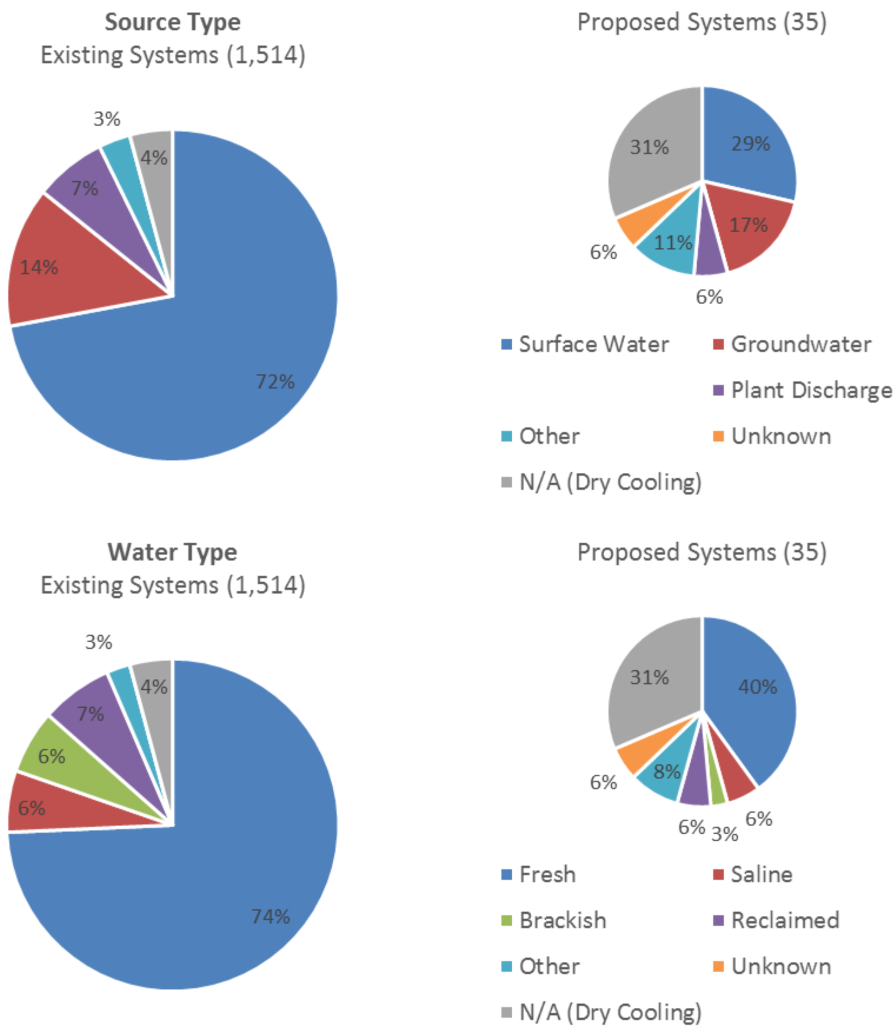


Figure 42. Number of existing and proposed (2016-2020) cooling systems by source type and water type. *Source type (upper panel) and water type (lower panel) are shown for existing cooling systems (left) and proposed cooling systems for 2016-2020 (right). The share of proposed systems that will use dry cooling is substantially larger than that of the current fleet.*

Data source: EIA Form 860 (2015 data, published in 2016)

➢ ***Impacts of climate change require additional flexibility in electricity generation***

- The projected spatial and temporal variation in precipitation patterns will have an impact on the electricity sector. With less precipitation in some areas, energy producers may turn to groundwater resources to supplement stressed surface water supplies. Timing of rainfall and/or snowmelt can also impact hydropower generation by requiring changes in operations to ensure water availability and appropriate water temperature for non-electricity purposes such as mitigating impacts to fish.

- For hydropower, a slow downward trend in average capacity factors across the U.S. since the 1970s is apparent from Figure 43. This is due to a range of factors, including some combination of environmental regulations, changing availability of water under climate change, aging equipment, and shifting priorities of water uses in multipurpose projects, among other factors.[150]

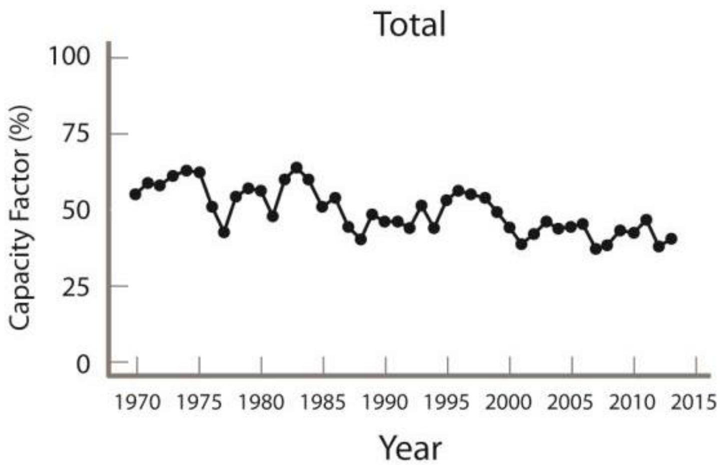


Figure 43. Long-run monthly hydropower capacity factor for plants across the U.S. built before 1970
Capacity factor varies by year, but a downward trend is apparent.
Data: EIA Form 920/921/923
Figure: 2014 Hydropower Market Report

- ***Population growth and migration patterns can intensify energy and water needs***

  - Energy and water needs will be shaped by population growth and migration patterns as well as by climate change. According to the US Census Bureau, the projected percent change in population by region of the United States varies significantly. The South and the West are both expected to see over 40 percent population growth by 2030, relative to 2000.[151] The Northeast and Midwest are expected to see less than 10 percent growth by 2030, relative to 2000.[152] Competing energy and water needs may become more serious in regions such as the South and West where large projected population growth overlaps with projected water constraints under climate change.

- ***Technology options, choices, and standards can impact the electricity system's vulnerability to water disruption and the energy performance of water systems***

  - Because thermoelectric cooling remains the largest recipient of water withdrawals in the United States, deploying alternative low-water or zero-water dry cooling systems remains an increasingly important area of electricity generation. However, dry cooling imposes an efficiency penalty of 4.2-16 percent for typical plants.[153] Currently, dry or hybrid cooling systems cool about 130 TWh of net generation in the United States. Most of the dry cooling systems currently online have been deployed in natural gas combined cycle plants since 2000. Additionally, according to the most recent data collected by EIA, 11 new dry cooling systems are expected to be operational by 2020.

- Wide-scale deployment of carbon capture and storage (CCS) could increase the demand for water for electricity production. The extent of the water demand increase is dependent on the CCS technology used.

- One example of how the development of standards can advance energy efficiency involves pumps; DOE has regulatory authority over pumps, including water pumps. In 2016, DOE finalized new energy conservation standards for pumps with compliance required starting in 2020.[x] These standards could result in significant energy savings through minimum efficiency standards. Moreover, requirements for compliance with these standards could have the ancillary benefit of enhanced data collection on energy use by pumps.

➢ ***Market structures and behavior impact hydropower's ability to fully realize its potential value to the electricity system.***

- Ancillary services provided by hydropower are not always explicitly compensated by existing market structures. For example, hydropower is one of the main providers of inertia and primary frequency response in WECC, but it is not explicitly compensated for either service.[154]

- Although variable speed generators are widely deployed in Japan and throughout Europe, none have yet been deployed in U.S. pumped storage, despite findings that existing pumped storage plants in the U.S. could increase revenues by 61 percent by upgrading existing capacity through mechanical changes such as advanced turbines.[155] Europe's wider deployment of pumped storage (including variable speed generators) relative to the U.S. has been due to a number of factors, including more expensive natural gas, higher VER penetration, significant carbon trading, larger feed-in tariffs, and ancillary services payments.[156] The distinctions of response speed are particularly important for balancing variable renewables, which require fast response down to the sub-second time scale.

Challenges and Opportunities

➢ ***Data limitations can hinder analysis in the energy-water nexus***

- Analysis of various aspects of the energy-water nexus suffer from a lack of data of sufficient quality, usability, and spatial and temporal resolution. Enhanced and more widely distributed remote sensing, smart metering, networks of real-time sensors,

[x] 10 C.F.R. 429, 10 C.F.R. 431. The Energy Policy and Conservation Act of 1975 (EPCA), as amended, sets forth a variety of provisions designed to improve energy efficiency. Part C of Title III establishes the "Energy Conservation Program for Certain Industrial Equipment." The covered equipment includes pumps.

improved survey methods, and attendant summarization and analytic capabilities, would provide a basis for improved analysis, modeling, and decision support.

- There are some inconsistencies between USGS and EIA thermoelectric water withdrawal data values. Improved harmonization and integration of energy-water data sets, particularly among federal agencies, is a critical need for improving confidence in the data and allowing advanced analyses of regional variability and trends over time.

- While EIA collects commercial and industrial energy use data through its surveys, it doesn't collect data on energy used by the water sector for municipal water and wastewater treatment and conveyance – making analysis of energy use and savings opportunities difficult.

➢ ***Technologies deployed will create tradeoffs among energy, water, and GHG emissions***

- Improvements in power plant efficiency could lead to substantial reductions in water use.

- Some energy technologies that reduce GHG emissions, such as CCS, CSP, and geothermal, have the potential to increase energy's water intensity; others, such as wind and PV, can lower it.

- Dry cooling can reduce water intensity, but may increase overall GHG emissions by decreasing generation efficiency.

➢ ***The U.S. could potentially learn from integrated energy and water policy pursued by other countries***

- Policy challenges related to energy and water are not unique to the United States; many other nations are addressing the energy-water nexus based on their own circumstances. Therefore, the United States could consider best practices from a wide range of efforts in water-scarce countries to integrate energy and water policies.

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