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Light Water Reactor Sustainability Program

Analysis of Water-Energy Issues for Nuclear Power with Industry Perspective

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EXECUTIVE SUMMARY

We present analysis and insights from stakeholder interviews focusing on the issues faced by the U.S. commercial nuclear energy industry within the water-energy nexus space. This report expands on the 2023 report "Updated Assessment of Water-Energy Issues for Nuclear Power" that was an update to the 2010 report "Cooling Water Issues and Opportunities at U.S. Nuclear Power Plants."

This report includes analysis of water-related topics that affect the continued operation of the existing U.S. commercial nuclear fleet including (1) An evaluation of water consumption and withdrawal reporting methods noting inconsistencies between modeling and reporting approaches; influence of plant-level cooling water system type and capacity; and impact of local conditions including plant age, system performance amongst other factors. (2) A discussion on water supply-related issues impacting power generation including the lack of water available for cooling, higher-than-anticipated water intake temperatures, and high water-discharge temperature; acknowledging that despite the variations in magnitude, frequency, and duration of extreme weather events, response has been effective due in part to safety requirements that avoid environmental damage. (3) A discussion and analysis of the evolving policy risks and challenges including extended requirements for National Environmental Policy Act, permitting and temperature considerations for adherence to requirements of Clean Water Act noting water quality certifications, thermal variance, and permitting modifications, emerging contaminants of the Safe Drinking Water Act influencing safety operations and decommissioning activities, mechanisms to address water scarcity noting the complexity of water markets, trading and institutional water availability and discussion of the supply gap of water interdependencies of a changing energy grid with climate influences and resource competition from population shifts. (4) An analysis of environmental issues including the potential impact of climate change on water availability and nuclear power plant performance (5) An initial assessment of environmental justice including noting the number of disadvantaged communities. (6) An analysis of opportunities to reduce water-related risks noting issues with changing to alternative water sources, increasing the cycles of concentration, employing water treatment, and implementing integrated systems.

From the analysis conducted, the literature reviewed, and discussions with stakeholders, we conclude there is a significant, ongoing need to understand the water-energy nexus issues affecting the U.S. commercial nuclear energy industry. The following insights were developed: (1) regulatory changes in both the water and energy space continue to make long-term planning difficult and financially burdensome. Understanding policy and implementing solutions is critical to maintaining performance. (2) Barriers to incorporating existing technological improvements need to be reduced to incorporate efficiency gains and risk reduction because climate change is consequential and will impact all aspects of the sector. (3) Business decisions have an impact on society and on the environment; therefore, proactive management of environmental justice could influence reputational risk and long-term sustainability of the sector.

Finally, we offer the following recommendations for the continued future of the commercial nuclear fleet in terms of the water-energy nexus: (1) Continued

investment in improved modeling efforts of "physical available water" including consumption/withdrawal and "institutional available water" including water rights, administrative controls, and environmental limits is necessary to evaluate risk and areas for improvement. (2) Ongoing commitment to develop and incorporate cost- and energy-efficient technologies to reduce the intensity and, eventually, eliminate the need for cooling water use, including advanced sensors, data, system design, and chemical treatments. (3) Work to help inform regulators of the impacts of regulations and policy on technology implementation and performance improvements. (4) Improve how environmental justice is considered and addressed. With continued monitoring and investment in the water-energy nexus, the light water reactor sustainability program could ensure an economically and environmentally stable light water nuclear fleet.

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ACRONYMS

AFFF	Aqueous Film-Forming Foam
BIL	Bipartisan Infrastructure Law
BWR	boiling water reactor
CWA	Clean Water Act
EA	environmental assessment
EIA	Energy Information Administration
EIS	environmental impact statement
ERCOT	Electric Reliability Council of Texas
EPA	Environmental Protection Agency
FEMA	Federal Emergency Management Agency
PFAS	polyfluoroalkyl substances
TWh	terawatt hour
USGS	U.S. Geological Survey
NRC	Nuclear Regulatory Commission
LWR	light water reactor
EPRI	Electric Power Research Institute
NEPA	National Environmental Policy Act
GEIS	generic environmental impact statement
NPDES	National Pollutant Discharge Elimination System
NERC	North American Electric Reliability Corporation

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Analysis of Water-Energy Issues for Nuclear Power with Industry Perspective

1. INTRODUCTION AND MOTIVATION

This report was prepared to expand upon a previous 2023 report, “Update Assessment of Water-Energy Issues for Nuclear Power,” which provided an assessment of the challenges and opportunities facing the U.S. commercial nuclear energy industry. Specifically, this report provides an update to the 2010 report, “Cooling Water Issues and Opportunities at the U.S. Nuclear Power Plants” (GAO 2009).

Analyses contained in this report address several water-related topics that affect the continued operation of the existing U.S. commercial nuclear fleet: (1) water use, consumption, and withdrawal issues; (2) water-related impacts of nuclear power generation; (3) evolving policy risk; (4) implications of water markets, trading, and water rights; (5) the evolving energy grid; (6) progressing environmental issues, especially climate risk; and (7) opportunities to reduce water-related risk.

2. STAKEHOLDER ENGAGEMENT

For this report, personal discussions were conducted with small groups of staff of industry stakeholders, including providers of water technologies, water treatments experts, nuclear reactor technologists, and nuclear utility operators. The focus of these conversations was to gather perspectives from stakeholders actively involved in areas of water-energy in the commercial nuclear power space. The stakeholders engaged covered a wide range of regions, including the water-rich Midwest and the arid Southwest. We relied on existing relationships and personal connections in order for the discussion to proceed candidly. The most interesting finding from the stakeholder discussions was the similarities and differences in their priorities, but there was a strong consensus on the significance of water and cooling for the light water reactor sector. Of the six discussions that included over fifteen participants, there was a consensus on three factors; (1) climate change is consequential and will impact all aspects of the sector and there is not a clear future on how to address it; (2) understanding policy and implementing solutions is critical to maintaining performance; and (3) recognition that business decisions have an impact on society and the environment. Further engagement that also includes non-industry stakeholders is needed.

3. ANALYSIS OF WATER FOR THE U.S. COMMERICAL NUCLEAR POWER INDUSTRY

This section provides an analysis of current water issues affecting the U.S commercial nuclear fleet of operating light water reactors (LWRs). Topics discussed include the positioning of the nuclear industry in the greater context of thermoelectric power generation, water consumption, water withdrawal, and a review of past water-related impacts on operations at nuclear power stations.

3.1 Setting the State; Background on Thermoelectric Power Overview

In 2022, about 4.2 terawatt-hours (TWh) of electricity were generated at utility-scale electricity generation facilities in the U.S., of which 18.2% of generation was from nuclear energy. This is a small decrease from previous decades where nuclear energy accounted for more than 19% of generation (EIA 2023). Most electricity in thermoelectric plants is generated using steam turbines that convert high-pressure steam into mechanical energy to produce electricity. Both water and air can be used to cool and condense steam in thermoelectric plants, but water-cooled systems are more common and typically more thermodynamically efficient.

Cooling systems are the largest source of water use in thermoelectric plants, but the type of cooling has a big impact on water use. In the U.S., 61% of the thermoelectric generation capacity uses recirculating cooling systems, 36% uses once-through cooling, and 3% uses dry and hybrid cooling systems (Ray 2018). In recirculating systems, water is "recirculated" through cooling towers where the water makes contact with heat exchangers and is evaporated to produce cooling. In once-through systems, water is returned to the source after circulating through the heat exchangers. Dry cooling systems use ambient air to cool and condense steam. Both recirculating cooling and once through cooling systems are employed in the U.S. LWR portfolio but LWRs facilities tend to be larger than fossil thermoelectric plants which may result in more concentrated stress on local water systems.

3.2 Cooling Water Withdrawal and Consumption and Use-Reporting Concerns and Historical Trends

As stated in the previous report, water withdrawal and water consumption are two different measures of water use. Water withdrawal is the total amount of water taken from a source regardless of where it is discharged or returned. Water consumption is the amount of water that is not returned to the source but is lost through evaporation, transpiration, incorporation, or otherwise not available for immediate use. Water withdrawal is typically higher than consumption.

Estimating water use at U.S. power plants can be difficult because they are complex systems and there are no standardized definitions and reporting criteria. The two primary sources for water-use estimates for thermoelectric power plants in the U.S. are the Energy Information Administration (EIA) and the U.S. Geological Survey (USGS). Data reported by EIA are based on power plant reports, while data from the USGS are based on modeling. EIA provides monthly water-related data for thermoelectric plants based on reports from individual power plants which include net and gross energy generated, water withdrawal and consumption, and water withdrawal and consumption intensity (EIA, 2023). Alternatively, USGS models water use at individual power plants using basic thermodynamic principles (i.e., based on plant characteristics and climatic conditions). EIA and USGS water use estimates for the nuclear power industry are presented in Table 1 (Harris, 2019; EIA 2023; USGS 2023). The 2020 USGS data uses different methods and data sources than the 2015 and 2010 USGS data. Overall, nuclear power generation accounts for about 40% of all thermoelectric water withdrawals and 28% of all water consumption (Harris 2019).

Table 1. Water use by the nuclear power industry for select years, million gallons per day (MGD).

	USGS		EIA	
	Withdrawal	Consumption	Withdrawal	Consumption
2010	43,723	929	43,856	761
2015	44,135	797	57,668	761
2020	42,045	946	55,291	716

Upon comparison, one would expect to see a slight decreasing trend in water withdrawal and consumption at the aggregate level due to the retirement of several nuclear power plants since 2017. Instead, the differences reflect improvements in the modeling process rather than actual changes in water use. Additionally, the rise in reported withdrawals corresponds with the time period over which EIA improved efforts in standardizing and reviewing plant-reported water use.

One would expect USGS withdrawal estimates to be lower than EIA reported data because USGS models estimate the amount of water required to cool the plant based on fuel use, electricity generation, and environmental variables but does not include water withdraw for other operational purposes. The differences in reported withdrawals (EIA vs USGS) in 2015 seem too large to be explained by plant operations alone; however, an alternative explanation is lacking at this point. Consumption estimates are more consistent between the two data sources, although USGS estimates are consistently higher than EIA. This occurs because the USGS estimates forced evaporation from surface waters due to heated discharge from once-through systems, while many plants with once-through systems report zero consumption to EIA (see below).

The presentation of national-level aggregated data, as in Table 1, hides important plant-level differences in water use. Two of the most important determinants of water use are the plant capacity and the cooling system type. Water use scales directly with the size of the plant—with plants varying in size from about 580MW to 3800MW. The relationship between water use and cooling systems is less direct and more complex than plant capacity. The U.S. fleet of nuclear power plants use either once-through (open-loop) or recirculating (closed-loop) cooling systems. Figure 1 shows the location of currently operating nuclear power plants, their installed cooling system, and the year operations started. Most nuclear power plants using once-through cooling began operation before 1980. Table 2 presents water withdrawal and consumption coefficients (gallons of water used per MWh of electricity generated) for nuclear power plants organized according to cooling technology (Harris 2019).

Once-through cooling systems operate by directing cooling water through a heat exchanger that is then discharged to the water source, conducting heat to the receiving river or lake. Plants with once-through systems are characterized by very high-water withdrawals but have limited water consumption. Recirculating cooling systems use an evaporation cooling tower, where heat is exchanged through evaporation. As such, recirculating systems withdraw much less water than open-loop systems, but consume more water. Recirculating systems cool steam to the wet bulb air temperature and are, therefore, effective at limiting heat input into source water bodies, but that comes with an average of 1.2% energy penalty compared with once-through for all thermoelectric generation (McCall 2016). A small number of plants employ a hybrid configuration by recirculating cooling through a pond rather than a tower. In this system type, water use is quite variable, somewhere between once-through and a recirculating tower, so an average is not reported, as shown in Table 2.

When compared to other fuel types, the water-use coefficients (i.e., water-use intensity) for nuclear power plants are similar or higher than all types but biomass (Harris 2019); that is, nuclear power is among the most water intensive means of generating electricity. Because almost half of the nuclear fleet's capacity employs once-through cooling, nuclear power accounts for about 40% of all thermoelectric water withdrawals (Harris 2019).

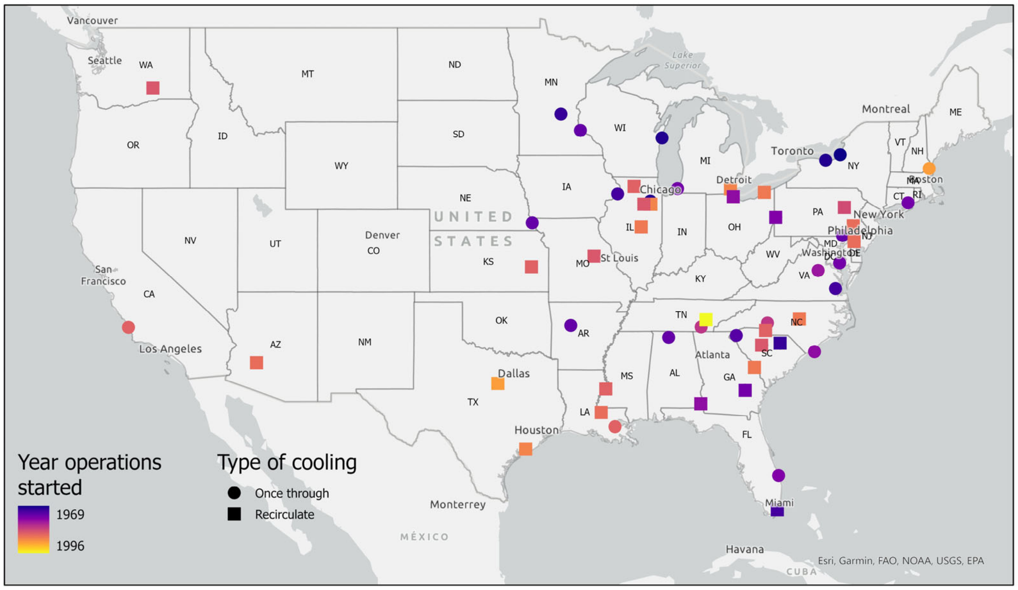

Figure 1. Map of current NRC-licensed nuclear power plants by cooling water type and year operations started (NRC 2020). Source: EIA.

Table 2. Water withdrawal and consumption coefficients for nuclear power plants employing different cooling systems (Harris 2019).

	Withdrawal (gal/MWh)	Consumption (gal/MWh)	Capacity (MW)
Once-Through	39,000	400	45,130
Recirculating Tower	700	500	34,350
Recirculating Pond	—	—	15,300

There are also local factors that influence water use at individual nuclear power plants. These include such considerations as the plant age, configuration of boiler/generator/cooling system, system operations, and environmental conditions. The method used to measure/estimate water use also impacts reported statistics. This variability is reflected in water withdrawal and consumption intensity values reported to the EIA (Figure 2). The Nine Mile Point Nuclear Station and Arkansas Nuclear One are examples of plants with complex boiler/generator/cooling systems, as both plants employ recirculating and once-through cooling systems. At Nine Mile Point Nuclear Station, the generator with a recirculating cooling system withdrew an average of 1,898 gal/MWh between 2014 and 2021, significantly lower than the average for the once-through cooling system (25,287 gal/MWh). A similar scenario was observed at Arkansas Nuclear One between 2014 and 2021, where the recirculating generator withdrew an average of 779 gal/MWh, and the once-through generator withdrew 54,720 gal/MWh. Water consumption intensity averaged 697 gal/MWh and 448 gal/MWh for the recirculating generator at Arkansas Nuclear One and Nine Mile Point, respectively. Water consumption data are not reported for the once-through generators in either of these plants during the period observed (2014–2021). The pattern observed in Figure 2 for 2021 indicates only five once-through generators report water consumption and water consumption intensity, which is also observed from 2014 to 2020. Operational constraints can limit power plant operators' ability to measure recirculating systems' water consumption. Additionally, measuring forced evaporation occurring in the water discharge source due to an increased temperature of the discharged water is challenging.

Reported water withdrawal intensities during 2021 were normally lower for plants with recirculating systems; however, some plants with recirculating systems (e.g., South Texas Project, Clinton Power Station, Turkey Point) withdrew similar volumes to once-through plants (Figure 2). Plant capacity and net energy generated do not appear to correlate with water consumption or withdrawal intensity (Figure 2). This complexity points to the need to identify factors that can explain the different water withdrawal and consumption intensity patterns observed. Plant operations and differences in measuring and reporting are potential explanations (Tidwell et al. 2019). Research is still needed to understand reported water consumption and withdrawal differences and how these values contrast with modeled estimates such as those generated by the USGS.

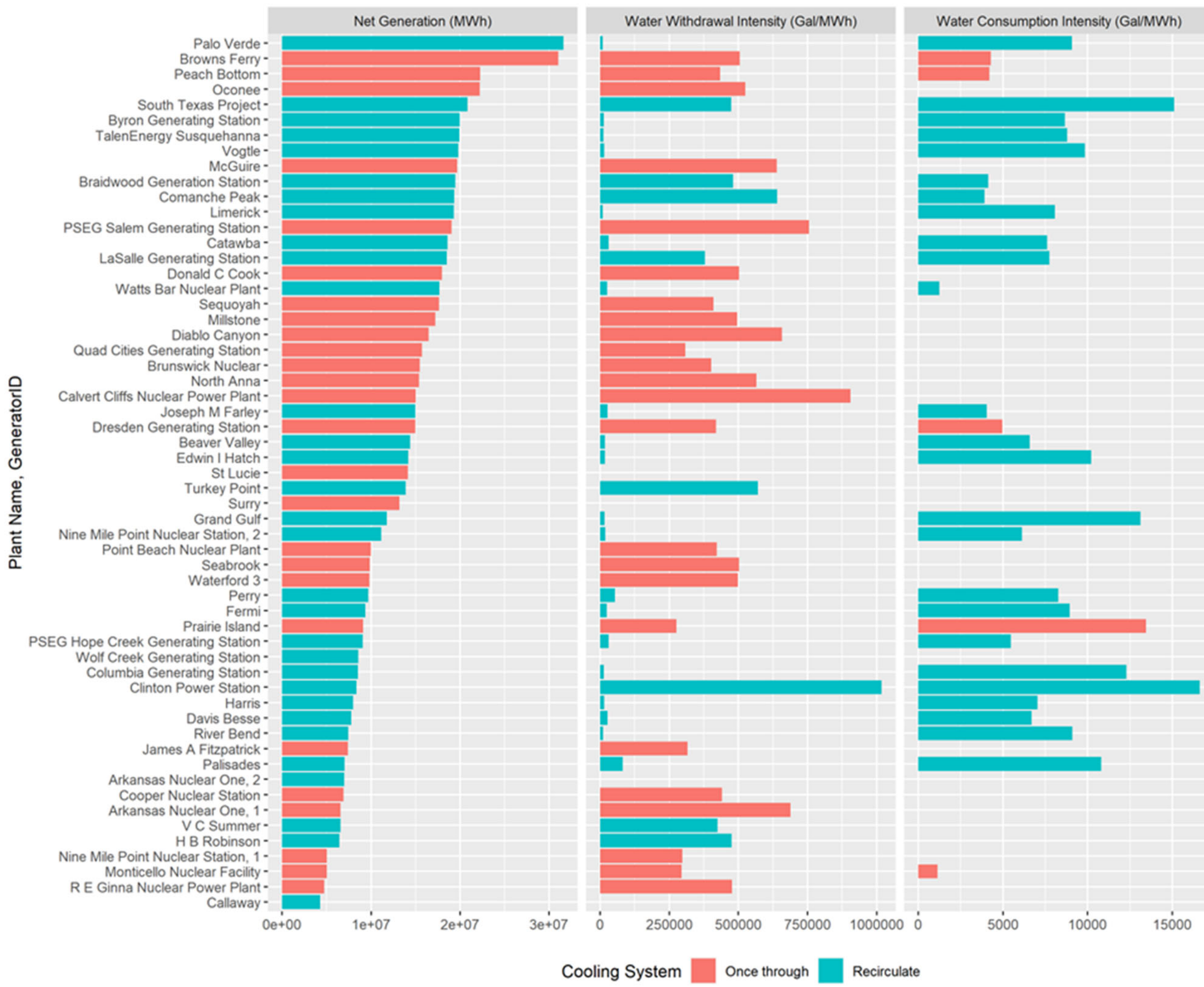

Figure 2. 2021 net generation, water withdrawal intensity, and water consumption intensity for operating nuclear power plants. Data is aggregated by the plant and cooling system. Nine Mile Point Nuclear Station and Arkansas Nuclear One have two generators with different types of cooling system each. Source data: EIA thermoelectric cooling water data (https://www.eia.gov/electricity/data/water/). Bars not shown represent missing data.

3.3 Impacts on Nuclear Power Generation

Water supply-related issues can impact power generation in three ways: (1) lack of water available for cooling, (2) higher-than-anticipated water intake temperatures, and (3) high water-discharge temperatures.

Lack of cooling water, regardless of the cause (e.g., resource competition, drought, climate change), can cause generators to curtail power production or shut down completely. Higher intake water temperatures can reduce plant operating efficiency, reduce maximum generation capacity, and force a generator to shut down. Higher intake temperatures can also result in higher discharge temperatures. High water-discharge temperatures can result in power generation curtailment and/or plant shutdown when discharged cooling water temperature exceeds the permitted water quality standards and environmental requirements.

The commercial nuclear industry has been designed to safely withstand events of great severity. Due to this criterion, there is a considerable safety margin against extreme weather events, which includes shutdown if necessary. The 2023 Electric Power Research Institute (EPRI) report "Climate Vulnerability Considerations for the Power Sector: Nuclear Generation Assets" states that 190 production days have been lost in the last decade due to weather-related events. This corresponds to about 0.06% of national power production lost, which is an estimated total of 470,000 MWh/year. Weather-related events in the study included extreme cold, extreme heat, external flooding, storms, lightning strikes, and biofouling.

The 2016 report "Water-Related Power Plant Curtailments: An Overview of Incidents and Contributing Factors" points to 25 drought-related incidents between 2000 and 2015 involving nuclear power stations (McCall 2016). Incidents occurred at 19 different plants, with two plants having experienced multiple events. Plants impacted were located throughout the Southeast, Northeast seaboard, and Midwest. Events included insufficient water (three instances), intake of water temperature that was too high (eight instances), discharge water temperature that was too high (eight incidences), and both intake and discharge water temperatures that were too high (six instances). These events generally lead to a shutdown or curtailment of generation, while in a few instances, discharge variances were granted or operations were modified. A specific example is the Millstone Nuclear Power Station in Connecticut that closed a unit during the summer of 2012 due to an increase in the temperature of the water used for cooling the reactor. In 2014, the NRC authorized the plant to use water up to 5°F warmer than the original design for reactor cooling. This suggests that an increase in water temperature was not initially considered when the construction of the plant was authorized in 1966.

Extreme flooding events have disrupted nuclear plant operations. The Brunswick plant was made inaccessible by flooding from Hurricane Florence in 2018 (NEI 2018, Reuters 2018). Similarly, the Fort Calhoun Station was shut down for several months, in part, due to floodwaters surrounding the plant in 2011 (Sulzberger 2011). Hurricane Sandy caused the Salem and Oyster Creek stations to shut down when high water levels threatened their water intake and circulation systems (UCS 2013). It is important to note that flooding presents numerous risks beyond inundation of the plant itself—threats can include loss of operations of water intake systems (flooding, high sediment load), loss of plant access, and loss of offsite power backup (Tidwell 2021). Additionally, NRC identified 34 nuclear power plants at heightened risk of flood damage due to upstream dam failure. The size and frequency of flooding events has varied differently for locations across the country. Large parts of the Northeast and the Midwest have experienced larger floods, while the West, southern Appalachia, and northern Michigan have observed a decrease in the magnitude of floods. Flood frequency has increased in the Northeast, Pacific Northwest, and Midwest and has decreased in other parts of the country, particularly in the Southwest (EPA 2023c). Note that this is a dynamic situation as California and much of the Mountain West experienced the worst flooding in generations from the heavy snows and rain during the winter of 2022–2023.

Since 1985, summer surface water temperatures increased for 32 of the 34 lakes studied by the U.S. Environmental Protection Agency (EPA) in 2009 (Sharma 2015) with increases larger than 4°F in the lakes, which are the largest increases reported. Analysis, such as those conducted by the EPA, are needed to observe temperature changes in water sources for existing nuclear power plants, determine existing trends, and design plans to respond, when needed.

Despite the variations in magnitude, frequency, and duration of extreme weather events, the U.S. nuclear industry has responded effectively to safety and environmental damage threats. This is partially due to detailed emergency response plans (ERP) designed to protect employees and the communities they serve (NEI 2016). The NRC and Federal Emergency Management Agency (FEMA) set guidelines and requirements for the development of the ERP, and nuclear plants have operated during multiple hurricanes, floods, snowstorms, and heatwaves (NEI 2018). During these events, most nuclear plants have operated at full capacity, some at reduced operation, and a small percentage at a temporarily stopped operations status due to safety concerns (NEI 2018). However, the 2022 report by Intergovernmental Panel on Climate Change (IPCC) states climate change will continue to disrupt energy systems, water security and availability, and other critical infrastructure, and it is anticipated that such impacts will continue to intensify (IPCC 2023). Analysis is needed to provide continued support to escalating scenarios of climate change for the U.S. nuclear industry to continue to be successful.

Water-related issues not only impact operations at existing power plants, as noted above, but also constrain opportunities for siting new thermoelectric power plants. The availability of a reliable source of water has been an increasing issue in the permitting of new thermoelectric power plants. Resource constraints include both the physical availability of water as well as the institutional availability as defined by water rights, administrative controls, or environmental limits. To aid in understanding where water supply could be an issue in plant siting, Tidwell et al. (2016) mapped the availability of water for both potable (surface and groundwater) and non-potable sources for over 3,000 watersheds in the continental U.S.

4. EVOLVING POLICY RISKS AND CHALLENGES

Industry stakeholder feedback cites the inability to keep up with changing regulations, particularly given the lengthy regulatory process and fluidity of requirements. While not unique to the commercial nuclear power fleet, as most of the U.S. infrastructure was built before the passage of the Clean Water Act (CWA) and other prominent environmental laws, these requirements are integrated into the NRC licensing requirements, which adds to the complexity. The 2015 report by the World Nuclear Association, “Licensing and Project Development of New Nuclear Plants,” states that the complexity arises from incorporating non-nuclear permits and requirements into the NRC licensing process. This complexity also extends to relicensing and licensing amendments as well as non-nuclear permits needed for water supply and discharge.

As an example, the Central Coast Water Board, as authorized by EPA for the state of California, issued the National Pollutant Discharge Elimination System (NPDES) for Diablo Canyon Power Plant in 1990 with a permit expiration of 1995. Since Diablo Canyon Power Plant was expected to shut down, the renewal process was not executed and was allowed to expire but since has been administratively extended. Following the NRC’s relicensing of Diablo Canyon Power Plant, the Central Coast Water Board plans to reissue an updated permit with updated requirements for once-through cooling and desalination intakes and discharges with the possibility of increased interim mitigation fees (California Natural Resources Agency 2023). The requests for more information and data are expected to be extensive and ongoing between the local utility and Central Coast Water Board. In 2021, PG&E reached a $5.9 million settlement to resolve alleged NPDES violations of once-through cooling water and associated thermal loads at Diablo Canyon Power Plant.

The following sub-sections provide a brief overview of some of the key evolving policy risks and challenges facing the U.S. commercial nuclear fleet. A detailed discussion of the revised definition of “Waters of the United States” was included in the previous report and while it continues to be an evolving statute it is not discussed further in this report other than noting it will continue to influence interpretation of regulations. Additionally, absent a federal climate change statute, there are federal mandates to reduce GHG emissions from the power industry and authority of EPA to regulate GHGs within the Clean Air Act. Additionally, cooling may be regulated due to emissions to the air depending on the system type which can provide direct contact between cooling water and the air passing through. The interface of water and air is outside of this report but further analysis is needed to understand the impact of the Clean Air act for cooling emissions as well as how climate emissions are being applied.

4.1 National Environmental Policy Act

The National Environmental Policy Act (NEPA) requires federal agencies to assess the environmental effects of their proposed actions prior to making decisions. Many federal agencies have developed tailored NEPA procedures to supplement NEPA requirements; specifically, the NRC complies with NEPA through its adherence to 10 CFR Part 51. The NRC conducts NEPA reviews for new licenses, license renewals, license amendments, and for exemptions and rulemaking. This review can involve one of three levels of analysis, depending on the significance of an action on the environment, including an environmental assessment (EA), environmental impact statement (EIS), or categorical exclusion. To qualify for a categorical exclusion, an action must not individually or cumulatively have a significant effect on the human environment. Additionally, the NRC has prepared generic NEPA analyses that document the environmental impacts of specific regulatory activities called generic impact statements (GEIS). The NRC has developed GEISs for (1) license renewal, (2) license decommissioning, (3) continued storage of spent nuclear fuel, (4) in situ leach uranium milling, and (5) license termination. Other proposals for GEISs that have been submitted include an Advanced Nuclear Reactor Generic Environmental Impact Statement on December 14, 2021. Additionally, a rulemaking to amend and clarify the categories of actions that do not require preparation of an EA or EIS was submitted November 30, 2020, with an anticipated ruling in January 2025 (NRC 2021).

In the early 1990s, when many plants were faced with relicensing, the NRC adopted the License Renewal GEIS for relicensing individual commercial nuclear power plants. In this process, the NRC lumped issues and impacts into “generic” determinations having considered 92 impact areas. Of the 69 Category 1 issues, ten directly related to surface water, four directly related to groundwater, and eight related to terrestrial and aquatic impacts from cooling tower systems. However, on February 24, 2022, the NRC issued new orders and the following staff requirements in “Rulemaking Plan for Renewing Power Plant Operating Licenses—Environmental Review.” These orders state renewed licenses will not be able to rely on the 2013 GEIS but must rely on the updated version, citing insufficient evaluations of Category 1 impacts. These additional requirements will likely delay the already lengthy process outlined in Figure 3.

The initial application process starts with an application for relicensing, followed by a notice of intent, scoping process, environmental site audit, request for additional information, draft supplemental GEIS, and a final supplemental to the GEIS. The License Renewal GEIS references plant equipment refurbishments for continual operation but does not include a retrofit scenario, which may need to be considered for design changes that could result from technology changes of going from a once-through to a recirculating loop or changes to the sources of intake water. Additionally, the NRC considers the impact of cooling systems (including potential impacts on water quality and aquatic ecology) in the environmental statements associated with the issuance of construction permits and operating licenses. However, once a plant is operating, the continuing regulation of nonradiological impacts on water quality and aquatic ecology is primarily the responsibility of EPA and the applicable state permitting agency.

The final, supplemental environmental impact statement (SEIS) that is prepared for each individual power plant tiers to the License Renewal GEIS and provides NRC’s staff analysis that considers and weighs the environmental impacts of relicensing the plant.

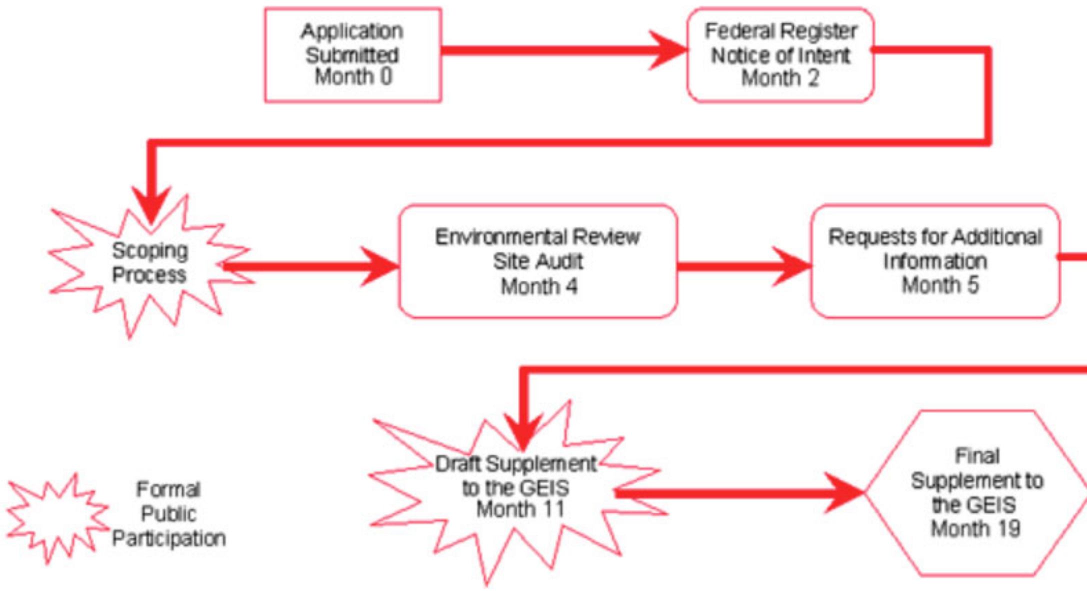

Figure 3. NRC licensing application process.

Figure 4 shows the involvement of cooperating agencies in the draft SEIS processes. Cooperating agencies are any agency other than the NRC with the jurisdiction by law or a special expertise with respect to any environmental impact involved in an action significantly affecting the quality of the human environment. By agreement with the Commission, a state or local agency of similar qualifications or a Native American tribe (when the effects are on a reservation) may become a cooperating agency.

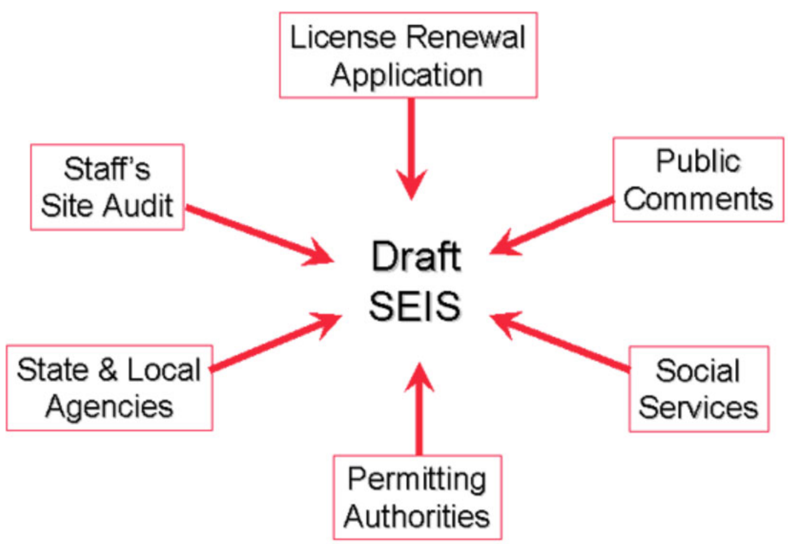

Figure 4. Cooperating agency participation in the SEIS draft.

The recently passed Bipartisan Infrastructure Law (BIL) provides generational investment to upgrade national infrastructure with a commitment to "timely and sound delivery" (White House 2022). Along with the BIL, the Permitting Action Plan recommends elements for strengthening the federal approach to environmental reviews and permitting, including: (1) accelerating permitting through early cross-agency coordination to appropriately scope reviews, reduce bottlenecks, and use the expertise of sector-specific teams; (2) establishing clear timeline goals and tracking key project information to improve transparency and accountability, which provides increased certainty for project sponsors and the public; (3) engaging in early and meaningful outreach and communication with tribal nations, states, territories, and local communities; (4) improving agency responsiveness, technical assistance, and support to navigate the environmental review and permitting process effectively and efficiently; and (5) adequately resourcing agencies and using the environmental review process to improve environmental and community outcomes. While these recommendations encompass all infrastructure, efforts to streamline regulatory processes need to be considered where efficiency and flexibility in administrative and regulatory processes could improve the adaptability of the commercial nuclear fleet to water-energy issues.

Extending beyond, the 2023 report “Recommendations to Improve the Nuclear Regulatory Commission Reactor Licensing and Approval Process” by the Idaho National Laboratory states “the U.S. benefits from having an agency such as the NRC, which is viewed internationally as the leader in nuclear safety licensing and regulation. Nonetheless, while acknowledging the important nuclear safety role provided by the NRC, it is apparent that one of the most significant time and resource intensive activities for developers of new nuclear systems, including advanced nuclear reactors, is the NRC licensing process.” The report provides recommendations for the reforms to 1) streamline NRC hearings 2) expedite NRC safety, 3) otherwise improve NRC licensing, and 4) provide financial benefits to new reactor projects.

Additionally, 2023 publication from the National Academy of Science, “Laying the Foundation for New and Advanced Nuclear Reactors in the U.S.,” provides many recommendations for advancing beyond the current commercial nuclear fleet. One recommendation is to adjust regulatory requirements to accommodate differences from the current commercial nuclear fleet while maintaining the commitment to safety, making the processes as efficient and effective as possible for advanced reactors to be commercialized in the next decade.

4.2 Clean Water Act

Discharges from thermoelectric power plants are regulated under the CWA and any wastewater discharge into surface water bodies must obtain an NPDES permit, which is issued by EPA or a designated state water quality agency. The NPDES permit specifies the standards and monitoring requirements that the facility must achieve for each point of discharge. NPDES permits must be renewed every 5 years, and during the renewal process, the plant must certify that no changes have been made to the facility that would alter aquatic impacts and no significant adverse impacts on aquatic resources have been observed.

Broadly, power plants can comply with CWA regulations regarding increased water temperatures by power curtailments, plant shutdowns, and the granting of a thermal variance. Allowable variances are granted by the state or the EPA branch that has authority over NPDES permits. Variances are only available through a Water Quality Standard variance or 316(a) variance implemented through issuance or modification of NPDES permits. For nuclear power plants, the NRC must be informed of the variance and ensure the plant is still operating within safety limits.

The CWA gives states, tribes, and authorized territories the flexibility to “waive” water quality standards under certain circumstances. The most common exemption is “mixing zones,” which exempt certain portions of a water body from meeting applicable designated uses and water quality criteria typically downstream of point source discharges. A mixing zone is an allocated impact zone where water quality criteria can be exceeded as long as acutely toxic conditions are prevented. Subject to EPA approval, states can implement zones with varying applications but are generally prohibited in effluent-dominated streams.

Mixing zone requirements must be met during the low flow conditions. Other factors that could affect the allowance or size of a mixing zone are critical habitat, municipal water intakes, and overlapping mixing zones. Figure 5 shows an example of a mixing zone for acute and chronic aquatic life criteria.

Improved sensors and advanced monitoring have the potential to improve the mixing zone capability. Additionally, combining mixing zones with advanced wastewater treatment technologies that target specific constituents could be a means to make discharges more efficient without unnecessary overdesign while minimizing environmental impact. In general, the discharge structures are jet or diffuser outfall types designed to promote rapid mixing with the receiving body of water. Biocides and other chemicals used for corrosion control and for other water treatment purposes are mixed with the condenser cooling water and discharged from the system.

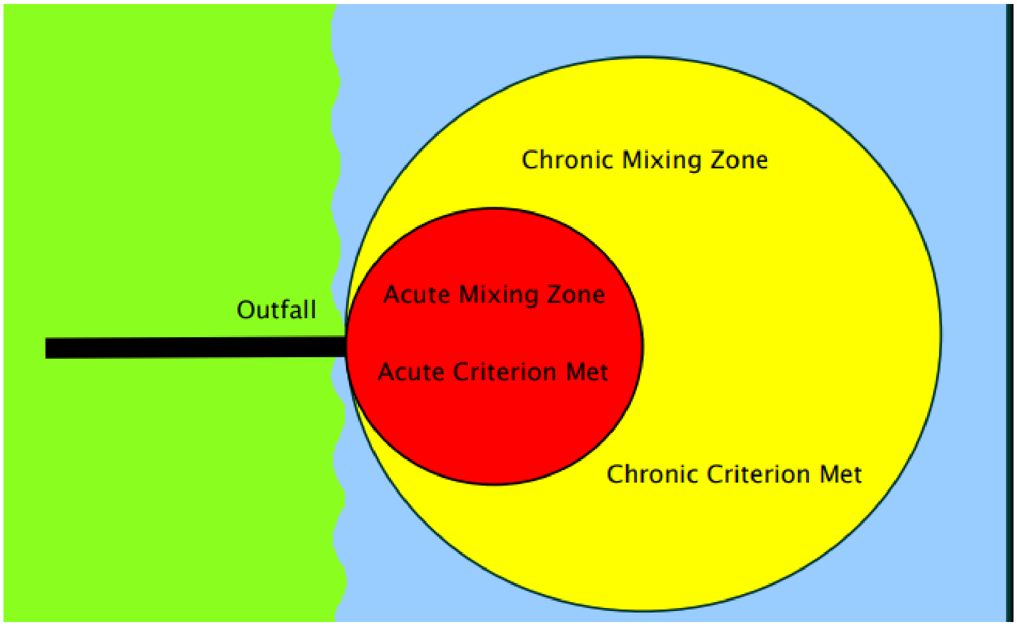

Figure 5. Mixing zones. Source EPA handbook (EPA 2014).

Like the NPDES permit, the 316(a) variance must be renewed every five years, and the applicant must provide evidence to the permitting agency as to why the variance is still appropriate. A 316(a) determination is not necessary for those power plants that are able to meet the state water temperature standard, but a biological assessment may be required to ensure that the mixing zone meets water quality standards. Variances for thermal discharge limits are not currently publicly available in a centralized location. Most of these data can be found in individual state environmental registers, but a month-by-month data analysis is still required to find which variances were granted.

Section 316(b) of the CWA requires that “the location, design, construction, and capacity of cooling water intake structures reflect the best technology available for minimizing adverse environmental impact.” Like NPDES permits and 316(a) determinations, 316(b) determinations are made by EPA or a state permitting agency based on data supplied in the applicant’s 316(b) demonstration. While 316(b) determinations are usually one-time judgments that are not periodically reconsidered, a determination under CWA Section 316(b) is not permanently binding. When circumstances have changed (e.g., fish population has changed, the initial determination was deemed inappropriate, or some adjustment in the operation of the intake structure is warranted), a full 316(b) demonstration could again be required by EPA during the license period.

The 316(a) and (b) demonstrations provide the permitting agency with a method for considering cooling system effects on aquatic biota, not just on water quality as other federal agencies that do not issue permits who are consulted in the development of NPDES permits and Section 316 determinations.

Stakeholders provided mixed feedback on the increased growth of algae, scaling, and corrosion in cooling towers requiring the need for additional chemicals. The limited set of participants did not allow for the extent to be evaluated. Regardless, these issues have the potential to become environmental compliance concerns, which are tracked by the EPA ECHO database, an online compilation of enforcement and compliance issues corresponding to NPDES permits. The database was searched for the North American Industry Classification System (NAICS) code 221113, which corresponds to Nuclear Electric Power Generation. Figure 6 illustrates the results. In the search, nine facilities were identified with current violations, 16 facilities were identified with violations in the last 3 years, and nine facilities were identified with informal enforcement actions. The most common issue was exceedance of total residual oxidant discharge time, which corresponds to chemicals used to meet discharge standards.

Figure 6. Nuclear-generating plants with NPDES noncompliance 2020–2023.

4.3 Safe Drinking Water Act

Emerging contaminants, such as the specific class of chemicals known as the per- and polyfluoroalkyl substances (PFAS), may be of significance to nuclear power plants. Under the Safe Drinking Water Act (SDWA), EPA has the authority to set enforceable National Primary Drinking Water Regulations for drinking water contaminants. Plant safety necessitates fire protection regulations that often involve use of firefighting suppressants such as aqueous film-forming foams that contain PFAS. Discharge of these foams, even in training operations, is of concern as PFAS are highly mobile if allowed to reach the environment. The NRC has a defense-in-depth concept of protecting the health and safety of the public from fires at nuclear power plants as described in 10 CFR 50.48, regulatory guide “Risk-Informed Performance-Based Fire Protection for existing Light-Water Nuclear Power Plants” and National Fire Protection Association (NFPA) 806 “Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants”.

In our brief review, AFFF was mentioned in Ginna Nuclear Power Plant Fire Protection Program, Revision 17, given a license amendment request associated with the implementation of NFPA 805 on June 25, 2018 (NRC, 2018). The American Nuclear Society published a 2022 article, "The Ubiquity of PFAS: An Emerging Issue in Decommissioning," that described PFAS complicating nuclear power plant decommissioning due to on-stie septic systems, landfills, and fire suppression activities. The article suggests increased sampling and analysis costs, potential remediation, and complications with mixed waste classifications. Figure 7 shows PFAS sampled and detected in selected drinking water systems across the U.S.

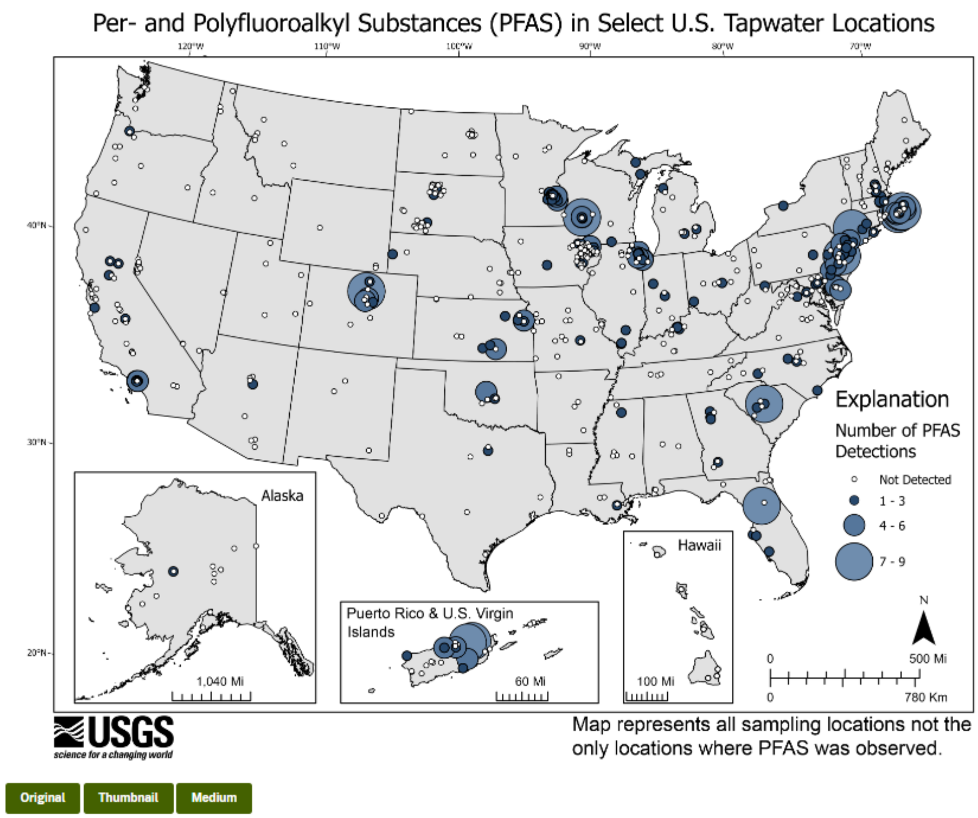

Figure 7. Detected PFAS in select U.S. tap water locations.

Stakeholders with onsite groundwater wells used for drinking water and/or firefighting operations expressed concern about upcoming regulation of these contaminants. Analysis is needed to understand the extend of AFFF and PFAS in the commercial nuclear power plants and the impact of both operation and decommissioning risks.

4.4 Water Management Challenges

Water management and decision making are shared between federal, tribal, state, and local governments, which creates complex management, coordination, and negotiation requirements among management agencies. The Department of Energy report, "Water-Energy Nexus: Challenges and Opportunities in 2014," describes how federal oversight of water is shared amongst 30 agencies in 10 different departments with federal funding mechanisms facing similar complexity (DOE 2014).

The U.S. also shares water management and resources with other nations. For example, the Columbia River basin includes Washington, Oregon, Idaho, Montana, Utah, Wyoming, and British Columbia. Negotiations are underway to modernize the Columbia River Treaty between the U.S. and Canada. The

U.S. entity consists of the Bonneville Power Administration (BPA) and the U.S. Army Corps of Engineers. The original treaty was implemented in 1964 to last 60 years and did not include current flood management risk, reliable and economical power concerns, or ecological constraints.

The Columbia Nuclear Generating Station, located ten miles north of Richland, Washington, is the only commercial nuclear energy facility in the Northwest. The plant provides electricity at cost to the BPA under a formal net billing agreement, and they can load follow at the request of BPA for grid stability, hydroelectric system management, and wind and economic considerations. There is growing interest in modeling, understanding, and eventually coordinating hydroelectric power with thermoelectric power, especially in response to climate-induced water stress.

Additionally, the U.S. and Mexico share multiple rivers across their border, most notably, the Colorado River and Rio Grande, which are pursuant to binational agreements. The international Boundary and Water Commission, as designated by a 1944 treaty, is charged with addressing issues and new developments that arise. Per the agreement, the U.S. must provide water to Mexico via the Colorado River, and Mexico must provide water to the U.S. via the Rio Grande. These allocations are calculated over a five-year cycle. Most recently, issues arose concerning the delivery of water to the U.S. as Mexico experienced extreme drought, rapid population growth, and poor water allocation planning.

The Colorado River Compact, signed in 1922, was developed to aid development of the western U.S. The compact was a means to divide Colorado River water between the seven states in the Colorado River Basin which allowed for federal investment in water infrastructure. At the time of the agreement, Native Americans were excluded from the agreement, and, despite a 1960s U.S. Supreme Court clarification, many senior water rights held by tribes are going unfulfilled due to a variety of barriers.

4.5 Water Markets, Water Trading, Water Rights

Water markets and water trading have been discussed as a way to combat water scarcity and supply volatility. Broadly, water markets and water trading are transactions to buy, sell, or lease a water right (entitlements) either in whole or in part. These transactions involve a willing buyer and a willing seller. Historically, these transactions have been local and informal and held within limited and often individual or one-off groups. Economists have theorized that water markets could be used to allocate water in an economically productive manner when water rights are freely traded between end users in a water market situation where the market price of water reflects the resource demand and supply with differences among regions and types of rights. In this situation, the market mechanism of water trades promotes water allocation to higher value uses, encouraging efficiency gains and promoting water conservation (Debaere 2020).

In the U.S., multiple institutional barriers exist that inhibit national-scale water markets and water trading, including state-specific water rights and non-existent or cumbersome administrative processes. Additionally, unlike land rights that have fixed boundaries, water flows and is subject to losses such as evaporation and seepage. Water right policies among states vary from absolute ownership, riparian water rights (i.e., no limit to amount of water withdrawn), to prior appropriations doctrine (i.e., first in time, first in right). Unlike the appropriative rights in the western U.S., in times of water scarcity, users of riparian water rights share a diminished water availability mutually limiting the supply and demand mismatch. With most of the commercial nuclear fleet located within pure or regulated riparian water right states, the impact of water markets will likely influence the plants in the west before plants in the east.

Local markets have gained traction outside of the commercial nuclear industry, especially in the western U.S. These markets take various shapes and formulations. Figure 8 shows water trading occurring in every western U.S. state with more than 20 distinct regions, California having the most activity followed by Colorado.

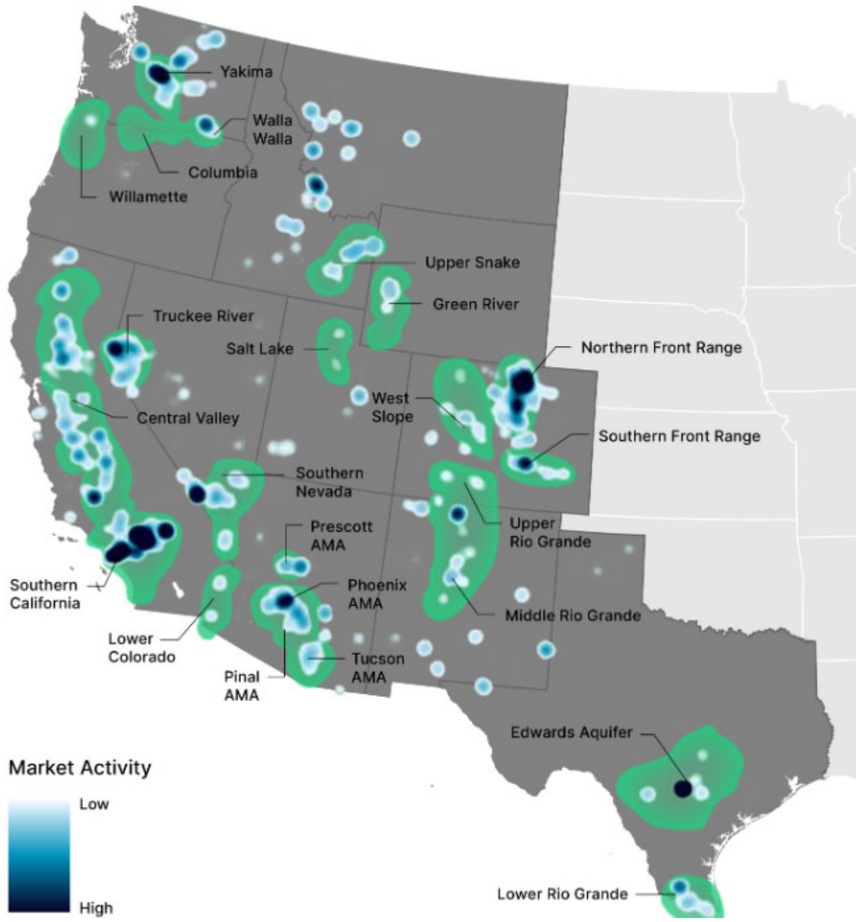

Figure 8. Water markets in the western U.S. Source: Nasdaq-Veles-water (Nasdaq 2023).

Most recently, Utah's 2020 Water Banking Act created a three-year pilot project exploring a water banking framework for the state. Additional grass root efforts are finding ways to fill emerging needs. For example, Western Water Market, LLC launched an independently owned online marketplace in 2020 as a formal way to connect water buyers and sellers.

Other means of valorizing water have come aboard, including spot markets and water indexes. Spot markets for water are local exchanges that occur for short durations between neighbors and may operate under different rules from water rights and trading markets. Alternatively, water indexes operate like the financial futures market. The Nasdaq Veles California Water Index (NQH2O) measures the volume-weighted average price of water in California's five most active surface water and groundwater market regions (Central Basin, Chino Basin, Main San Gabriel Basin, and the Mojave Basin). Compared to other commonly traded natural resources, the overall size of water markets is relatively small (Nasdaq 2023).

The retirement of thermoelectric power plants, and in many cases their associated water rights, could have a pronounced impact on water resources. Siddolk et al. states, "likely these water rights will be sold to support new urban development or other high-value uses. If the water rights of retired power plants are sold to downstream water users, the increase of instream flows between the power plant and new user can create co-benefits by improving ecosystem health along the way."

Using a coupled energy-water management model, Siddik et al. (2023) showed annual water withdrawals and consumption of fossil fuel-fired power generators will be significantly curtailed (85% and 68% reduction, respectively) by 2035 if generators follow typical retirement timelines. Most rivers with fossil fuel-fired power plants diverting and/or discharging water will have a net increase in annual streamflow after plant retirement (maximum decrease of 2%, maximum increase of 57% by 2050), with the most pronounced increases occurring in the summer months. The retirement of fossil fuel-fired power plants will lead to a large relative change (>5%) in streamflow at least one month per year by 2050 in 31 subbasins." In general, where water is governed by riparian rights, these retirements simply mean more water in the river and less tension over availability of water—states with appropriative rights will realize new water for development as these retired rights can be sold to other new water users.

For any particular water right, the issues are fraught with detail and complication. Therefore, applying generalized statements from sector-level interpretation can be misleading. For example, Figure 9 shows the planned U.S. utility-scale electric generator retirements for 2023 by fuel source. In the figure, more than 2,200 MW of natural gas electricity generation is planned for retirement located in California, which has a dual system of water rights that recognizes both riparian and appropriative uses. As riparian rights are for the reasonable and beneficial use of water on land that is adjacent to a watercourse, these rights are not good candidates for transfer for environmental purposes even though they have priority over appropriative rights. Riparian rights attach to land and can be lost if a property's connection is severed through parcel development. Additionally, an owner, in general, cannot lose a riparian right through non-use and typically cannot transfer the right to another user. Historically, riparian water right holders were not required to obtain a permit for use, and reporting the actual use of water was limited. In 1914, California formally recognized the need for an administrative process to issue water right permits, licenses, and changes to already issued permits. Holders of pre-1914 appropriative rights have more flexibility in changing the purpose of use, place of use, and points of diversion than post-1914 holders. Finally, there are other less common types of water rights in California that are available for environmental transfer but are often attached to land and/or are subject to specific limitations that complicate the transfer ability (Trust for Public Land 2013). We searched the Electronic Water Rights Information Management System (eWRIMS) for San Luis Obispo County, California, revealing 1,421 records, one of which was owned by PG&E with a riparian date of 1968.

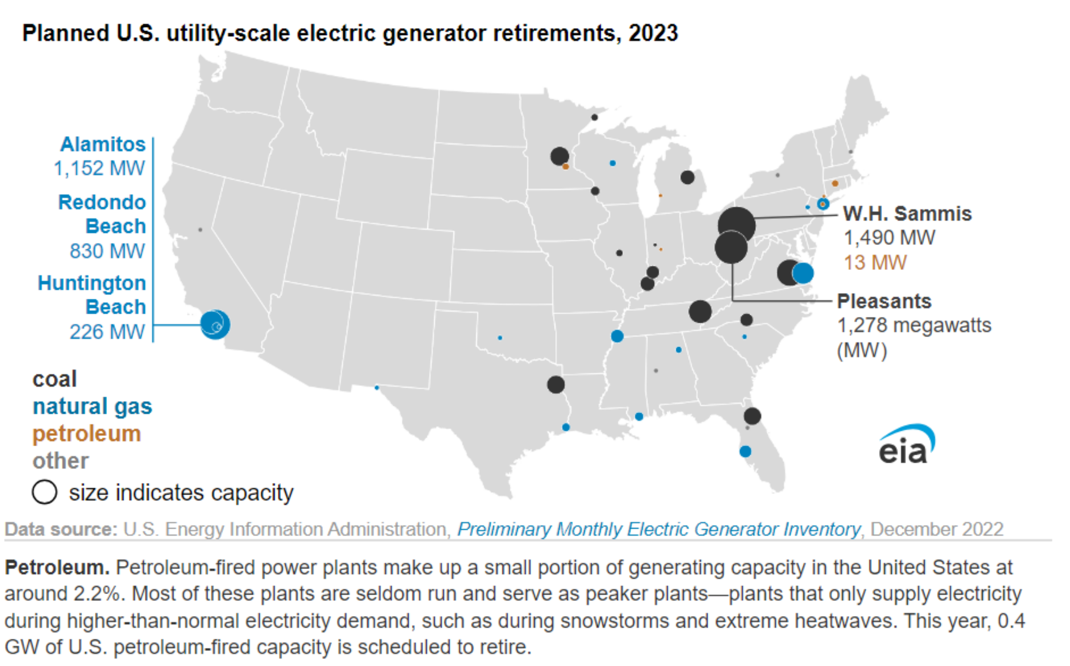

Figure 9. Planned U.S. utility-scale electric generator retirements in 2023.

4.6 Energy Grid and Water Interdependencies Supply Gap

Since 2018, more than fifteen states have passed legislation to increase or expand their renewable or clean energy targets; however, seven states have allowed their targets to expire. These renewable portfolio standards require that a specific percentage of electricity utilities sales are generated from renewable energy sources (NCSL 2021). The pathway to achieve net-zero carbon emissions by 2050 has provided an interesting paradigm for the energy-water nexus. The 2023 Department of Energy report, "The Pathway to: Advanced Nuclear Commercial Liftoff," suggests that the U.S. will need about 550–770 GW of additional clean capacity to reach net zero (DOE 2023). Additionally, Executive Order 14057, "Catalyzing Clean Energy Industries and Jobs Through Federal Sustainability," directs federal facilities to transition operations towards a focus on clean zero-emission technologies by increasing energy and water efficiency (White House 2021).

Mongrid et al. explored current energy-water interdependencies at the scale of the three primary electricity interconnections within the U.S.. Figure 10 compares the varying scale of water supply and discharge for nuclear cooling compared to other water uses and electrical generation within specific interconnections, including the Electric Reliability Council of Texas (ERCOT), the Eastern Interconnection, and the Western Interconnection (WECC) (Mongird 2023). This study extends beyond the 2014 Department of Energy report that showed national-scale energy and water connection, which is important because of the regionality associated with nuclear generation and the local characteristics that dictate discharge and cooling requirements. Of the three interconnections, the Eastern Interconnection has the most nuclear-related generation/water use, while the WECC and ERCOT show little nuclear generation.

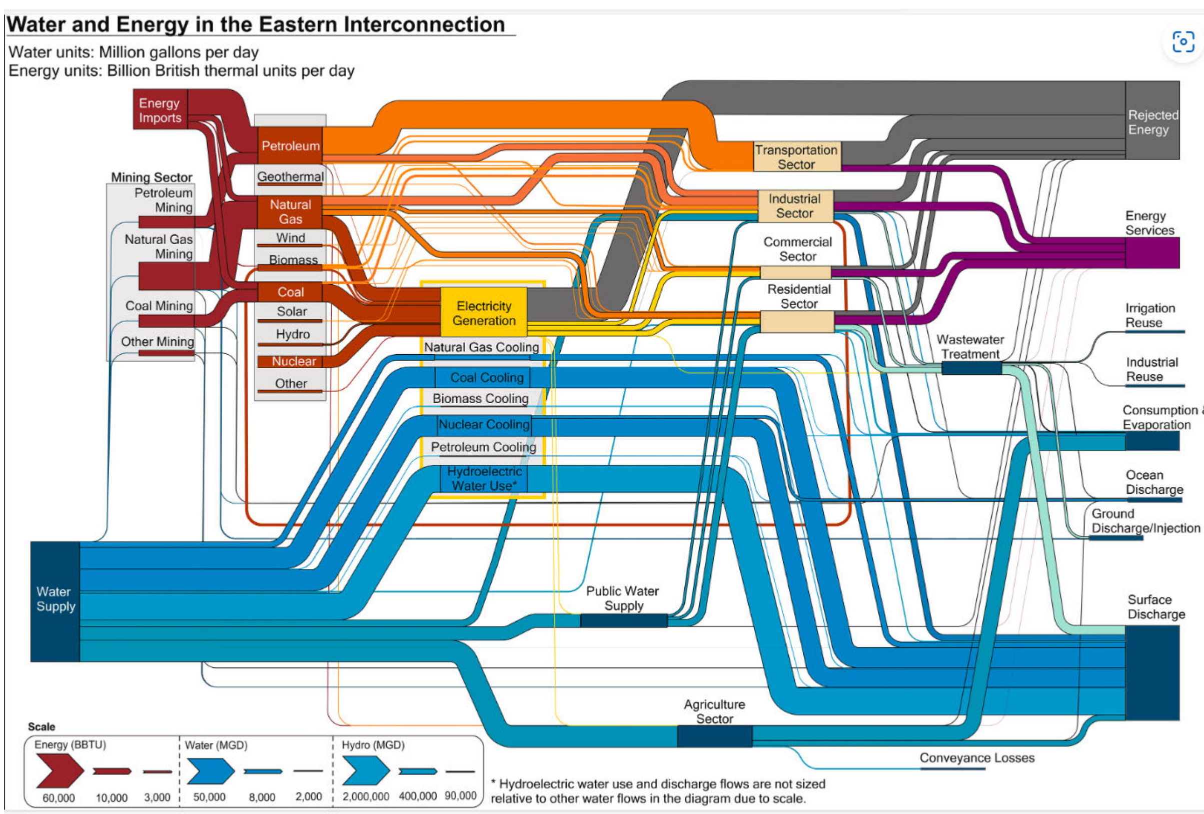

Figure 10. Energy-water interdependencies within the Eastern U.S. electrical interconnection.

Additionally, efforts have been made to project potential future electricity generation mixes, considering a variety of technological, economic, and political drivers. A recent study by Miara et al.

(2019) projected changes in the generation fleet to 2050 for each North American Electric Corporation (NERC) region. The study considered four different future scenarios: a business-as-usual, high renewables, high nuclear, and high coal. Carbon emissions and technology/fuel costs were the primary drivers of change. All cases, even the high nuclear, showed a slow decline in nuclear capacity and peak power production driven by cost as the primary reason for decline. Reductions in nuclear generation only slightly decreased when climate change was factored into the projection. More analysis is needed to understand the impact of water availability both physically and institutionally outside of climate factors.

Additionally, questions have been raised about energy demand and water demand changes due to population shifts. The following census data from the 2020 census was evaluated for county-level changes to population from 2010 to 2020. The total population of the U.S. on April 1, 2020, was 331.4 million, 7.4% larger than the population in the 2010 Census. The 7.4% increase was the lowest increase observed since 1930 (U.S. Census Bureau 2021). There are significant gaps in our understanding of city-scale impacts of population growth on electricity demand under a changing climate (Wang 2023). Increases in the efficiency of electric devices and appliances have partially offset the impact of population growth in U.S. energy consumption. However, it is estimated that the U.S. energy consumption will increase between 0% and 15% when compared to 2022 levels, and a 14–22% increase on purchased electricity is expected for the residential sector (EIA 2023). Population losses can also impact utilities' ability to provide water and energy by reducing revenue, a critical issue for small utilities. Figure 11 shows that counties with lower population are more likely to suffer population loss while large urban areas gain population.

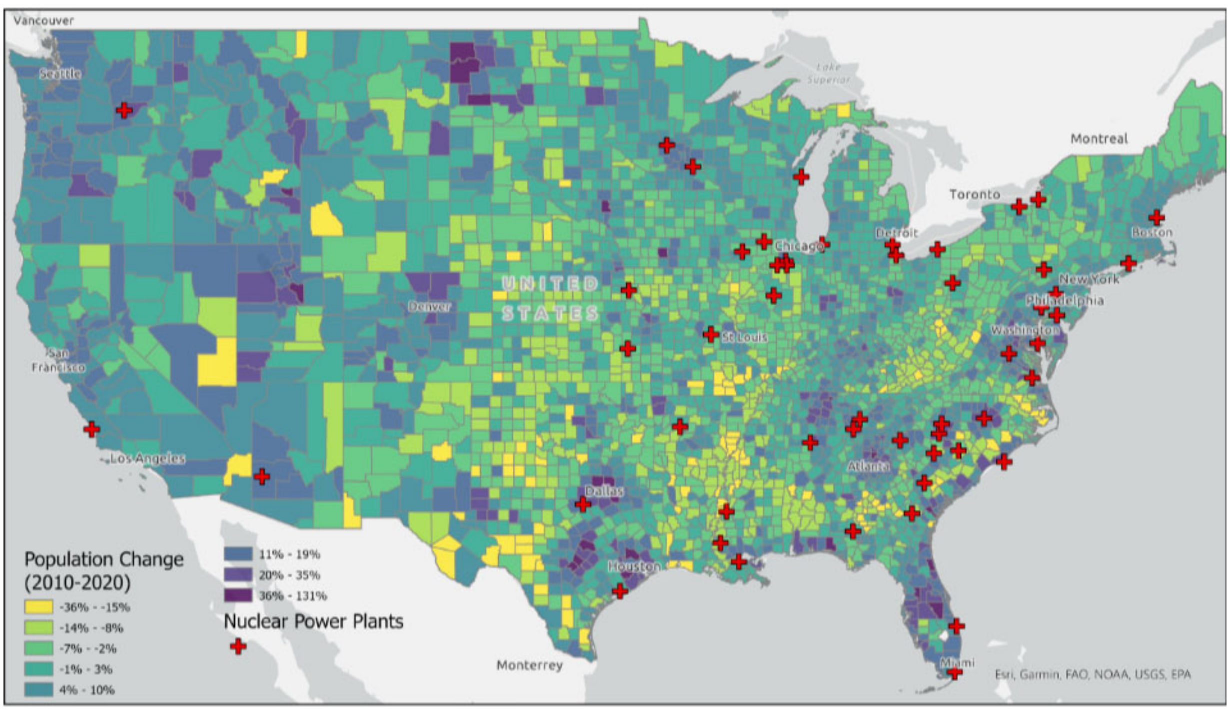

Figure 11. Population change 2010–2020 overlayed by current commercial nuclear fleet.

5. ENVIRONMENTAL ISSUES

Environmental challenges arise due to the limitations to discharge cooling water or the inability to obtain enough water for cooling. These limitations can be physical or institutional, as in the case of water management and priority water rights. Physical limitations can be caused by too little or too much water, such as during flooding or storm surge activities. Since the 2010 report, two topical areas, climate change and environmental justice, have risen in magnitudes of emphasis and concern. Section 4 discusses these topics in more detail.

5.1 Climate Change

Water-related extreme events have impacted thermoelectric power plant operations, as documented in Section 3 of this report. Climate change is expected to exacerbate operational challenges through increased air and water temperatures, more intense storms (e.g., flood and surge damage), and longer and more intense droughts. This evolving threat has been explored by a variety of studies at both national and international scales. The basis of the analyses are physical hydrology models coupled to models that simulate the thermal budget of individual power plants (i.e., simulate the discharge of heat to air and water). These models differ considerably in their representation of key hydraulic processes (e.g., river dynamics, grid resolution, thermal transport, mixing), the degree of coupling with electric grid operations, policy/regulation simulation, and representation of water and electricity infrastructure (e.g., number of power plants modeled and reservoirs and/or their operations). These simulations are forced by various climate projections (air temperatures and precipitation) and competing future electricity and water demands while calculating the resultant power production. Power production is reduced when stream flow is below plant cooling water demands, elevated condenser inlet temperatures lower thermal efficiencies and power output river temperatures, and/or CWA regulations on thermal pollution trigger curtailments.

5.1.1 Overview of Climatic Studies

In one of the earliest studies, Van Vliet et al. (2013) explored the vulnerability of thermoelectric power generation in Europe and in the U.S. to future climate change. The study found that 4–16% of the generation capacity in the U.S. could be lost by 2050. Considering only recirculating power plants in the western U.S., Bartos and Chester (2015) found that climate change could reduce generating capacity during the summer by an average of 1–3%, with reductions up to 7–9% under more extreme drought conditions. Miara et al. (2017) extended these studies by considering not only the vulnerabilities to individual plants but more broadly the implications to the broader regional electric grid, specifically, potential impacts to reserve margins. They found that earlier studies that failed to place climate-water impacts on individual plants in a broader power systems context overestimated system vulnerability. Liu et al. 2017 further considered operation optimization at a given plant, provisional variances approval, and co-management of power plants. When considering these factors, 2–3% of the usable capacity will be unavailable by 2060 due to the effects of climate change, while another 10–12% of the usable capacity will be unavailable if current environmental requirements are enforced without thermal variance waivers. Zhang et al. (2020) took the next step by investigating how river regulation (including water withdrawal and reservoir operation) might affect electricity generation potential in the U.S. within the context of climate change. They found that through river impoundment for flood control and water supply, river regulation reduces stream temperature warming rates and improves cooling water availability by changing flow seasonality and enhancing summer low flows. Specifically, they found that stream temperature decreases and water availability improvement by water management can offset reductions in thermoelectricity generation caused by climate warming. Finally, it is important to consider that many power plants considered in these studies are likely to be retired by the 2060s as the current U.S. energy system is gradually transitioning from a fossil fuel-dominated portfolio to one with a sizeable fraction of renewable generation. Together, the results of these studies demonstrate the complexity of climate assessments of individual power plants and of the broader grid and indicate the need to consider many competing factors in such assessments.

5.1.2 Analysis of Relative Climatic Threat to Individual Plants

The studies described in Section 4.1.1 largely fail to report potential climate change impacts for individual nuclear power plants in the U.S. As evidenced above, a comprehensive assessment would require considerable effort. Rather, a data-driven approach is taken to explore the changes on climate and their potential impact on nuclear power assets in the U.S. using both current and projected (future) climate conditions (Section 4.1.2.1). Additionally, in Section 4.1.2.2, data resulting from model simulations aiming at assessing the impact of future climate conditions on power plants' generation capacity are analyzed.

5.1.2.1 Current and Future Climate Conditions Risks

Risks of climate conditions on the current nuclear fleet were initially considered. Figure 14 shows the number of nuclear power plants and county-level risk for a set of extreme events that can impact nuclear power plant operations. County-level risk was obtained from the FEMA National Risk Index, and power plant location was obtained from EIA (EIA 2022a). The National Risk Index is defined as the potential for negative impacts resulting from a natural hazard, and it is calculated considering (1) the risk of a natural hazard, (2) a consequence-enhancing component, and (3) a consequence-reducing component (FIMA 2023). Figure 13 shows the drought risk overlayed by the location of the current nuclear reactors. A limitation of this analysis is that risk level was observed at the county level (FEMA 2023), considering only the county where the plant is located. This can be a problem as water supply is often provisioned from watersheds that are a considerable distance from the plant.

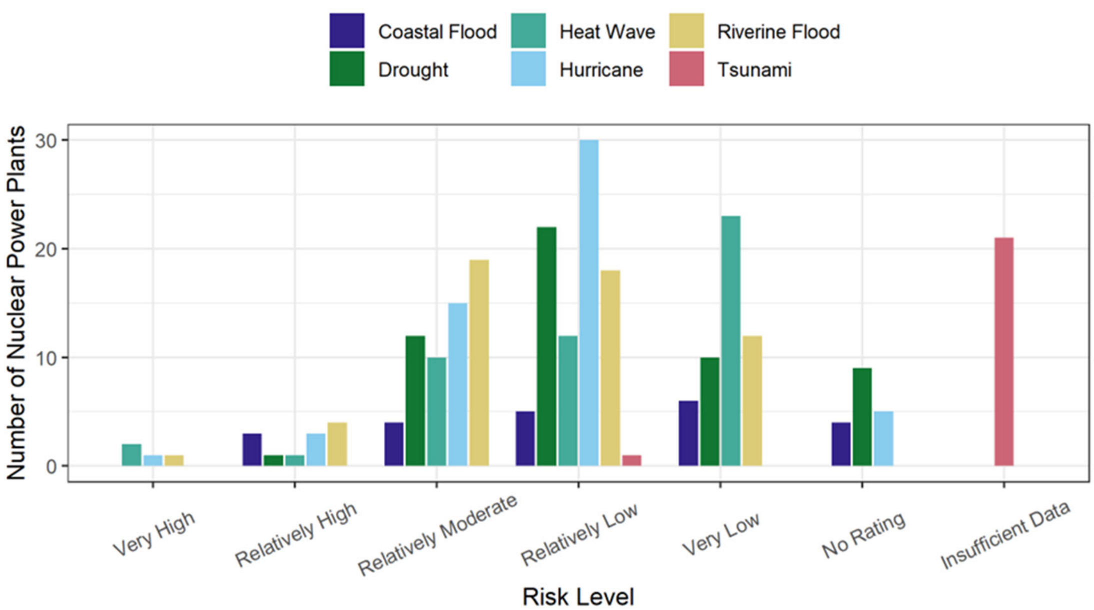

Figure 12. Relative risk of climate-related events at U.S. nuclear power plants.

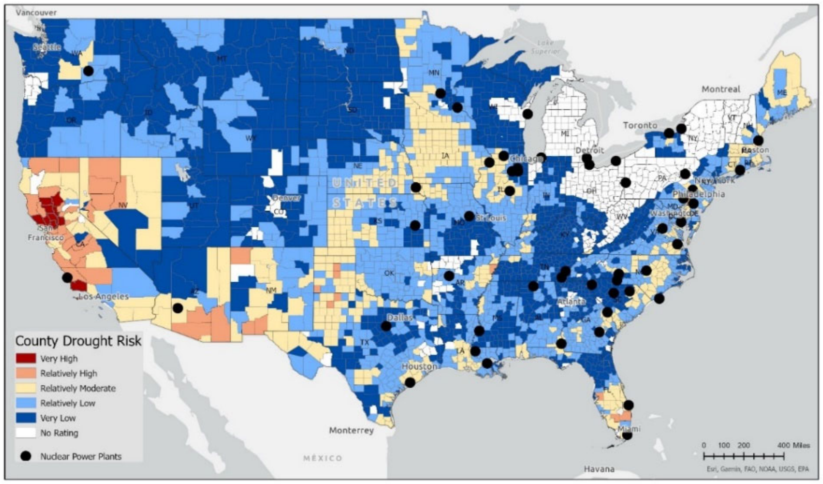

Figure 13. County-level drought risk index and operating nuclear power plant location.

Climatic risk to individual nuclear power plants due to projected future climate conditions was considered for both water scarcity and flood conditions. To do this, we draw from a global resource, Aqueduct from the World Resources Institute (WRI), which is a data platform comprised of tools that help companies, governments, and society respond to water issues like water stress, availability, seasonal variability, pollution, and water access. The 2017 report from WRI titled, “No Water, No Power,” illustrates potential future global water stress as projected from the Aqueduct platform. Figure 14 shows the baseline water stress for nuclear power plants by cooling type under current climatic conditions.

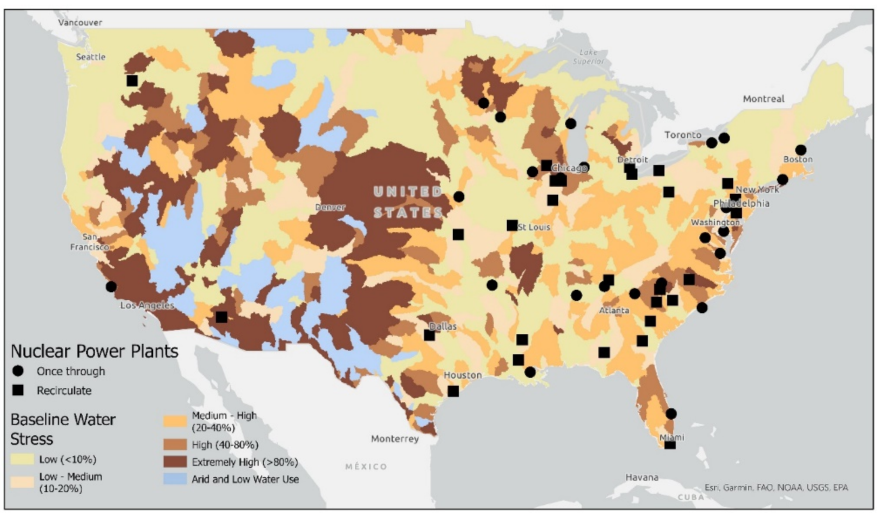

Figure 14. Baseline Water Stress in the U.S. with nuclear power plant location by cooling type (35).

Using Aqueduct water stress global data, we analyzed the risk level for the subbasins where nuclear power plants are located. Aqueduct water stress is calculated considering water use and water supply using HydroBASINS Level 6 hydrological subbasins, which has a median area per subbasin of approximately 2,053 mi^2 (Kuzma et al. 2023). These GCM data are temporally aggregated by three future time periods, 2030 (2015–2045), 2050 (2035–2065), and 2080 (2065–2095), and by a baseline, 2014 (1960–2014), consisting of historic data. Additionally, three scenarios, (1) optimistic (shared socioeconomic pathways [SSP] 1 RCP 2.6), (2) pessimistic (SSP 5 RCP 8.5), and (3) business-as-usual (SSP 3 RCP 7.0), are considered for each future period. The SSPs represent changes in population, economic growth, education, urbanization, and the rate of technological development that would affect future greenhouse gas emissions, providing a storyline of how we could reach certain levels of warming. SSPs are closely tied to the representative concentration pathways (RCPs). Further information about modern climate models and the associated numbers are discussed in depth by USDA and are outside the scope of this report. Aqueduct uses the median value across five GCMs (GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1–2-HR, MRI-ESM2-0, and UKESM1-0-LL) as the default representation for each scenario, and these were the values analyzed to generate Table 3 and Figure 15.

Table 3. Water stress risk level for operating nuclear power plants for three periods (2030, 2050, and 2080) under three future scenarios (business-as-usual SSP 3 RCP 7.0, optimistic SSP 1 RCP 2.6, and pessimistic SSP 5 RCP 8.5).

Water stress risk level	Baseline	2030			2050			2080		
		opt[1]	bau[2]	pes[3]	opt	bau	pes	opt	bau	pes
Extremely high (>80%)	3	4	4	6	11	5	7	11	4	11
High (40-80%)	9	13	10	11	7	10	13	12	9	13
Medium-high (20-40%)	9	10	11	9	10	12	7	6	13	6
Low-medium (10-20%)	8	8	8	8	8	7	8	5	7	10
Low (<10%)	25	19	21	20	18	20	19	20	21	14

[1] opt: optimistic SSP 1 RCP 2.6
[2] bau: business-as-usual SSP 3 RCP 7.0
[3] pes: pessimistic SSP 5 RCP 8.5

Data for the 2030 scenario show an increase in the number of nuclear power plants that are subject to extremely high, high, and medium water stress levels for all scenarios considered. Figure 15 shows that when analyzing water stress for individual nuclear power plants, multiple combinations are possible. For example, LaSalle Generating Station has a high water-stress level under the baseline scenario (under current climate conditions), and it is expected that it will change to a low-medium stress level for the 2030 period in all three scenarios considered. In contrast, Surry Power Station and Catawba Nuclear Stations water stress levels are expected to increase from low-medium (baseline) to extremely high in all scenarios considered. Further research is needed to evaluate the drivers of the water stress changes and identify the impacts on specific nuclear power plants.

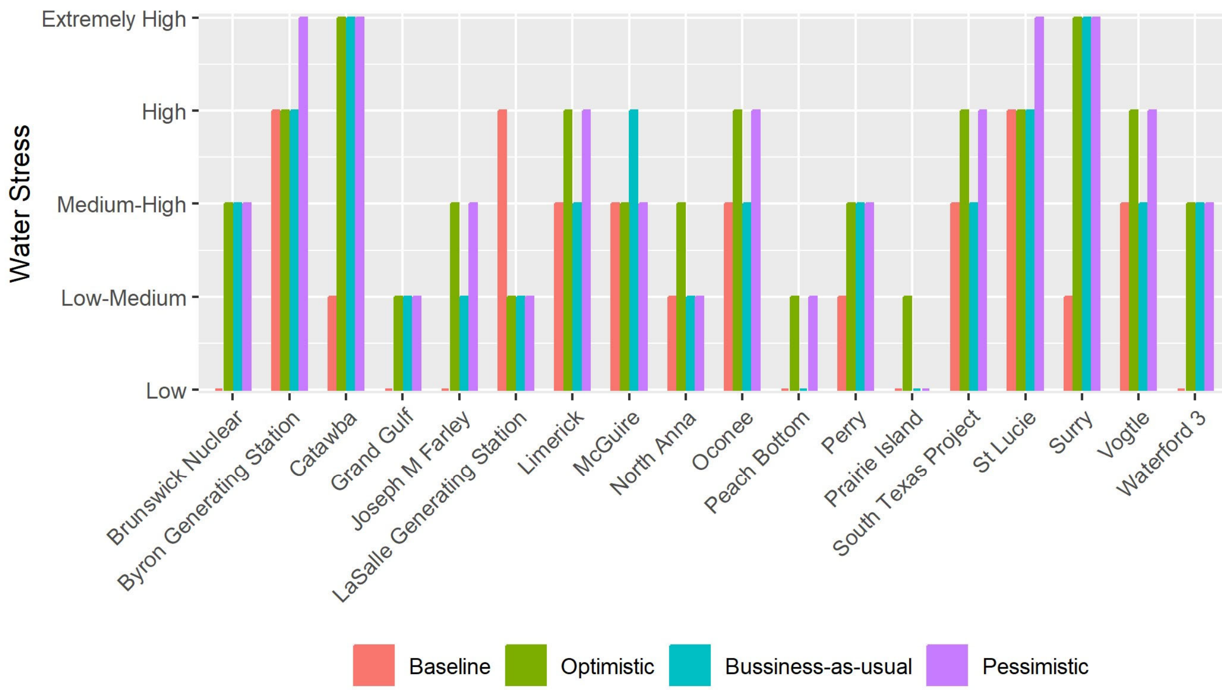

Figure 15. Baseline and 2030 water stress under three scenarios (business-as-usual SSP 3 RCP 7.0, optimistic SSP 1 RCP 2.6, and pessimistic SSP 5 RCP 8.5) for nuclear power plants located in basins with expected change in water stress level.

Aqueduct Floods hazard maps (Ward et al 2020), a data product that includes inundation depth for riverine floods, was used to evaluate changes in flood at the location of the currently operating nuclear power plants. Aqueduct Floods includes current baseline and future projections in 2030, 2050, and 2080 for flood, from five different GCMs (NorESM1-M, GFDL_ESM2M, HadGEM2-ES, IPSL-CM5A-LR, and MIROC-ESM-CHEM) and two RCPs, RCP 4.5 and RCP 8.5. Figure 16 shows the most variations in flood depth across the tree return periods shown (5, 250, and 1,000 years) are within a 1-ft range. Dresden Generating Station experiences an increase in inundation depth for the 5-year time of return and a decrease for larger times of return. Beaver Valley and Cooper Nuclear Station experience changes of different magnitude (decrease and increase) for the scenarios considered. The variation in inundation depth observed in the models indicates flood events will vary across different future scenarios. NRC guidance for design-basis floods for nuclear power plants considers multiple flooding mechanisms (e.g., precipitation, dam failure, intense precipitation, storm surge) and recognizes the challenges and limitations associated with probabilistic methods for flood estimations (NRC 2022).

Flood evaluations for nuclear power plants should include a range of floods instead of a single large event. Analysis of the impact of variations in flood magnitude for nuclear plants must be individually analyzed. The design of specific flood protection features or structures, and equipment for flood mitigation can only be considered on specific analysis for each power plant.

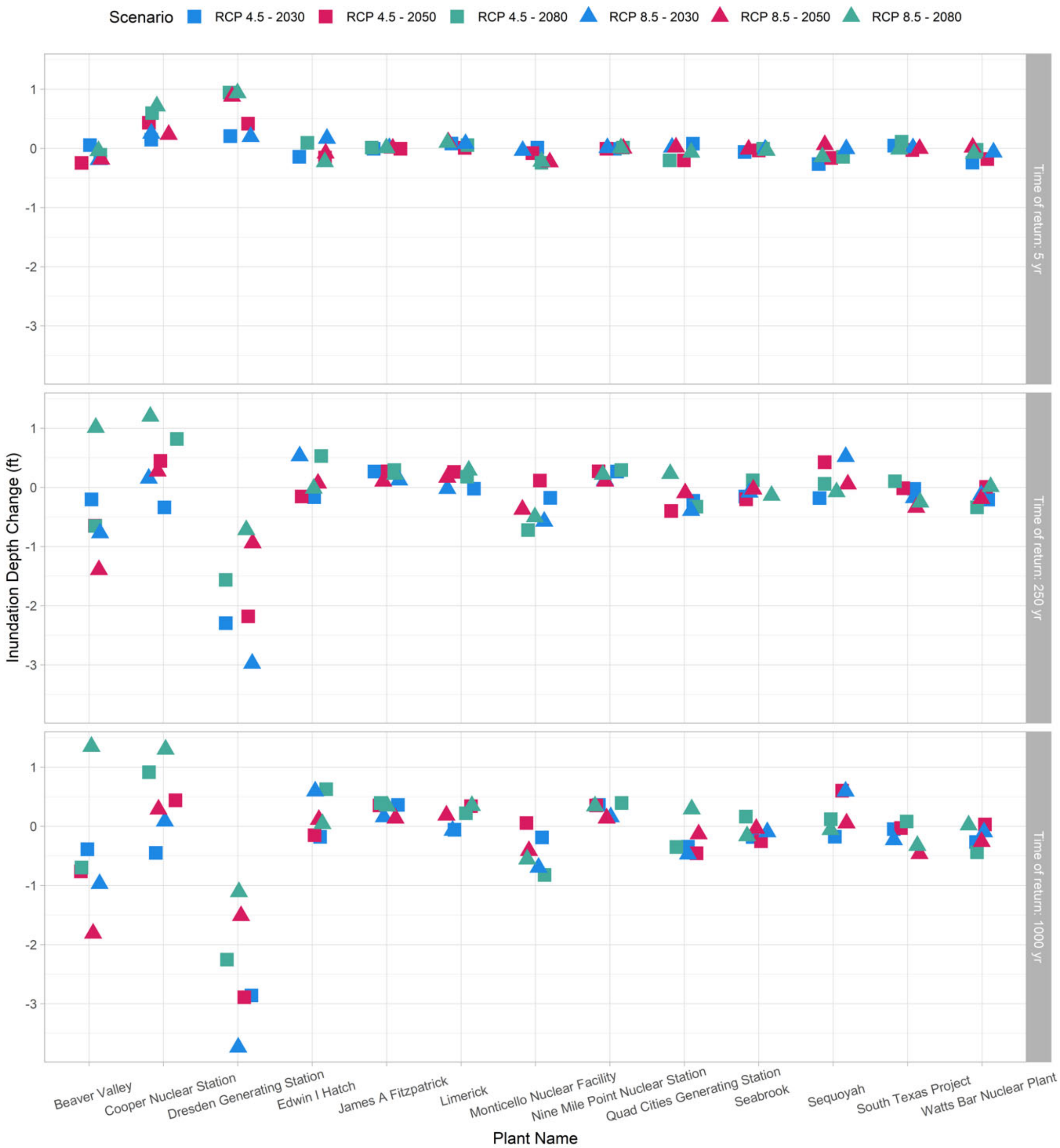

Figure 16. Median inundation depth change (ft) across five GCMs (NorESM1-M, GFDL_ESM2M, HadGEM2-ES, IPSL-CM5A-LR, and MIROC-ESM-CHEM) for three different return periods (5, 250 and 1,000 years). Inundation depth change is calculated by subtracting the inundation depth expected under each scenario (RCP 4.5 and RCP 8.5) from the baseline inundation depth for the same time of return. Points positioned on the x-axis are slightly randomized to prevent overlapping. The figure only shows plants (13) where changes are observed. No changes were observed for 31 plants. Data for 10 plants are missing. Data source: (Ward 2020).

5.1.2.2 Potential Climate Impacts on Nuclear Energy Generation

Moving beyond climate data-driven analysis (as above), we turn our attention to model simulation results of potential climate impacts on thermoelectric power generation. At our request, authors of a recent study (Miara et al. 2017) extracted effects specific to operational nuclear power stations, which are presented in Figure 17. The adjusted average capacity (AAC) at power plants is expressed as a percentage of nameplate capacity, accounting for losses in thermal efficiencies and CWA-forced curtailments resulting from changes to air temperature, humidity, water temperature, and water availability (Miara et al. 2017). A multi-model platform was used to simulate changes in water supply to determine potential impacts to power plant operations due to insufficient water supply and/or elevated intake or discharge water temperatures. Simulations span the period from 1985–2064 and explore 12 scenarios consisting of four different GCMs (GFDL, noresm1, micro-esm, Hadgem), a baseline (1985-2004), and two different forcings (RCP 2.6 and 8.5) for the 2045–2064 period. In general, the most vulnerable were plants utilizing once-through cooling systems, which are at particular risk of discharge water exceeding permitted temperature limits. Browns Ferry, Peach Bottom, and Prairie Island (all using once-through cooling systems) nuclear power plants have a projected AAC of 78%, 86%, and 95%, respectively, across the four GCM models considered under the 8.6 RCP scenario. Smaller reductions (ranging from 1–2%) in AAC are observed for both RCP scenarios in most power plants (Figure 18). In the original study, risk more than doubled between the present and the 2060s. Plants at highest risk were located in the southern Midwest and Southeast. We presents a closer look at the same data for nuclear power plants only, yet further analysis is needed to evaluate the implications of these results on the commercial nuclear industry.

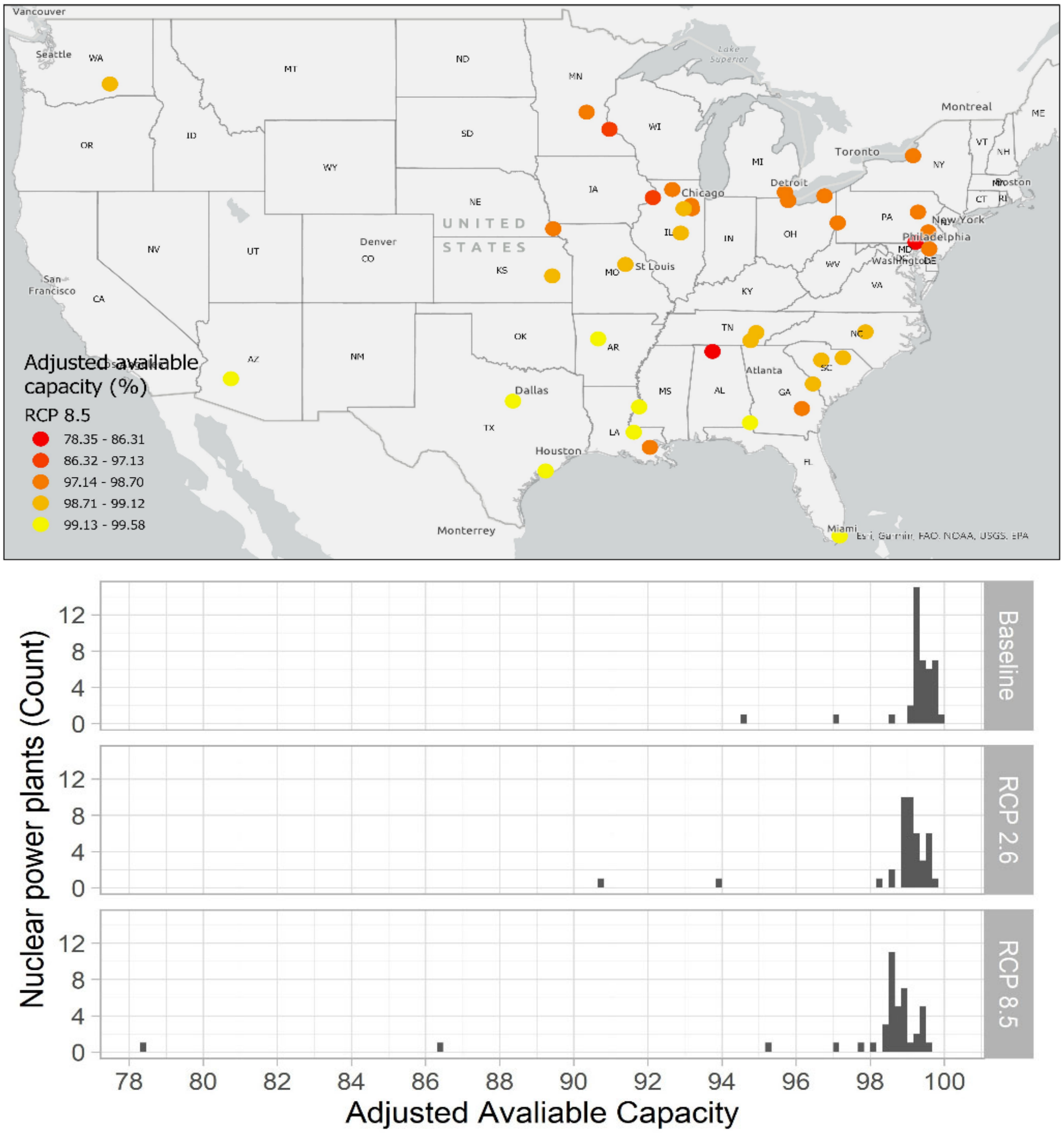

Figure 17. AAC histogram for 41 nuclear power plants under two future climate scenarios. Data source: (Miara et al. 2017). Results were modified to consider average summer temperatures as the inlet temperature thresholds, above which derating begins, to reflect regional design conditions more accurately for power plants. Data includes electricity generation performance for the months of June–August under a baseline (1985–2004), RCP2.6 (2045–2064), and RCP8.5 (2045–2064). Each AAC value is calculated as the mean of the four global circulation models (GFDL-ESM2M, HadGem2-es, MIROC-ESM-CHEM, and NORESM1-M) outputs. Power plant operations were simulated using the coupled Water Balance Model and Thermoelectric Power and Thermal Pollution Model (WBM–TP2M) at a daily time step.

5.2 Water-Energy Environmental Justice

To ensure its long-term sustainability, the Light Water Reactor Sustainability (LWRS) program must consider environmental and social implications in addition to the safe, efficient operation of plants. Fostering inclusive engagement with stakeholder communities near power plants and understanding their needs and concerns are necessary steps in addressing environmental justice. This includes building a mutually beneficial relationship that involves transparency, open communication, and engagement from the public in decision-making processes to encourage consideration of environmental justice issues and ensuring that the benefits and risks associated with nuclear energy are equitably distributed. We mapped the currently licensed commercial nuclear plants to the Department of Energy's (DOE) Climate and Economic Justice Screening Tool, which identifies disadvantaged communities (DAC) based on their burdens and low-income thresholds. Of the 94 plants, 11 were located in DACs.

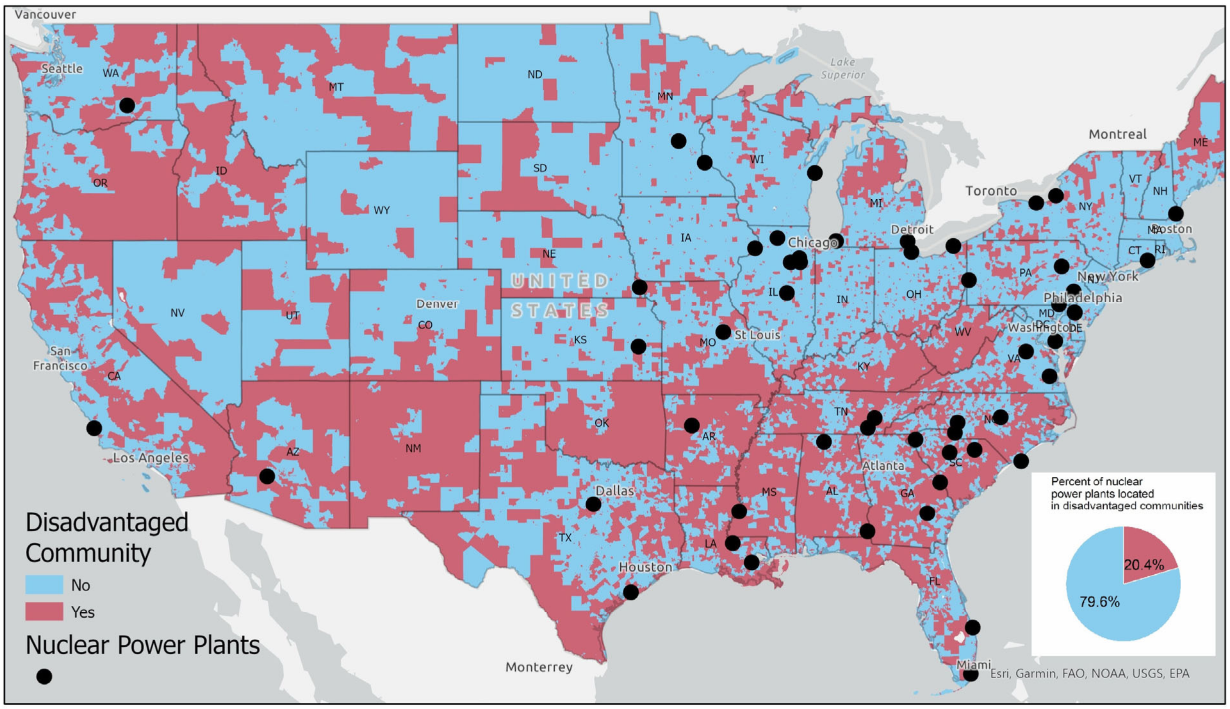

Figure 18. Disadvantaged community status and nuclear power plant locations. Eleven nuclear power plants are located in areas identified as DACs.

Broadly, feedback from stakeholders indicated a limited understanding of how the commercial nuclear fleet should address environmental justice, either individually or as a sector.

The Nuclear Energy Institute (NEI) outlined a comprehensive set of principles related to environmental justice in the context of nuclear power operations. These principles emphasize (1) fair treatment and meaningful involvement of all communities, including minority, Indigenous, low-income, and other disadvantaged populations; (2) transparency and community engagement, integration of environmental justice into business practices, equitable distribution of benefits, support for justice policies, and data-driven decision making; and (3) commitment to fostering trust and understanding by actively engaging with DAC and seeking their input. They prioritize timely and accessible information sharing to ensure that communities are well informed about facility operations.

NEI intends to integrate environmental justice into its operational practices and supply chain sourcing, educate employees on environmental justice issues, and use data and input from communities to identify and address concerns. Equitable distribution of benefits from nuclear power operations and support for just policies are also key pillars of NEI's approach. These principles reflect NEI's dedication to aligning its activities with the principles of environmental justice and ensuring that nuclear power contributes to the well-being of all communities, particularly those historically marginalized or disadvantaged.

Beyond proactive environmental stewardship and responsibility, meaningful consideration of environmental justice issues could help educate the public on the benefits of continued operation of the commercial nuclear fleet and minimize future reputational risk to the industry. Environmental social governance is becoming more of a factor in investments and long-term decisions. Under the BIL, the significant investment in the U.S.' infrastructure aims to address critical needs across various sectors, including water infrastructure improvements, which ensures access to clean and reliable water resources. From an environmental, social, and governance perspective, this legislation serves as a commitment to sustainable development by allocating substantial funding to projects that encourage community engagement and enhances environmental resilience such as modernizing transportation to reduce carbon emissions and fortifying water systems for cleaner and more efficient resource management. The BIL's comprehensive approach aligns with environmental, social, and governance principles by promoting transparency and accountability in the governance of these investments, reflecting a national commitment to fostering long-term environmental sustainability, social inclusivity, and responsible governance.

6. OPPORTUNITIES TO REDUCE WATER-RELATED RISKS

There are opportunities to reduce water-related risks; the following sections describe this in detail. As stated in Section 2.3, issues with water can impact the commercial nuclear industry in three ways: (1) lack of water available for cooling, (2) higher-than-anticipated water intake temperatures, and (3) high water-discharge temperatures. Solutions to these issues are discussed below; however, the details of any individual power plant's situation are complicated, and any one solution is not a catch-all for all nuclear operations and has its own tradeoffs. A detailed techno-economic analysis for each opportunity could help evaluate the technology, but the variability within each plant caused by differing source-receiving bodies, water quality, and environmental and climatic conditions, coupled with local requirements, limits the value of these technology assessments for the commercial nuclear power fleet. Where possible, we draw on existing analysis, which typically includes all thermoelectric generation and not the individual nuclear plant.

6.1 Alternative Sources

Exploring alternative water sources for cooling processes is a solution worthy of evaluation in many regions, as the dependence on particular freshwater solutions could become restricted by use competition and intensifying drought. Currently, commercial nuclear power plants use a variety of water sources (Energy.gov 2011b) as spatially illustrated in Figure 19. As of 2021, two plants are reported as using reclaimed water with a combined capacity of 5.6 GW, four plants make use of coastal brackish water with a combined capacity of 5.6 GW, and an additional five plants use seawater with a combined capacity of 9.4 GW. Alternative water sources account for about 21% of total nuclear power sector water withdrawals. This is a growing trend that could represent a pathway to longer fleet sustainability, but it is not without challenges.

Plants using non-fresh sources may be insulated from the effects of drought, and depending on siting, from flood. For existing power plants relying on freshwater, retrofitting options include recycled wastewater, brackish groundwater, and potentially produced water (water produced during the extraction of oil and natural gas). Retrofitting an existing plant to use non-fresh water requires a transition to recirculating cooling for those plants relying on once-through cooling, and construction of water treatment facilities, and potentially concentrate management facilities.

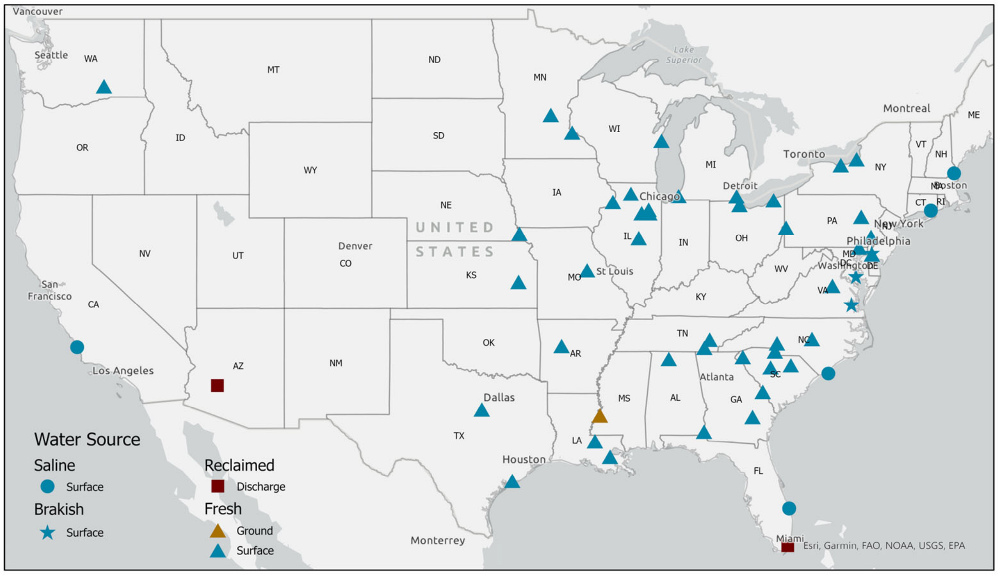

Figure 19. Commercial nuclear fleet cooling water source types. Data source: IEA.

Generally, cost, both capital and operating, is the primary challenge to such retrofitting; however, studies have shown there are many opportunities to retrofit where the added cost is a fraction of that of the current operations (Tidwell et al 2014, Wu et al 2023). Importantly, research investments (NAWI 2023) are yielding improvements in brackish water treatment technology while decreasing deployment and operating costs (Mayor 2020). In contrast, the increasing trend of wastewater reuse has increased the value of treated wastewater, which has made the Palo Verde nuclear station reconsider cooling water options.

The cost of retrofitting also needs to include the cost and extent of a potential NRC licensing amendment. Changing cooling technologies could constituent additional hazard evaluation and environmental assessment. Hourly fees for interacting with NRC could cost more than $200,000 (NRC n.d.) for review and approval of an amendment. Further discussion concerning regulatory requirements is given in Section 3.3.

The cost of retrofitting to include alternative water sources must be balanced with the reduction of the risk of losing access to cooling water, especially during periods of drought or excess heat or, as was the case of Palo Verde, in areas without exhaustive water sources options. Relying on multiple source alternatives could be another way of reducing the risk profile but could come with expensive contractual penalties.

6.1.1 Non-Water Cooling

Advanced reactor technologies, while not incorporated into the current fleet, seek to stimulate a paradigm shift in the perception of nuclear energy and address some of the existing limitations to growth. These reactors employ innovative cooling systems that use non-water coolants, such as gas, molten salt, and liquid metal (e.g., sodium and lead), and integrate enhanced safety measures.

Advanced reactors offer the potential for non-electrical, thermal products, including high-temperature heat for industrial processes that have traditionally relied on fossil fuel combustion. In these instances, non-water-cooled reactors would require a thermal transfer fluid system to supply heat to these process applications. Alternatively, hydrogen production by high-temperature electrolysis or desalination by multi-stage flash distillation or reverse osmosis could diminish the energy intensity of these processes but will still require water.

6.2 Increasing Cycles of Concentration

Another way to reduce water-related risk is to increase the efficiency of the water being used. This can be done by getting the most out of the water in the system. In the cooling cycle, heated water leaving the heat exchanger enters the top of the cooling tower where it falls and is broken into droplets from contact of the cooling tower fill. The water is cooled by the lower temperature of the countercurrent flow of air, and heat is released as water evaporates. The cooled water at the bottom of the cooling tower is returned to the heat exchanger where the cooling loop begins again. As water evaporates, the dissolved and suspended solids become more concentrated in the cooling water, which eventually must be wasted to avoid scale and deposition in a process called blowdown.

Increasing cycles of concentration reduces water demand because it increases the use of the facility's recirculating water before blown down. When increasing cycles of concentration, water quality is an issue as levels of dissolved minerals elevate, increasing scaling and corrosion risk. Dissolved minerals have a saturation limit that, if exceeded in local regions, leads to scale formation, which reduces cooling efficiency and, ultimately, power output of the plant. Additionally, high levels of dissolved minerals (high cycles of concentration (COC) increase the water's erosion corrosivity. Cycles of concentration can often be limited by the makeup water quality. For example, if the makeup water comes from a lower quality source and does not undergo onsite treatment, this can reduce the number of cycles. Chemical and mechanical treatment programs allow the thresholds of scaling tendencies and corrosion to be adjusted; however, limits persist, necessitating management of dissolved minerals (conductivity) levels by eliminating high mineral content water by periodic blowdown of the cooling water.

6.2.1 Water Treatment

Traditional water treatment systems are designed to prevent scale deposits, inhibit corrosion, minimize suspended solids fouling, and control the growth of bacteria and other microorganisms. To increase the COC, pretreatment can be used to adjust the impurities in the makeup water. For example, acid injection combined with corrosion inhibitors can be used to reduce the carbonate alkalinity and maintain a near-neutral pH in the cooling water but must be coupled with biocide as conditions cause increased biological growth. Water softening could be used to remove calcium and magnesium hardness, allowing for an increased pH, which reduces the need for biocides. If alternative sources are used for makeup water, additional pretreatment, such as filtration or reverse osmosis, may be necessary to improve the quality. Alternative treatment options like ultraviolet or nanofiltration could be coupled with these other technologies to improve operations.

6.2.2 Zero-Liquid Discharge

The operation of a facility for zero-liquid discharge (ZLD) is a strategy to manage wastewater so that no wastewater is discharged offsite, and water recovery is maximized. Historically, blowdown water from cooling cycles has either been discharged to source water bodies without or with treatment (e.g., a settling pond) or injected into deep wells. However, injection into deep wells is not typically considered in the commercial nuclear fleet.

ZLD facilities treat cooling tower blowdown for reuse as cooling-cycle makeup water, steam-cycle makeup water, and/or water for auxiliary services. Auxiliary services use "service water" for cooling systems that have small-diameter tubing (as small as 6.35 mm [1/4 in.]). Higher quality water is required for auxiliary services more than it is required for the main cooling system (that typically uses 25.4 mm [1 in.] tubing) because smaller diameter tubing plugs more readily.

Evaporation ponds are primarily designed based on the flow rate of water that will be discharged to the pond and the regional evaporation rate. Higher flow rates and/or lower evaporation rates require a larger evaporation pond area. Evaporation ponds are more common in arid and semiarid climates where evaporation rates are high. Evaporation ponds can have high capital costs (e.g., to acquire land area and purchase liner materials) but generally have low operating costs.

6.3 Integrated Technology Systems

In both the energy and water space, there has been a push to integrate technologies outside of the core function of the operations. For example, power plants exist to make electricity, but they produce heat in the process. Therefore, integrated technologies utilize heat to make the overall system more efficient. However, this is not without drawbacks. For example, extracting heat at high temperature will cause a reduction in generation efficiency, so applications that require lower temperatures are more effective. For example, waste heat recovery for industrial applications or combined heat and power operations (Frick 2022). Improvements in process technology for cooling are applied outside of the commercial nuclear fleet, but these technologies have been slow, if at all, to be integrated into nuclear. The 2019 report, “Case Study: Integrated Nuclear-Driven Water Desalination-Providing Regional Potable Water in Arizona,” describes the coupling of a reverse osmosis water desalination facility with a nuclear power plant,” stating requirement of additional evaporation ponds a necessity to dispose of additional concentrate (Epiney, 2019). Alternatively, other options have been explored to increase the overall system efficiency by creating or capturing energy that is otherwise lost. The 2022 report, “Assessment of Hydropower Potential at National Conduits,” considered opportunities for conduit hydropower (small scale 110kW - 10MW, micro-scale <100kW) at cooling water discharges at thermoelectric power stations. The report states, “based on a review of Federal Energy Regulatory Commission (FERC) qualifying application data, there is little industrial sector development of conduit hydropower.” The study used flow-based water withdrawal data, like the information reported in Table 1, coupled with Google Earth maps to obtain rough elevations as a preliminary first cut assessment. A more realistic evaluation of hydropower capacity depends on the available hydraulic head in the system, which comes from system designs. The cost/benefit factors, including the need for more permanent access to localized power, will also need to be considered for each individual plant. Tools are needed at the individual plant level to consider impacts of integrated technologies that include economic, policy, physical water availability and institutional water availability.

7. CONCLUSIONS AND RECOMMENDATIONS

This report provides analysis to understand the challenges and opportunities facing the U.S. commercial nuclear power industry and offers candid insight from industry stakeholders who are working to provide water technology and operations. We evaluated existing and emerging performance risks and opportunities and potential technology solutions and investments to address those risks and opportunities. This report includes analysis of water withdrawal and consumption by operating nuclear reactors, evolving policy risk that could impact operation, implications of water markets, trading and water rights, changing water and energy grid dependencies, progressing environmental risks including impact of climate change and water availability on performance, and offers opportunities to reduce water related risk including evaluating alternative sources, improving technology and incorporating integrated technologies.

From the analysis conducted, the literature reviewed, and discussions with stakeholders, we conclude there is a significant, ongoing need to understand the water-energy nexus issues affecting the U.S. commercial nuclear power industry. The following insights were developed: (1) regulatory changes in both the water and energy space continue to make long-term planning difficult and financially burdensome. Understanding policy and implementing solutions is critical to maintaining performance. (2) Barriers to incorporating existing technological improvements need to be reduced to incorporate efficiency gains and risk reduction because climate change is consequential and will impact all aspects of the sector. (3) Business decisions have an impact on society and on the environment; therefore, proactive management of environmental justice could influence reputational risk and long-term sustainability of the sector.

Given the analysis in this report, stakeholder perspectives, and our understanding of the current commercial fleet and cooling technology, we offer the following preliminary recommendations discussed below. With continued monitoring and investment in the water-energy nexus, the light water reactor sustainability program could ensure an economically and environmentally stable LWR fleet.

7.1 Recommendation 1: Modeling

Secure and reliable cooling is necessary for the sustainability of the LWR nuclear power sector in the U.S. Modeling efforts need to advance the understanding of the potential physical water at each plant as well as the institutional water availability. Continued investment in improved modeling efforts that include both physical water withdrawal/consumption and institutional water including water rights and administrative controls is necessary to evaluate the risk of the continued operation of the LWR fleet. This can be accomplished by a continued effort toward the following:

1. Improve measurement, modeling, and understanding of water withdrawal/consumption at the individual power plant level, specifically identifying key factors influencing water use.
2. Improve estimates of the intensity, duration, and return period of extreme events that threaten operations across the fleet of nuclear power plants (e.g., drought, flood, hurricane, winter storms). These estimates need to be location dependent and should be developed in conjunction with other agencies (i.e. DOE BER, NOAA, and FEMA)/
3. Improve multi-sectoral modeling tools for assessment of coupled water, energy, environmental modeling under a changing and uncertain future.
4. Integrate data and modeling information to identify potential risks and system failures to minimize the risk of generation disruption induced by potential future changes in climate while maintaining efficient operating and asset management costs.
5. Keep an updated assessment of the state of technology, including emerging technology, validation, and deployment, in conjunction with DOE EERE, WERF, and trade associations.
6. Track climate change assessments, extreme events, and shifts in water-energy supply, demand, and economic activity in conjunction with DOE BER, EPA, FEMA, and DOC.

7.2 Recommendation 2: System Technologies

Increased system efficiency both in energy and water will be necessary for the continued success of the LWR fleet. This will require an ongoing commitment to develop and incorporate cost- and energy-efficient technologies, including the innovative use of advanced sensors and data to reduce the intensity of cooling water use. This can be accomplished by the following:

1. Develop cost- and energy-efficient technologies to eliminate the need for water cooling (air cooling/dry cooling). This could also include integrated technologies to increase overall efficiencies.
2. Continued development of cost- and energy-efficient technologies to decrease the intensity of water use (improved condensers). This could also include technologies to achieve ZLD.
3. Innovate applications of sensing and monitoring to increase efficiency. This could include developing standardized (plug and play) programs to ensure water quality (e.g., temperature, TDS, BOD, COD). Develop and implement real-time sensing technologies that integrate with compliance requirements to enable dynamic system optimization.

4. Improve water treatment technologies, including those that treat biological and chemical constituents and emerging constituents (e.g., TDS, algae, PFAS), making alternative sources more attractive. This also includes securing co-products (e.g., critical minerals) from impaired water to improve the economics of water use.
5. Support machine learning and artificial intelligence (ML/AI) tools to advance water treatment and optimize energy production.

7.3 Recommendation 3: Inform Policy for Efficiency

There is a concern about the effects of climate change impacting the ability of the current fleet to continue operations as usual. The fleet has not extensively adapted new technology; barriers to this have been explored in the space of new and advanced nuclear systems but this needs to be extended to the existing fleet. In the specific context of water-energy nexus for the current nuclear fleet, mechanisms need to be explored for a pathway to deploy improved systems. It is important to continue work to help inform regulators of the impact of regulations and policy in regard to technology implementation.

1. Develop communication tools to coordinate activities between water policy makers (mostly local and regional) and nuclear policy makers (mostly national).
2. Continue to survey existing and emerging changes in policies and recommendations at national, regional, and local levels in areas with an LWR footprint in conjunction with EPA.
3. Apply modeling tools to regulatory scenarios to inform regulators on the impacts, including cost, timing, and risk of curtailing operations.
4. Host workshops to inform regulators of emerging technology trends to guide development of new policies such as sensing and monitoring reporting requirements.
5. Convene experts to weigh water related risks in the context of current regulations governing modification of cooling systems. Explore opportunities for technology demonstrations to explore risks in the regulatory environment.

7.4 Recommendation 4: Environmental Justice and Equity

Environmental justice and equity are not well understood by the industry. Commercial nuclear fleet operators will need to respond to assure equity under rapidly changing influences of climate, land use, population, and energy grid demand.

1. Conduct environmental justice assessments for individual plants to develop baselines for future actions to include geographic locations, affected environmental justice communities and stakeholders, plans for meaningful community and stakeholder engagements, and workforce development and education.
2. Incorporate community concerns into future environmental justice assessment. Expand tools to promote public engagement and education in support of future resource planning and relicensing exercises.
3. Develop additional tools to evaluate risk profiles to manage differing energy-water scenarios that include environmental justice considerations. Use these tools to explore current nuclear fleet operations and cooling tower technologies in the context of the dynamic nature of climate change, land use, population changes, and energy grid equity.

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