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Light Water Reactor Sustainability Program

Updated Assessment of Water-Energy Issues for Nuclear Power

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ABSTRACT

There is significant ongoing need for understanding the water-energy nexus issues in the U.S. commercial nuclear energy industry. The water-energy nexus is a dynamic, ever evolving challenge involving technological changes, regulatory updates, economic constraints, environmental issues, and political attributes. This report provides a brief update on the water-energy nexus challenges facing the U.S. commercial industry since the 2010 report titled "Cooling Water Issues and Opportunities at the U.S. Nuclear Power Plants".

Since the 2010 report, nuclear power has experienced significant curtailments due to drought, intake and discharge temperatures, and flooding. These events will be exacerbated by global climate and resource competition. Water and energy regulation changes have accelerated and pose a particular risk to the commercial nuclear fleet compliance. The definition of Water of the United States continues to be litigated as water rights are being evaluated for fair and equitable allocation. The ability to maintain compliance with state and federal water regulations offers a substantial risk to the commercial nuclear industry, and therefore understanding the energy-water nexus is necessary for maintaining success of the current fleet.

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1. INTRODUCTION AND MOTIVATION

The interdependence between water and energy has long been recognized but is growing in importance as water and energy demand increases. Water is used in all phases of energy production and energy generation while energy is required to treat and transport water. This intricate linkage between water and energy is commonly denoted as the water-energy nexus. Historically, interactions between energy and water have been considered on a regional scale and energy and water systems have been developed, managed, and regulated for the most part, independently. The U.S. commercial nuclear energy fleet is not immune to these concerns as all commercial nuclear plants in the U.S. use water for cooling and most are located near lakes, rivers, and oceans.

This report has been prepared for the purpose of providing a status update on the challenges and opportunities facing the U.S. commercial nuclear energy industry. It is an update to the report from 2010 titled "Cooling Water Issues and Opportunities at the U.S. Nuclear Power Plants" (26). This report highlights several key issues that have continued, increased, or appeared more prominent since the delivery of the original report. These issues include 1) advancements in cooling water technologies, 2) water policy updates, 3) environmental issues.

2. CURRENT STATE OF THE U.S. COMMERICAL NUCLEAR POWER INDUSTRY

This section provides a status update on the U.S commercial nuclear fleet relating to its portfolio of operating light water reactors. Topics discussed include the position of electricity generation in the greater context of thermoelectric power generation, water consumption, cooling technology improvements and advanced reactor technologies.

2.1 Thermoelectric Power Production Overview

Thermoelectric power plants account for a large percentage (63% in 2017) of the U.S. electricity generation. Thermoelectric plants include nuclear, coal, oil, natural gas, and other less common methods (e.g., geothermal, biomass, waste-to-energy). In 2022, ~4.2 terrawatt-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, a decrease from previous decades where it accounted for more than 19% of generation (3). Most electricity in these plants is generated using steam turbines that converts high-pressure steam into mechanical energy that can be used to produce electricity. Water or air is used to cool and condense steam in most thermoelectric plants. Water cooled systems are typically more thermodynamically efficient. Cooling systems are the largest source of water use in thermoelectric plants. In the U.S., 61% of the thermoelectric generation capacity uses recirculating cooling systems, 36% uses once-through cooling, and dry and hybrid cooling systems account for 3% (4). In recirculating systems, water is "recirculated" through cooling towers where the water comes in contact with heat exchangers, and evaporated to produce the desired, 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. This process is equivalent in the U.S. commercial nuclear power industry and its light-water reactor (LWR) portfolio. The most noticeable factor is that the LWR facilities tend to be larger than fossil thermoelectric plants and could result in more concentrated stress on local water systems.

Currently, there are 93 light water reactor (LWRs) units licensed by the U.S. Nuclear Regulatory Commission (NRC), consisting of 62 Pressurized Water Reactors (PWRs) and 31 Boiling Water Reactors (BWRs), both of which are light water reactors (LWRs). Seven nuclear generating units with a total capacity of ~ 5.5 gigawatts (GW) have retired since the end of 2017, including the Michigan's Palisades nuclear plant, which closed in May 2022. Additionally, California's Diablo Canyon is scheduled to retire two generating units, one in 2024 and one in 2025, with a capacity of 1,122 MW and 1,118 MW, respectively (3, 5). Two generating units, Georgia's Vogtle 3 and 4, are scheduled to begin operation in 2023 and 2024, adding 1,114 MW each. Vogtle 3 and 4 are the first new nuclear reactors constructed in the U.S. in 30 years (5).

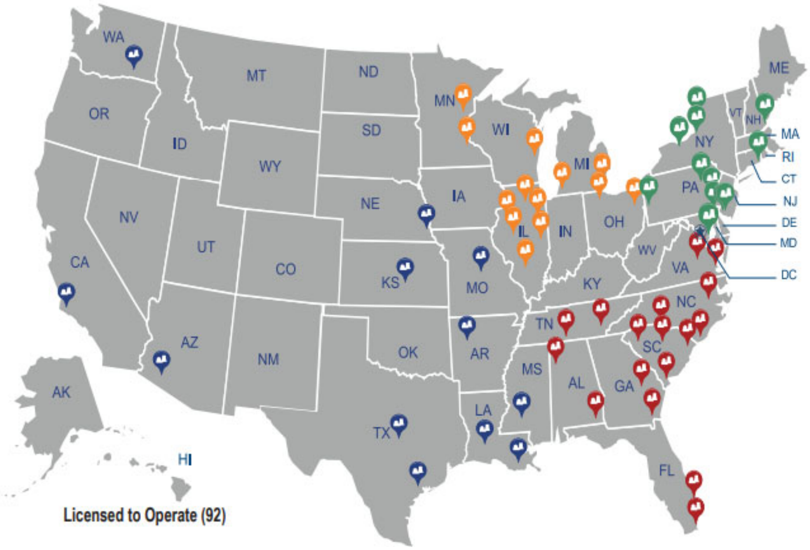


Figure 1. Map of current NRC licensed nuclear power plants (28).

2.2 Water Consumption-Reporting Concerns and Historical Trends

The 2010 report employs varying water terminology that complicates descriptions of water "usage". Lacking standardized definitions causes a great deal of confusion and potential misrepresentation of the status of the water-energy nexus. Since 2010, this issue has been further exacerbated by the increased availability of online data resources.

Both the US Geological Survey (USGS) and the Energy Information Administration (EIA) have considerable experience estimating water use for thermoelectric power plants. Since 1950, the USGS has published estimates of U.S. water use (both withdraw and consumption) every five years across all water use sectors and reported at the county level. The EIA has also published water use estimates; however, estimates are limited to thermoelectric water use (EIA-860 and EIA-923). These data have the advantage that they are reported annually at the unit level. Until recently, nuclear power plants were exempt from reporting water data to EIA.

Estimating water use at our nation's thermoelectric power plants has proven to be a difficult endeavor. Complexity of these systems and their operations along with the lack of standardized definitions and reporting criteria are central to this challenge. In fact, it is widely acknowledged that water use estimates prior to ~2010 were fraught with errors and inconsistencies. In 2009, the Government Accountability Office (15) raised issues specific to USGS and EIA water use estimates for thermoelectric power plants. In response, EIA expanded and improved water use reporting processes resulting in new data products beginning in 2014 (7). These included estimates of water use at nuclear plants.

The USGS pursued similar improvements. The avoid reporting errors the USGS (Harris et al. 2019) began modeling water use at individual power plants using basic thermodynamic principles (i.e., based on plant characteristics and climatic conditions). Water use estimates for select years are presented in Table 1 for the nuclear power industry. Data reported by EIA are based on power plant reporting, while data from the USGS is based on modeling). USGS estimates for 2020 have not yet been published and consumption of saline and brackish water is not reported or modeled in USGS aggregated data (16).

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	-	-	55,291	716

Upon comparison of the USGS and EIA water use, one would expect to see a slight decreasing trend in water withdrawals and consumption due to the retirement of several nuclear power plants. However, withdrawals estimated by the USGS remain relatively constant around ~44MGD, while consumption estimates show a significant decline over the 5-year period considered (2010-2015). These differences reflect improvements in the modeling process rather than actual changes in water use. In contrast, EIA withdrawal estimates jump from ~44MGD in 2010 to 57.7MGD in 2015 with a slight decline thereafter. Consumption shows only a slight decrease over the ten-year period. The rise in reported withdrawals correspond to the time period over which EIA improved efforts in standardizing and reviewing plant reported water use. We suggest that analyses and decisions use more negative estimates (greater withdrawal and consumption) to prepare for risks in the energy sector.

USGS withdrawal estimates should be lower than EIA because USGS models estimate the amount of water required to cool the plant based on fuel use, electricity generation, and environmental variables, and not how much water they may withdraw for other operational purposes. Nevertheless, these differences appear much too extensive to be explained by plant operations alone. More in-depth analysis is needed to identify the underlying differences. Meanwhile, 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. Overall, nuclear power generation accounts for ~40% of all thermoelectric water withdrawals and 28% of all water consumption (16).

Additionally, the presentation of national level aggregation of data, as reported 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 type of cooling system. Water use scales directly with the size of the plant—with plants varying in size from about 580MW to 3800MW. The choice of cooling system also influences water withdrawals and consumption but in a more complex manner. 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 (16). Plants with open-loop cooling systems are characterized by very high-water withdrawals but limited water consumption. The other major cooling type employed by nuclear facilities are recirculating natural draft, which have ~two-orders of magnitude less water withdrawals than open-loop cooling but slightly higher consumption. A small number of plants employee recirculating cooling through a pond rather than a tower. In this type of system, water use is quite variable, somewhere between once-through and recirculating tower, so an average is not reported. When compared to other fuel types, water use coefficients for nuclear power are similar or higher than all but biomass (Harris et al. 2019); that is, nuclear power is among the most water intensive means of generating electricity. As almost half of the nuclear fleet's capacity employs once through cooling; this explains why nuclear power accounts for such a large fraction of total thermoelectric water withdrawals.

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

	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

Finally, aggregated data from a 5-year time frame, no matter the source, does not account for the regionally or sub-annual (i.e., monthly) variation in water withdrawal and consumption. While discussed in more detail in Section 3, these values are important in planning for and predicting the impacts of extreme weather and resource competition. More in-depth analysis is needed to determine the regional and sub-annual variation in water use across the existing commercial nuclear fleet.

2.3 Cooling Technology Improvements

A primary consideration for the operation efficacy of cooling tower systems is the quality of the make-up water source. Commercial nuclear power plants use a variety of water sources (9). As of 2020, two plants are reported as using reclaimed water with combined capacity of 5.6 GW, four plants make use of coastal brackish water with combined capacity of 5.6 GW, and an additional five plants use seawater with combined capacity of 9.4 GW. All but one of these plants are located near the coasts. Alternative water sources account for ~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.

One means of reducing water related risk would be to retrofit nuclear power plants to use non-fresh water sources that have less resource competition. In general, these non-fresh sources are also insulated from the effects of drought or flood. As mentioned earlier, over 20,000MW of nuclear power capacity depend on non-fresh sources including seawater (saline and brackish) and recycled wastewater. For existing power plants relying on freshwater, retrofitting options include recycled wastewater, brackish groundwater, and potentially produced water (water produced by the production of oil and natural gas). Retrofitting an existing plant to utilize 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. 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 faction of that of the current operations (33, 37). Importantly, research investments (22) are yielding improvements in brackish water treatment technology while decreasing deployment and operating costs (18). In contrast, the increasing trend of wastewater reuse has increased the value of treated wastewater, which has made the Palo Verde nuclear station reconsider their cooling water options. While cost of retrofitting for alternative water sources is a consideration, it must be balanced with the reduction of the risk of losing access to cooling water, especially during periods of drought or excess heat or in the case of Palo Verde, in an area without exhaustive water sources options.

As an alternative to utilizing non-fresh water sources, increasing cycles of concentration reduces water needs because it essentially makes more use of the water already being used by recirculating the water longer through the system before being blown down. When increasing cycles of concentration, water quality is an issue as levels of dissolved minerals elevate, and scaling and corrosion potential also increase. All dissolved minerals have a saturation limit that, if exceeded, will lead to scale formation which in turn lowers efficiency of the system. Additionally, high levels of dissolved minerals (high cycles of concentration) increase the water's tendency to be corrosive (corrosion is discussed in section 3.4). Chemical and mechanical treatment programs allow the thresholds of scaling tendencies and corrosion to be pushed; however, limits persist necessitating management of dissolved minerals (conductivity) levels through elimination of high mineral content water through blowdown.

We are conducting a detailed review of the technical literature of the state of technology and interviewing operators of nuclear power plants regarding implementation. A more detailed technology evaluation will be provided in the next phase of the report.

2.4 Advanced Reactor Technologies and How They Relate to Water

Advanced reactor technologies, while not incorporated into the current fleet, seek to induce a paradigm shift in the perception of nuclear energy and solve some of the existing concerns. These reactors employ innovative cooling systems that utilize non-water coolants such as gas, molten salt, and liquid metal (e.g., sodium and lead), and integrate enhanced safety measures. However, their interaction with water remains critical in many aspects such as power conversion cycles and basic ancillary plant systems.

Advanced reactors and small modular reactors (SMRs) (e.g., the NuScale and Westinghouse SMRs) often incorporate water pools in their designs. These water pools help manage the cooling water inventory and reduce the risk of reactor overheat. Moreover, these reactors frequently use passive cooling systems that rely on natural circulation and gravity, ensuring that the reactors remain cool even during power outage situations. This is crucial for preventing severe accidents such as the Fukushima meltdown.

Advanced reactors also explore the integration of non-electric generation applications such as supplying high-temperature heat for various industrial processes that have traditionally relied on fossil fuels. In these instances, non-water-cooled reactors would require an intermediate water-based 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.

3. WATER POLICY UPDATES

Since the 2010 report, there have been three White House administrations, with distinct priorities in environmental policy and regulation. First, the Obama administration sought to expand federal protections then the Trump administration loosened and rolled back requirements while the Biden administration has since restored and attempted to streamline protections. This section provides an update to pertinent environmental regulations mentioned in the 2010 report including section 316 (b), "Revised Definition of Waters of the Unites States, national pollutant discharge elimination and other regulations that have emerged such as the post-Fukushima safety flood evaluations and per and polyfluoroalkyl substances as they relate to emerging issues.

3.1 Section 316 (b) Cooling Water Intake Structures

On August 8, 2014, the final ruling was published in the Federal Register “Regulation to Establish requirements for Cooling Water Intake Structures at Existing Facilities and Amend Requirements at Phase I Facilities.” This rule requires power generating facilities with cooling water intakes and structures to take actions to reduce impingement and entrainment of fish and aquatic organisms. Per the definition, commercial nuclear is included in the ruling and as a result, must submit detailed information about their cooling water intake systems as part of the National Pollutant Discharge Elimination System (NPDES) permit renewal applications to inform the permitting authority’s best available technology determination.

As discussed in the 2010 report, EPA divided the section 316(b) rulemaking into three phases, under a 1995 consent decree with environmental organizations. The 2014 final rulemaking clarifies the initial rulemaking and responds to judicial pushback from Phase II and Phase III. In particular, the 2014 rule defines the term “cooling water intake structure” to mean the total physical structure and associated constructed waterways used to withdraw cooling water from waters of the United States (WOTUS). The definition of WOTUS additionally has been heavily contented since the 2010 report and is further discussed in detail below.

Recall, Section 316(b) of the Clean Water Act requires that National Pollutant Discharge Elimination System (NPDES) permits for facilities with cooling water intake structures ensure that the location, design, construction, and capacity of the structures reflect the best technology available to minimize harmful impacts on the environment. The withdrawal of cooling water by facilities removes billions of aquatic organisms from waters of the United States each year, including fish, larvae and eggs, crustaceans, shellfish, sea turtles, marine mammals, and other aquatic life. Most impacts are to early life stages of fish and shellfish through impingement (being pinned against cooling water intake structures) and entrainment (being drawn into cooling water systems and affected by heat, chemicals or physical stress.

3.2 Waters of the United States

The “Revised Definition of Waters of the United States” (13) rule was published in the Federal Register on January 18, 2023, and took effect March 20, 2023. This most recent definition builds on the pre-2015 definition stating that “much harm has been imposed by the revolving change of definition in 2015, 2019 and 2020”. Prior to the 2015 definition, the pre-2015 definition set the stage for clean water regulation for 45 years. Most of the existing nuclear fleet was developed in the pre-2015 definition.

The report by the EPA “Economic Analysis for the Final “Revised Definition of ‘Waters of the United States’” Rule,“" lists 7,602 potential permits affected. Some of these permits are held by the nuclear power industry for NPDES and section 401 requirements. More analysis is required to understand the full impact to the nuclear fleet. However, most recently, the May 25, 2023 ruling by the U.S. Supreme Court in *Sackett vs EPA* overturned the revised definition in the context of “significant nexus” for wetlands. It is likely the definition of WOTUS will continue to be debated as it has been for decades; *United States v. Riverside, 1985, Solid Waste Agency of Northern* Cook *Country v. U.S. Army Corps of Engineers, 2001, Rapanos v. United States, 2006,* and the trend continues *Sackett vs. EPA, 2012*, *Texas vs. EP, 2023, West Virginia v. EPA, 2023, Kentucky v. EPA.*

3.3 Clean Water Act NPDES Program Status

Under the CWA, EPA has the authority to grant qualified states, territorial, or Tribal government agencies the ability to implement all or parts of the National Pollutant Discharge Elimination Program. On July 1, 2021, the Idaho Department of Environmental Quality obtained primacy from the EPA to grant

NPDES permits and inspections. Per the 1976 memorandum “Note that the EPA can grant states the authority to issue NPDES permits, which gives those States the authority, having issued a NPDES permit to an NRC licensee, to inspect and assure compliance with the permits,” (NRC, 1976).

3.4 Water Quality Concerns

Since the 2010 report, a specific class of chemicals known as the per- and polyfluoroalkyl substances (PFAS) has been proposed for regulation by the EPA (10). This group of human-made chemicals has been used in consumer products and industry across the world since the early 1950s. Initial investigations on the extent of PFAS contamination focused on manufacturing releases and use of a specific fire-firefighting suppressant known as aqueous film forming foam (AFFF), which are common in places with fire training operations or required fire suppression equipment such as nuclear plants. PFAS is persistent once it enters the environment and is very mobile in groundwater and surface water.

On October 18, 2021, EPA released the PFAS Strategic Roadmap. This document outlined strategy to increase understanding of sources of PFAS into the environment and since, PFAS has been detected in locations of AFFF use, discharged effluents, and biosolids in municipal wastewater and wastewater with and without a direct industrial source. The commercial nuclear industry may also be indirectly influenced by PFAS proliferation as reclaimed and reused water sources are being considered due to resource competition. Currently, Palo Verde Generating Station, one of the largest nuclear energy facilities in the United States uses treated wastewater from local cities for condenser cooling water which is then disposed of in lined evaporation ponds. Traditional wastewater treatment technology does not treat PFAs in reuse or recycled scenarios, but the presence of PFAS has been detected in these waste streams.

The major PFAS manufacturers and suppliers have been subject to multi-billion-dollar litigation, mostly from drinking water facilities to implement treatment technologies. It is not clear whether other water intake facilities will become party to litigation or require mitigation. The current non-enforceable health advisory limit is 0.004 ppt. The issue of PFAS will also complicate decommissioning of power plants as the regulatory burden of nonradiological contamination is within the authority of state environmental regulation.

On April 21, 2023, EO 14096, “Revitalizing our Nation’s Commitment to Environmental Justice for all,” highlighted the requirement of access to clean drinking water and a healthy sustainable environment and expanded the definition of environmental justice. Both old and new water quality issues will be scrutinized under the new EO, which includes PFAS and other issues like the revised lead and copper requirement. On January 15, 2021, EPA published final regulatory revisions to the National Primary Drinking Water Regulation (NPDWR) for lead and copper under the authority of the Safe Drinking Water Act (SDWA). The revisions highlight corrosion control and actions to replace lead service lines in more communities across the country. Lead can corrode and leach from system pipes and fixtures that were constructed prior to the 1991 lead free requirements. This is especially a concern of the commercial nuclear portfolio as the average age of plant leans to 40 years, which is well beyond the 1991 requirements.

3.5 Water Management and Water Rights

The 2010 report highlighted competing national goals relating to water usage but left out much about the true complexity of water management amongst competing industry, geographical regions, and governing agencies. For example, the Department of Energy Report “Water-Energy Nexus: Challenges and Opportunities in 2014” describes how federal oversight is shared amongst 30 agencies in 10 different departments with federal funding mechanisms facing similar complexity (2). Furthermore, water management and decision making are shared between federal, Tribal, state, and local governments. This combination of different levels of government creates complex groundwater vs. surface water rules and variations amongst states. The report states “groundwater rights and laws are extremely complex.” Figure 2, illustrates the variation of water right policies amongst states which varies from absolute ownership (no limit to amount of water withdrawn), to prior appropriations doctrine (first in time, first in use).

The United States 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 United States 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, and ecological constraints.

The Columbia 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 its border; most notably, the Colorado River and Rio Grande which are pursuant 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, water must be provided 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 up the Colorado River 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 unfilled due to a variety of barriers. The disparity of groups in the water-energy nexus has risen in part to some of these issues and environmental justice is discussed in detail below.

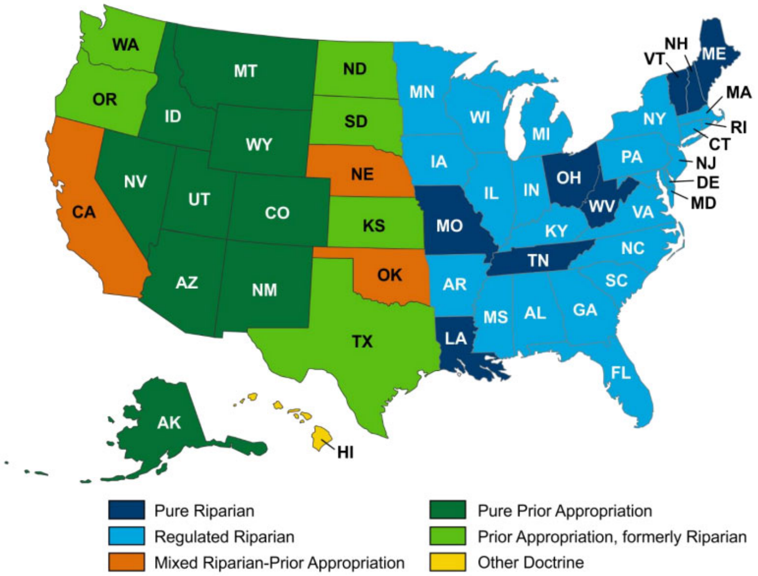
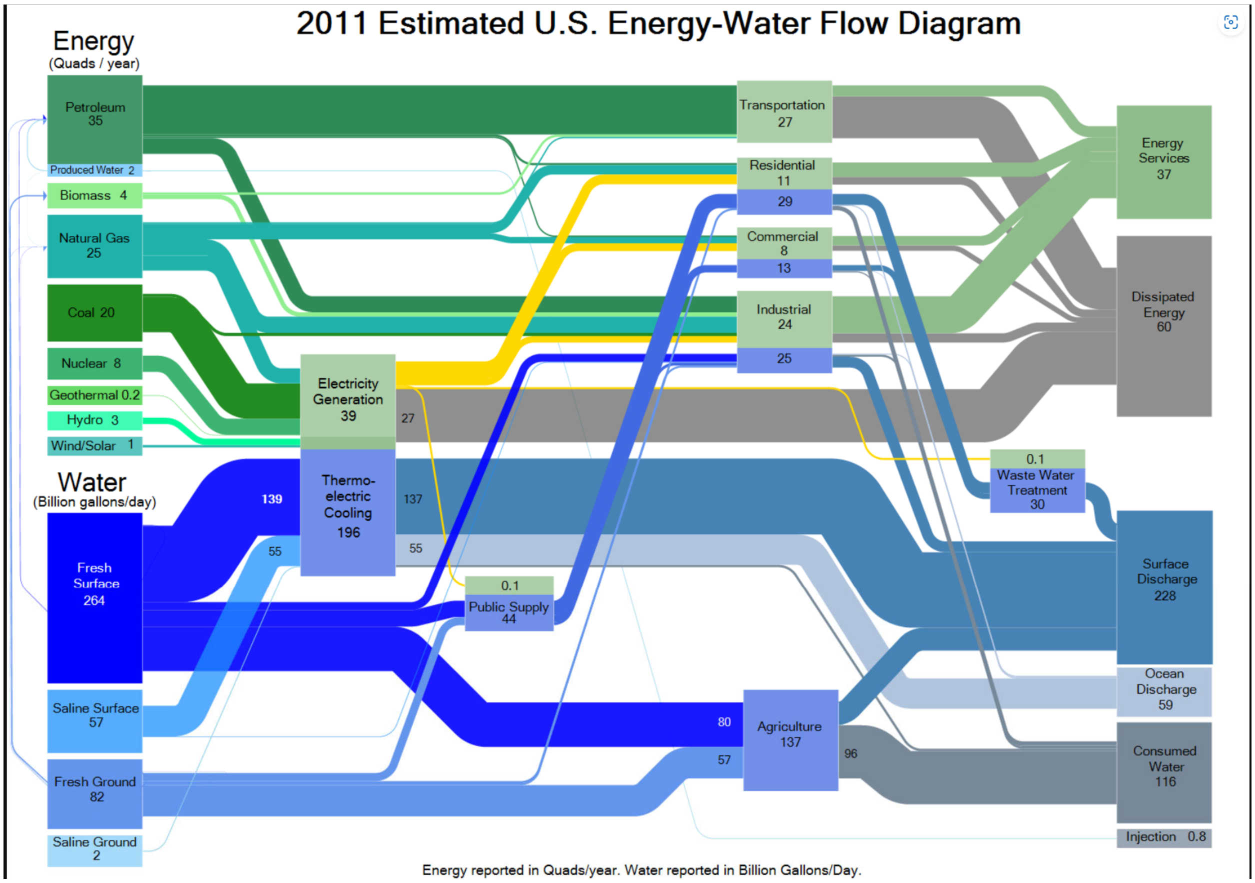


Figure 2. Water Right Policies in United States (2).

3.6 Energy Grid Regulation and how it relates to water.

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 sell come from renewable energy sources (23). The path to net-zero emissions has itself provided an interesting paradigm for the energy-water nexus. The 2013 report by McKinsey & Company titled "What will it take for nuclear power to meet the climate challenge?" estimates 400-800 GW of new nuclear are needed to meet the energy transition demand for dispatchable power (20). More importantly, in the near term the report recommends maintaining "the reliable and safe operation and maintenance (O&M) of current plants while continuing to improve financial performance," this includes staying financially competitive in strict markets where wind and solar competition have reduced margins and addressing the regulatory hurdles (water included) instead of shutting them down.

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 (36). As shown in Figure 3, energy and water are heavily connected. More analysis is required to understand the impacts of Executive Order 14057 and the relationship to the nuclear fleet.



Energy reported in Quads/year. Water reported in Billion Gallons/Day.

Figure 3. 2011 Estimated U.S. Energy-Water Flow Diagram, (2, 8).

3.7 Post-Fukushima Safety Enhancements and Flooding Evaluations

The NRC created a formal task force of senior experts to examine the safety of the U.S. nuclear power plants in response to the March 11, 2011, earthquake and tsunami that left Japan's Fukushima Dai-ichi Facility nuclear facility heavily damaged. The following orders were issued in March 2012 in response to the task force review: 1) obtain and protect additional emergency equipment (pumps and generators etc.) to support all reactors following a natural disaster, 2) install enhanced water level monitoring equipment for spent fuel pools, 3) improve emergency venting in reactors of similar Fukushima plant design (27). Additionally, NRC requested U.S. reactors to update evaluations of potential impacts of flooding and seismic events which necessitated forty-seven sites to complete limited flooding evaluations and five sites to complete integrated assessments of flooding impacts.

4. ENVIRONMENTAL ISSUES

Environmental challenges arise due to the limitations to discharge cooling water or the inability to obtain enough water for cooling. This limitation can be physical or institutional like in the case of water management and priority water rights. Physical limitations can be caused by too little or too much water as in the case of flooding or storm surge activities. Since the 2010 report, two topical areas 1) climate change 2) environmental justice have risen in magnitudes of emphasis and concern. This section discusses these topics in more detail.

4.1 Climate Change

The 2013 report "U.S Energy Sector Vulnerabilities to Climate Change and Extreme Weather" describes instances where climate change caused adverse impacts to energy systems (1). While these events may be almost a decade old at the time of this report, they illustrate the types of issues that have been faced and will continue due to climate change. Events were divided into three categories 1) increasing temperature, 2) decreasing water availability and 3) increasing storms, flooding, and sea level rise. All categories except decreasing water availability contained a nuclear water related event. Alternatively, the 2016 report titled ""Water-related power plant curtailments: An overview of incidents and contributing factors" points to twenty-five drought related incidents between 2000 and 2015 involving nuclear power stations (19). Incidents occurred at nineteen different plants with two plants having experienced multiple events. Plants impacted were located throughout the Southeast, Northeast seaboard and Midwest. Events included insufficient water (3 instances) intake water temperature too high (8 instances), discharge water temperature too high (8 incidences) and both intake and discharge water temperature too high (6 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.

Similarly, there are more current examples of plant operations being curtailed by flooding. The Brunswick plant was made inaccessible by flooding from Hurricane Florence in 2018 (25, 29). Similarly, the Fort Calhoun Station was shutdown for several months in part due to floodwaters surrounding the plant in 2011 (31). Hurricane Sandy caused the Salem and Oyster Creek stations to shut down when high water levels threatened their water intake and circulation systems (34). 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 off-site power backup (32). Additionally, the NRC identified 34 nuclear power plants as being 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 decreased in other parts of the country, particularly in the Southwest (12).

The Millstone Nuclear Power Station, in Connecticut, closed a unit during summer in 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. Since 1985, summer surface water temperatures increased for 32 of 34 lakes studied by the EPA in 2009 (30) with increases larger than 4°F in the lakes that reported the largest increases. Analysis like 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, where needed. Furthermore, two nuclear power plants are in counties with a 'very high" risk for heatwaves, three are in areas with 'relatively high' risk, and 15 in counties with 'relatively moderate' risk. Heat waves are occurring more often (increasing from two to six per year, on average), with a longer duration (1 day longer), in a longer season (49 days longer), and are more intense (increasing from 2°F to 2.3°F above the threshold) than they used to, in several areas of the United States (11).

Despite the variations in magnitude, frequency, and duration of extreme weather events, the U.S. nuclear industry has responded effectively to threats. This is due in part to detailed emergency response plans (ERP) designed to protect employees and the communities they serve (24). The NRC and FEMA set guidelines and requirements for the development of the ERP and nuclear plants have operated during multiple hurricanes, floods, snowstorms, and heatwaves (25). During these events, most nuclear plants have operated at full capacity, some have reduced operation, and a small percentage have temporarily stopped operations due to safety concerns (25). 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 (17). Analysis is needed to provide continued support to escalating scenarios of climate change for the U.S. nuclear industry to continue to be successful.

Figure 4 shows the number of nuclear power plants and county-level risk for a set of extreme events that can impact nuclear power plant operations. The figure was developed using FEMA data. Risk level was observed at the county level (14) considering only the county where the plant is located. County level risk was obtained from the Federal Emergency Management Agency (FEMA) National Risk Index, and power plant location was obtained from EIA (6).

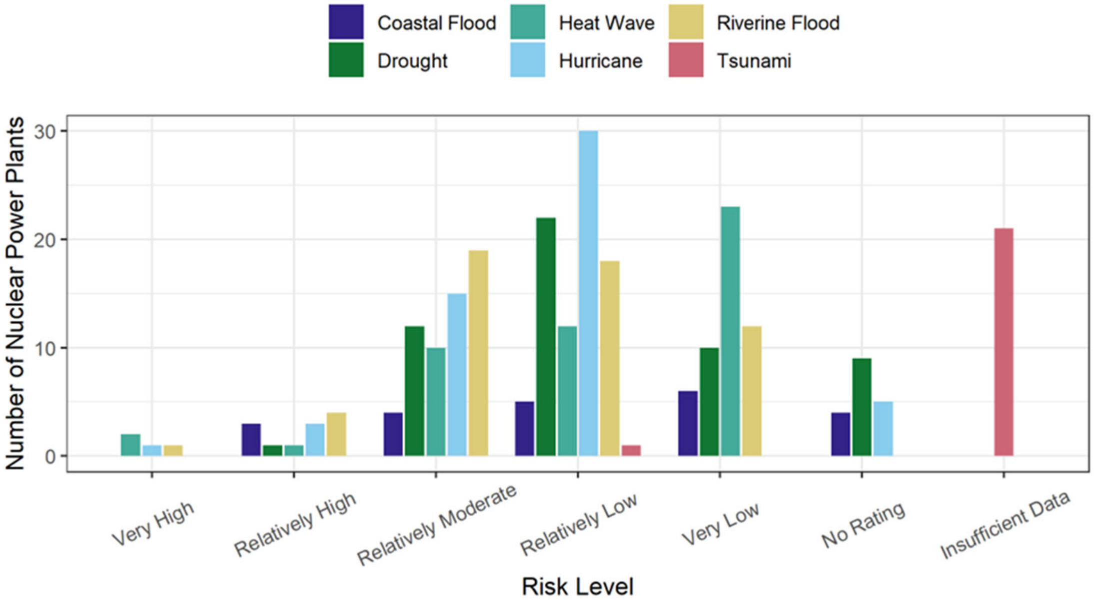


Figure 4. Relative Risk of climate-related events at U.S. Nuclear Power Plants

The actual impact of climate-related events however can extend beyond the county boundaries. For example, Diablo Canyon and Palo Verde nuclear plants (California and Arizona) are in counties with relatively moderate and relatively high risk for drought, respectively, but nearby counties have higher risk levels for drought that could impact their operation. Drought impacts extend beyond county boundaries and must be analyzed at the hydrological system scale. Figure 6 shows the drought risk overlayed by the location of the current nuclear reactors. More work is needed to analyze the impact of extreme events at the watershed scale and their possible impact for nuclear power plants operation. Figure 6 shows the outcome of modeling efforts on the performance of thermoelectric plants across the contiguous U.S. under future climate scenarios; 2035-2064 (21). A multi-model platform was used to simulate changes in water temperature to determine potential impacts to power plant operations due to elevated intake and discharge water temperatures. In summary, the most vulnerable were plants utilizing once-through cooling systems which are at particular risk of discharge water exceeding permitted temperature limits. Risk more than doubled between present and the 2060s. Plants at highest risk were located in the southern Midwest and Southeast. Analysis is needed that is specific to the commercial nuclear industry.

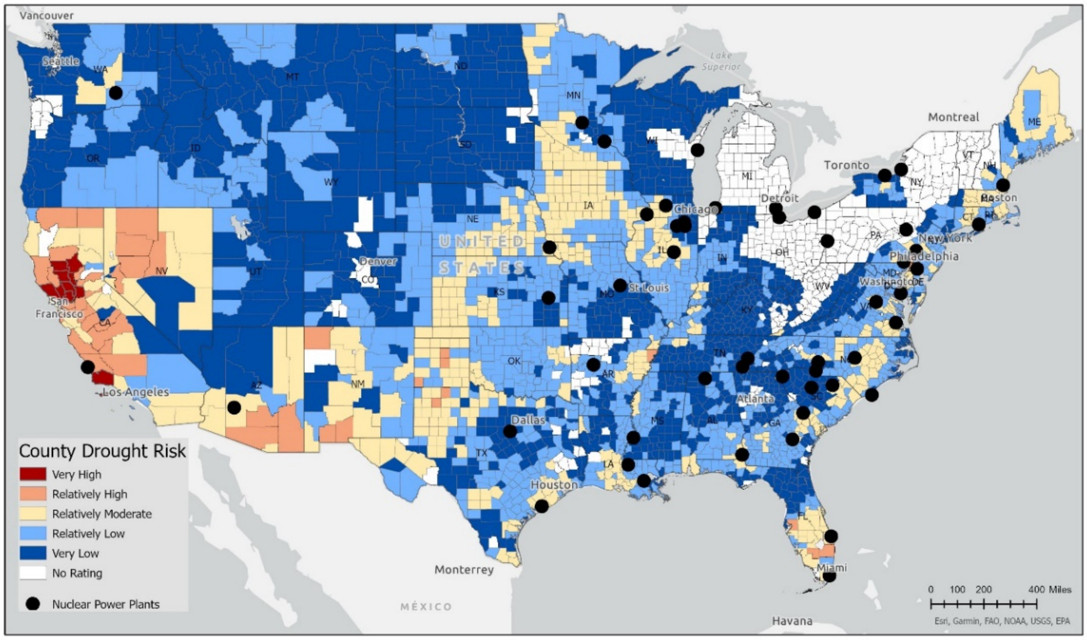


Figure 5. County-level drought risk index and operating nuclear power plant location.

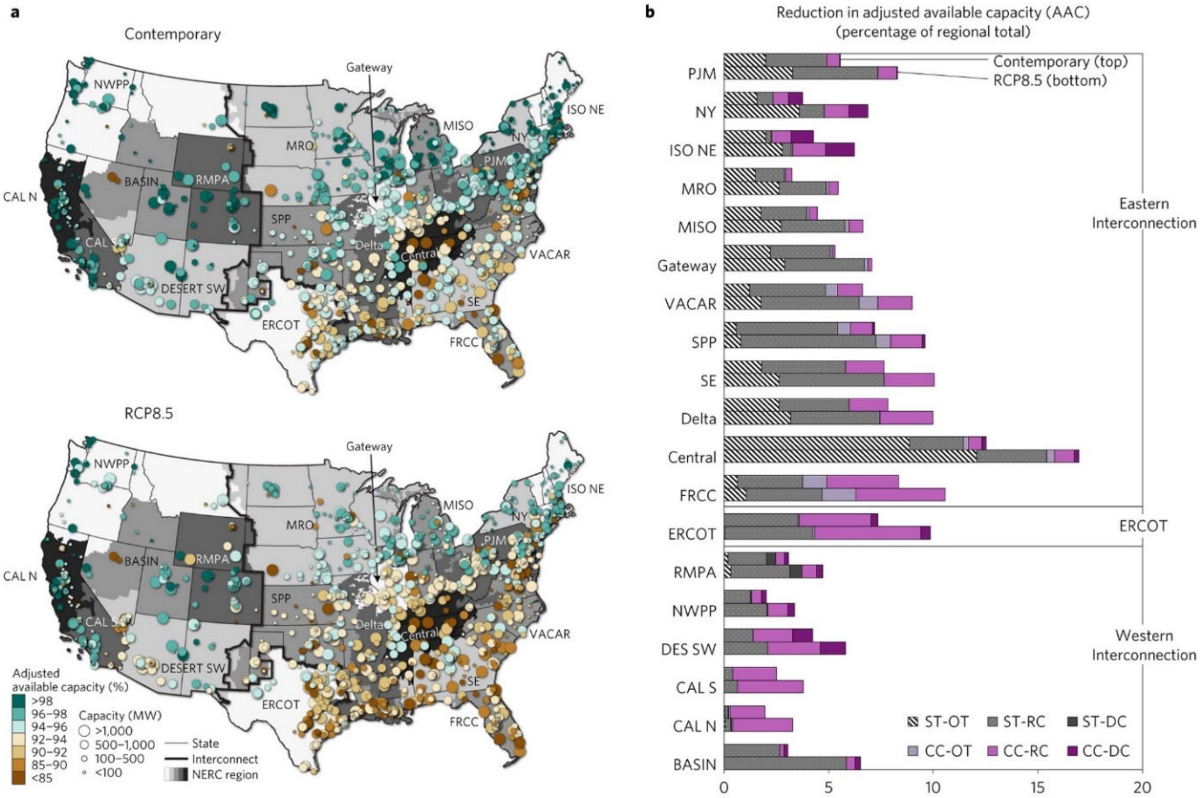
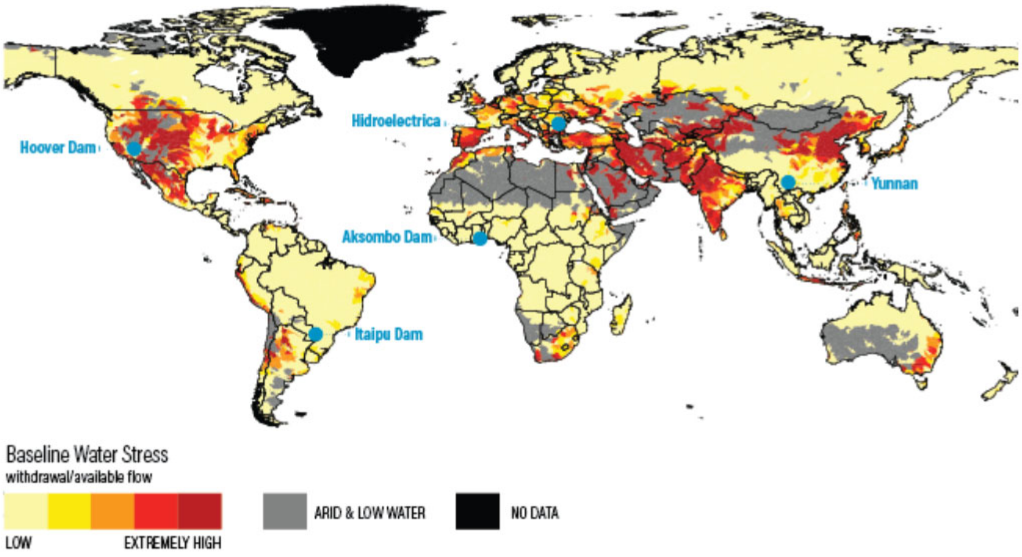


Figure 6. Adjusted Available Capacity of power plants under future climate scenarios (21).

Drawing from global resource, Aqueduct from the World Resources Institute (WRI) is a data platform comprised of tools that helps companies and 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 global water stress as projected from the Aqueduct platform. Nuclear power plants in the United States are subject to different climate-related risks, as observed described in numerous events and scenarios. Additional analysis is forthcoming.



Source: Aqueduct: Baseline Water Stress.
aqueduct.wri.org

WORLD RESOURCES INSTITUTE

Figure 7. Baseline Water Stress by Country (35).

4.2 Environmental Justice

The United States Environmental Protection Agency defines environmental justice (EJ) as the fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income, with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies. Including that everyone enjoys the same degree of protection from environmental and health hazards, and equal access to the decision-making process to have a healthy environment in which to live, learn, and work. However, many minority, Tribal, low-income, and disadvantaged communities are within close proximity to power plants and fuel cycle facilities, which raises concerns about potential health and environmental impacts, including issues related to social and economic equity.

In April 2022, the U.S. Nuclear Regulatory Commission completed its systematic assessment of the NRC approach to environmental justice (EJ). The assessment provided the following areas for improvement:1) recommends revising the NRC’s 2004 Environmental Justice Policy Statement by engaging with stakeholders to produce additional clarity and consistency and transparency of the existing policy; 2) update the 1995 Environmental Justice Strategy to account for all the changes in NRC programs, policies and activities; 3) enhance outreach activities related to EJ, particularly for EJ communities and Tribal nations, including establishment of staff positions for improved accessibility to guidance and procedures pertaining to EJ; 4) provide a formal mechanism for NRC to address EJ through creation of an outside advisory committee and through periodic meetings with communities and Tribal nations; 5) assess changes to current prohibition on intervenor funding, and; 6) assess enhancements in the Agreement State application process and activities.

While the primary goal of the LWRS program is aimed at ensuring the safe and efficient operation of existing LWR's and to enhance their long-term sustainability within the nuclear energy industry, it also considers the environmental and social implications. Fostering inclusive engagement with stakeholder communities near power plants and in understanding their needs and concern is necessary for 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.

The recently released Executive Order 14096, *Revitalizing our Nation's Commitment to Environmental Justice for all*, embeds environmental justice into federal agency work by strengthening engagement with communities to address legacy barriers and injustices, increase accountability and transparency in federal environmental justice policy, and includes publishing of the first-ever Environmental Justice Scorecard. The energy justice core tenets will need to be considered throughout the continued operation of the U.S. commercial nuclear fleet.

5. SUMMARY

This report has provided a status update on the challenges and opportunities facing the U.S. commercial nuclear energy industry as a brief summary since the 2010 report "Cooling Water Issues and Opportunities at the U.S. Nuclear Power Plants" (26). This report highlights need for further analysis to continue to support the success of the nuclear energy industry as it faces changes and challenges due to regulations and environmental issues. The combined effects of climate change and growing demands on water resources will work to intensify the effects of extreme events on nuclear power plant operations.

In the next phase of this project, we will develop a series of recommendation for action to inform the LWRS program. The recommendation will include needs for deep risk analysis along the timeline of the life of the plants, including potential policy changes that could impact the LWRS program. The next phase will include interviews with water technology providers and nuclear operators to evaluate existing and emerging performance risks and opportunities, potential technology solutions and investments to address those risks and opportunities.

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