CLIMATE READi

RESILIENCE AND ADAPTATION INITIATIVE

EPRI

TECHNICAL REPORT

CLIMATE VULNERABILITY CONSIDERATIONS FOR THE POWER SECTOR: NUCLEAR GENERATION ASSETS

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EXECUTIVE SUMMARY

EPRI's Climate REsilience and ADaptation initiative (READi) [1] is dedicated to developing a comprehensive and consistent approach to assessing physical climate risk to power industry assets and systems and identifying a framework to address those risks and enhance resilience of the systems. The objective of this effort is to develop a common approach to risk identification, adaptation, and planning for the impacts of climate change on energy grid assets and the integrated power system. The initiative includes three focus areas or workstreams: physical climate data and guidance, energy system and asset vulnerability assessment, and resilience/adaptation planning and prioritization. This report documents a literature review to characterize asset vulnerability to climate change for the nuclear power plant (NPP) asset class, documenting the current state of knowledge on the topic as well as identifying research gaps. This report serves as one volume in a series of related literature reviews that cover all aspects of the electric power sector. Other volumes include non-nuclear generation [2], transmission and distribution (T&D) [3], distributed energy resources and end use products [4], and cross-cutting topics (e.g., worker health and safety, environmental justice, and shifts in ecological patterns) [5].

Development of a common approach to assessing vulnerability includes the following components:

- Determining how to effectively apply climate trends and projections when selecting, specifying, designing, and installing new assets, as well as when refurbishing existing assets
- Establishing methods to understand the ability of existing assets to withstand a range of potential future climate conditions
- Identifying and assessing potential adaptation strategies' impact on climate risk
- Providing a consistent approach to energy system and asset vulnerability assessment to inform investment decision makers

In this literature review, we seek to review methods for assessing vulnerability, resilience, and adaptation and to consider their applicability to safe and reliable operation of NPPs, with a focus on climate risk. The effort is focused on sources addressing how current and changing climate can impact NPPs and what the climate-related impacts are anticipated to be. This report is intended to inform NPP decision makers about potential climate change risks and assessment strategies, but it is also intended to set up the next phase of this READi research, which involves the development of a framework for climate change vulnerability and adaptation assessment specific to NPPs.

The review of vulnerability and resilience frameworks in the literature revealed that there is a large set of frameworks that have been developed to address climate change vulnerability [6]. These frameworks focus on different applications and systems, but most have similar elements. Four elements were generally evident: 1) scoping and screening, 2) decision criteria and data, 3) risk modeling and assessment, and 4) adaptation assessment. However, most of these frameworks are still rather high level and could generally apply to any generating asset or facility.

The development of a framework to assess climate change risk and vulnerability at NPPs would guide an organized, thorough, and efficient approach to managing climate change risk. The framework elements identified in this report, along with some of the findings from NPP-specific climate risk studies, could be used to develop a framework specific to NPPs.

This framework should consider and complement existing risk management measures at NPPs. In conjunction with the framework, a set of suggested climate change adaptation measures would also benefit NPP managers in identifying ways to reduce risk.

It is important to distinguish between nuclear safety and operational resilience for NPPs. NPPs are specifically designed to safely withstand events far more severe than those considered for other parts of the critical infrastructure. This design philosophy results in substantial capacity to safely withstand extreme weather conditions. NPP designs incorporate multiple redundant safety features that can safely shut down or trip the plant. However, operational reliability refers to the ability of the plant to produce electricity when needed. Impacts on operations can affect the plant's ability to produce reliable power and its capacity factor (the percentage of the time it is running at full power and providing electricity to the grid). Although NPPs are designed with considerable safety margin against extreme weather-related events, these events have occasionally had a negative effect on operations and the ability to supply reliable electrical power to the grid. It is resilience to these climate impacts on operational reliability or generation output that is the focus of this review.

KEY TAKEAWAYS

NPPs are potentially susceptible to changes in climate-related variables such as air and water temperatures, precipitation and flooding, sea level rise and storm surge, drought, storms and high winds, and extreme events. Changes in trends for these variables may result in multiple and cascading risks. Impacts of higher air and water temperatures on NPP cooling systems and generation efficiency are most prominently discussed in the literature. However, additional acute and chronic impacts are likely, such as water scarcity due to drought, impeded site access due to flooding, and worker health and safety concerns due to more frequent hot weather days. NPP operators should be aware of potential impacts from climate change tipping points, which can cause abrupt shifts in climate [7]. Tipping points or "cliff edges" are thresholds beyond which there are irreversible changes or changes of higher magnitude than expected based on previous experience [7]. Examples of such changes are biological impacts of algae blooms due to changes in water temperature or chemistry, or fish or zebra mussel fatalities due to high water temperatures. NPPs should consider all potential ranges of climate extremes as they assess climate vulnerability at their facilities. The Texas electric power crisis that occurred in 2021 serves as an example of risk associated with extreme cold weather [8].

Key components of vulnerability and adaptation assessment include setting boundaries for the assessment and establishing decision criteria. Regardless of the specific approach taken, NPP owners/operators may find that the effort to evaluate climate change risk will expand resilience thinking in the organization.

SECTION 1: INTRODUCTION

1.1 EPRI Climate READi and Energy System and Asset Vulnerability Assessment

EPRI's READi is focused on developing a comprehensive and consistent approach to physical climate risk assessment and adaptation planning. The initiative includes three focus areas:

1. Physical climate data and guidance
2. Energy system and asset vulnerability assessment
3. Resilience/adaptation planning and prioritization

This report serves as a literature review on a topic within the second focus area: assessing the vulnerability of nuclear power plant (NPP) systems and assets. READi aims to develop a common approach to risk mitigation for the impacts of climate change on energy grid assets and the integrated power system. It includes establishing methods to understand the ability of existing assets, which have been in service for decades and were likely designed to different standards, to withstand future events. READi will develop a framework for determining how to effectively apply climate trends and projections when selecting, specifying, designing, and installing new assets, as well as when refurbishing existing assets. The initiative will identify and assess the impacts on risk of potential adaptation and mitigation strategies. To inform investment decision makers, EPRI will provide a consistent approach to energy system and asset vulnerability assessment.

1.2 Climate Change Risk and NPPs

Extreme weather is one of the main causes of wide-area electrical outages worldwide. In the U.S., 78% of major power interruptions are due to weather-related events; the annual impact of weather-related blackouts is $20 million to $55 million [9, 10]. Extreme weather events impact the reliability and operation of electrical components and the resilience of the entire power infrastructure [10]. The U.S. Department of Energy (DOE) has identified climate change as a risk to energy infrastructure but does not have an overarching strategy for addressing the risk. Presidential Policy Directive 21, issued in February 2013, describes federal priorities for addressing potential risks, including climate change [11].

Observed and projected climate change will continue to impact the frequency and intensity of extreme weather events as well as average temperatures and precipitation. Climate and weather stressors include changes in average and extreme air and water temperatures; sea level; freshwater availability, including lake, river, and reservoir levels; drought; flooding; wildfires; summer storms; and winter storms, among others [12, 13]. **Table 1** shows observed trends and anticipated future changes for select climate impact stressors in North America. Multiple stressors occurring together can result in increased risk [14]. Of note in **Table 1** is that cold spells have decreased in frequency and intensity in most places, and projections from global climate models suggest this will continue. This is due to the overall global trend of warming; however, variability in temperatures will persist, allowing for occasional extreme cold events that may threaten power system operations.

Table 1. *Observed trends and projected changes in climate impact drivers in North America (Source: EPRI [1])*

CLIMATIC IMPACT-DRIVER	OBSERVED TREND	FUTURE CHANGES
Extreme heat	Upward trend	High confidence of increase
Cold spell	Downward trend	High confidence of decrease
Snow and glaciers	Downward trend	High confidence of decrease
Heavy precipitation	Upward trend	High confidence of increase
Drought	No assessment given	Medium confidence of increase
Fire weather	Upward trend	High confidence of increase in Western NA, medium confidence of increase in Central and Eastern NA
Coastal and river flooding	Upward trend	High confidence of increase
Tropical cyclone, severe wind	No assessment given	Medium confidence of increase

NPPs are robust facilities designed to withstand events such as tornados, hurricanes, and floods of a far higher magnitude than most other infrastructure can endure. In fact, experience has shown that NPPs are arguably the most robust portion of the electrical grid, which includes T&D as well as other forms of generation. Nuclear plant designs incorporate multiple redundant safety features that can safely shut down or "trip" the plant.

However, it is important to distinguish between nuclear safety and operational resilience when looking at physical climate risk. As stated, the design philosophy for NPPs results in substantial capacity to safely withstand extreme weather conditions—by shutting down, if necessary. However, recent weather-related events have highlighted the important role that NPPs and other generation sources play by remaining online to supply power and provide grid stability during extreme weather events. Even though extreme weather events may not impact the safety of nuclear plants, they can present operational challenges to remaining online and supplying power.

Climate change impacts on both weather extremes and averages can challenge plant operations [15]. While climate change is less likely to affect plant safety than operations, hazard assessments should be reviewed periodically to reflect the latest climate projections, and potential effects of changes in hazards should be identified and addressed [16]. Siting and design for new NPPs should consider climate projections through the lifespan of the plants.

Climate change can be expected to introduce deep uncertainties in certain climate variables, that is, situations in which decision makers do not know or cannot agree upon the full set of risks and their probabilities [17]. Climate change may have impacts on air and water temperatures; patterns, frequency, and strength of winds; characteristics of precipitation; flow rates of rivers; and changes in sea levels [18]. NPPs should consider the full range of potential outcomes regarding changes to climate variables.

Weather-related disruptions to operations at NPPs continue to occur, particularly disruptions associated with elevated air and water temperatures and with drought. During the 2003 European heat wave, 17 nuclear reactors in France had to be shut down or reduce output due to water abstraction and discharge restrictions [19]. The DOE [7] identified the following examples of climate-related impacts on NPP operations. In July 2006, an NPP shut down due to high temperatures in the containment building and because intake water from Lake Michigan was too warm to be used for cooling; this resulted in reduced power output for five days. In August 2006, an NPP had to reduce production to less than 60% because the temperature of the Mississippi River was too high for the river to receive heated cooling water without impacting aquatic life. In 2007, 2010, and 2011, an NPP had to reduce power output because the temperature of the discharge river was too high for it to receive heated cooling water without ecological harm. In September 2010, an NPP had to reduce power because the intake water temperatures from rivers were too high for it to effectively use the water for cooling. In August 2012, an NPP shut down one reactor for two weeks because the intake cooling water temperature exceeded the technical specifications of the reactor. In 2021, during the Texas extreme cold electric power crisis, an NPP tripped offline due to a frozen sensing line.

There have also been NPP impacts due to severe storms and flooding. In June 2011, floodwaters from the Missouri River surrounded an NPP in Nebraska, forcing the plant to remain closed during the summer [7]. Shutdowns related to Hurricane Isabel occurred in 2003 due to electrical faults from saltwater deposits at two co-located NPPs and loss of power to intake pumps at another NPP [18].

EPRI [20] completed a review of operational impacts on U.S. NPPs of weather-related events over the past 10 years (2011–2020). Operational impacts were defined as lost production due to a derate or a plant trip. A summary of the operational impacts is presented in **Table 2**.

Table 2. *Weather-related operating events with loss of generation reported in the U.S. nuclear fleet (excluding T&D effects), 2011–2020. Source: EPRI [20].*

WEATHER EVENTS	AVERAGE RECOVERY (DAYS)	RANGE OF RECOVERY (DAYS)	NUMBER OF EVENTS OVER	TOTAL NUMBER OF PRODUCTION DAYS LOST (DAYS)
High Winds / Storms	2	0 to 18	25	52
Extreme Cold	3	0 to 10	11	19
Flooding	7	1 to 16	6	44
Biofouling	2	0 to 6	22	34
Lightning	2	0 to 6	9	19
Extreme Heat	2	0 to 13	12	22
		Total	**85**	**190**

1.3 Objective of this Literature Review

The objective of this literature review is to inform NPP decision makers about physical climate risks and possible vulnerability assessment strategies for NPPs. It is also intended to inform the next phase of READi, which includes the development of a framework for physical climate vulnerability and adaptation assessment specific to NPPs. Recent climate-related operational disruptions at NPPs across the globe highlight the need for physical climate change vulnerability assessment and adaptation. The DOE's Climate Adaptation and Resilience Plan notes priority actions, including assessing vulnerabilities and implementing resilience solutions; enhancing climate adaptation and mitigation co-benefits; institutionalizing climate adaptation and resilience; providing climate adaptation tools, technical support, and climate science information; and advancing deployment of emerging climate resilience technologies [21]. These priorities are all relevant for NPPs. There are many different methods for assessing vulnerability and resilience in energy systems and other infrastructure, as well as in communities. In this effort, we seek to review methods for assessing vulnerability, resilience, and adaptation and to consider their applicability to NPPs, with a focus on climate risk.

SECTION 2: APPROACH

2.1 Literature Review Focus

The literature review is focused on key sources addressing how current and changing climate can impact NPPs and what the climate-related impacts are anticipated to be. **Table 3** provides an overview of some potential climate-related impacts on NPP performance and operation.

Table 3. *Potential climate-related impacts on NPP performance and operation. Source: EPRI [1].*

Nuclear Power Plant Component		Primary Climate-Related Variables	Potential Climate-Related Impacts on Nuclear Power Plant Performance and Operation[1]
Plant Operational Impacts (Efficiency and availability)[2]	Cooling system	Air temperature Humidity Water temperature Precipitation	• Plant performance is a function of cold cooling water temperature. Higher water temperatures can reduce electric (turbine) cooling efficiency and reactor cooling efficiency (decay heat removal). • Increased water temperatures can increase bio-growth and lead to de-rating. • Discharge limits can be impacted by higher water temperatures. • Drought can reduce cooling water levels below inlet (performance penalty) and reduce cooling water flow rates (fouling and corrosion).[3]
	Steam turbines and condensers	Air temperature Humidity	• Increased air temperature can reduce generation capacity and increase heat rate.
	Cooling towers	Air temperature Humidity Wind speed Wind direction	• Higher air temperatures can result in higher cooling water temperature, reducing tower efficiency. • Cooling towers experience performance penalties with increased in wind speeds. High winds can cause physical damage to cooling towers.
Direct physical infrastructure impacts		Air temperature Precipitation Wind	• Extreme weather conditions and storms like hurricanes, derechos, extreme heat, and extreme cold events pose physical and operational threats to plant infrastructure and grid components. • Loss of grid power during storms may trigger plant shutdown. • Debris from severe storms can clog cooling water intake structures.
		Sea level rise (SLR)	• Rising sea levels can worsen nuisance flooding and storm surge with potential to impact infrastructure or operations at plants through flood risk and/or coastal erosion.[3, 4]

Notes for Table 2:

1. Many of the operational impacts identified for NPPs are similar to those for other thermoelectric plants. See EPRI [1], Table 1, for additional references.
2. For analysis of potential operational impacts at NPPs, see Linnerud et al. [22].
3. Brockway and Dunn [23].
4. For more detail on sea level rise projections, see USGCRP Chapter 2 [24] or Sweet et al. [25].

Table 3 identifies only a few key NPP components. For adequate resilience work to be carried out, all the major NPP process systems (e.g., reactor, steam system, cooling system, air intake [including instrument air for safety, kinetic energy, and electrical systems], electrical protection and controls, heavy water systems if applicable, and process safety management systems), as well as major equipment components (e.g., large pumps, valves, buildings/housings, open-air electrical power switchyards, and emergency and backup systems such as diesel generators), will need to be technically assessed from a resilience viewpoint.

2.2 Literature Review Methodology

The literature review began with review of sources identified as relevant through past work or previous interaction as well as topical web searches. These included reports, primarily from government entities, focused generally on climate resilience and in some cases more specifically on resilience in the energy sector. These reports came from the Asian Development Bank [19, 26, 27], the Government of Canada [28], the National Academies of Sciences, Engineering, and Medicine [29], Southern California Edison [30], and the U.S. DOE [7, 12, 31]. The literature review also included key EPRI publications.

A literature search was performed using Google Scholar to identify literature focused on climate change hazards and NPPs. Search terms included nuclear power + climate change and nuclear power + individual hazards, including temperature, flooding, sea level rise, coastal flooding, drought, thunderstorms, lightning, hurricane, and wildfire, as well as multiple hazards.

Upon review of the literature found in the search, additional targeted literature searches were performed to uncover additional information about specific topics or to confirm gaps in the literature. Efforts were made to include only quality and unbiased sources in this review. These were primarily sources from reputable government agencies and research organizations, along with peer-reviewed publications. When multiple sources were available on a search topic, newer sources generated within the last ten years were selected. With rapid expansion of climate change research and advances within recent years, it was assumed that newer literature would be more informative. The literature search was not intended to be exhaustive but more representative of the state of knowledge, with a focus on the state of practice.

The literature review was performed using the English language, which may have resulted in the exclusion of relevant sources in other languages. Some of the sources used focused on a specific country or region, such as Asia, Canada, Finland, France, or the United States; however, the intent was to uncover information that is relevant globally. A next phase of the asset vulnerability assessment will be engaging with additional NPP stakeholders as well as those from other asset classes to identify additional and common sources of information.

2.3 Synthesis and Analysis

Findings from the literature were synthesized and are discussed in Section 3, Literature Review Summary and Results. Definitions are included for key climate change risk terms to aid in clarity. Climate change risks to NPPs identified in the literature are presented, and climate change risks that may impact NPPs but are not addressed in the literature are mentioned. In Section 4, the applicability to NPPs of frameworks for assessing vulnerability and resilience and for adaptation decision making is discussed (these frameworks and approaches are discussed in more detail in a separate Climate READi report [6]). A discussion of apparent research needs is provided in Section 5.

SECTION 3: LITERATURE REVIEW SUMMARY AND RESULTS

3.1 Definitions

Terminology used in discussing climate change risk assessment and management is described in this section for clarity.

Adaptation refers to adjustments in ecological, social, or economic systems in response to actual or expected climatic stimuli and their effects or impacts. It includes changes to moderate potential damages or to benefit from opportunities [28].

Climate risk management is defined by Travis and Bates [32] as "a process for incorporating knowledge and information about climate-related events, trends, forecasts, and projections into decision making to increase or maintain benefits and reduce potential harm or losses. It is a multidisciplinary activity that calls for an integrated consideration of socioeconomic and environmental issues." To support successful action, climate information must have three characteristics: salience (relevance and timeliness), credibility (quality, accuracy, and reliability of data), and legitimacy (perception that information is unbiased and fair) [32].

Deep uncertainty is a situation in which decision makers do not know or cannot agree upon the full set of risks to a system or their associated probabilities [17].

Likelihood in terms of risk is the chance of an event or an incident happening. Likelihood in quantifying climate change uncertainty is the chance of a specific outcome occurring, where this might be estimated probabilistically [28].

Mitigation includes the steps taken to reduce future climate change, such as efforts to reduce emissions or enhance sinks of greenhouse gases [29].

No regrets adaptation approaches provide other positive contributions outside of those required for future climate conditions and generate net benefits independent of a certain level of climate change [28, 35]. A similar term, low-regrets adaptation, is also used. Low-regrets actions provide a positive return regardless of the future state of risk and typically have a high benefit-cost ratio [34].

Resilience is the ability to withstand and reduce the magnitude and/or duration of disruptive events. It includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from such events. While reliability refers to the ability of the system to consistently perform its intended design function without disruption, resilience is about the capability of a system, in this case an NPP, to minimize the disruption caused by an unplanned event. Reliability prioritizes consistent performance and the prevention of failures, while resilience emphasizes the ability to recover quickly and maintain functionality in the face of disruptions.

Risk considers the magnitude of potential consequences, including failures in prevention and mitigation, and their corresponding likelihood. Risk tolerance and protection levels are important to how risk information is used. For instance, probability-weighted expected outcomes may be appropriate for some applications, but in other applications, risk management of catastrophic failures may require planning for extreme events never before observed, even if their likelihood is small.

Vulnerability is a set of conditions determined by physical, social, economic, and environmental factors or processes that increase the exposure of an asset to the possibility of harm due to the impacts of hazards [28]. It is the degree to which a system is susceptible to adverse effects of climate change, including variability and extreme events [29]. The U.S. Department of Defense [21] describes three components that determine vulnerability: exposure, sensitivity, and adaptive capacity. Exposure is susceptibility to climate change based on location characteristics. Sensitivity is susceptibility to climate change based on characteristics of assets. Adaptive capacity is the existing ability to address potential climate impacts.

3.2 Climate Risks for NPPs

Because of strict safety standards and design margins, NPPs are already prepared for a much larger range of adverse climate conditions than other types of generating assets [20]. Safety assessments for NPPs include climatic design criteria and extreme weather events such as those related to maximum air temperature, minimum air temperature, maximum external humidity, wind speed and high wind speed, tornado return periods, cooling water temperatures, seawater level, low seawater level, rainfall, snowfall, and lightning. They also include hazards with potential effects on plant parts and site proximity hazards [35]. Physical climate impacts in the NPP sector are addressed through guidelines, safety standards, and regulation which account for risks across a very large range of potential climate conditions in design, technology, planning and plant management, and demand-side management [35]. For example, International Atomic Energy Agency Specific Safety Guide SSG-18 [36] provides guidance on evaluating risk from meteorological and hydrological phenomena, including consideration of uncertainty and climate change. Unger et al. [37] found that Swedish and Finnish NPPs are well prepared for climate change beyond the 2050s because of the high level of safety in the nuclear power sector, with NPPs designed to withstand extreme weather events. Nevertheless, it is important to be aware of and ready for future impacts of climate variables that may exceed historical values. From a safety perspective, nuclear plants are well protected from weather-related events. However, changes in climate may impact the operation, maintenance, and efficiency of NPPs as well as the health and safety of their employees.

The Intergovernmental Panel on Climate Change projects upward trends in North America for extreme heat, heavy precipitation, fire weather, and coastal and riverine flooding. It projects downward trends in cold spells and snow and glaciers. No assessment is given for drought or tropical cyclones. Mean precipitation is expected to increase in regions where it is already relatively high and decrease in regions where it is low. Seasonal shifts in precipitation are also expected, as is an increase in the frequency and intensity of heavy precipitation events [35]. Beyond these general trends, addressing vulnerabilities and impacts associated with climate-related hazards requires localized information on observed and projected trends [15]. Climate change has the potential to impact NPP component performance, system functionality, design margins, and plant operations [15]. Given the long operating period of an NPP, climate change impacts on safety and operations should be considered at the design and siting stages to limit the need for costly adaptation measures later [35]. Plant retrofits may be needed for existing plants to meet environmental and regulatory standards and to maintain efficiency [35].

At least three major climate change trends are relevant to the energy sector and NPPs:

- Increasing air and water temperatures
- Decreasing water availability versus need (water stress)
- Increasing intensity and frequency of extreme events, including extreme temperatures, severe storms, and drought

Key physical climate-related vulnerabilities for NPPs include availability and quality of cooling water, reliability of components, events that impact the transmission grid, and climate change impacts on the supply chain (i.e., the uranium mining sector) [35].

Cooling systems at NPPs remove heat from plant systems and components and condense the steam used to drive the turbine generator back into water. The service water system at a nuclear plant may also be called the cooling water or saltwater system. Often the system is broken down into safety (essential) and non-safety (non-essential) portions. Safety-related service water systems ensure that adequate heat is removed from the reactor and the fuel pool through heat exchangers during normal and accident conditions. The ultimate heat sink (UHS) is a safety system and includes the structures, components, and associated assured water supply and atmospheric condition(s) credited for functioning as a heat sink to absorb reactor residual heat and essential station heat loads after a normal reactor shutdown or a shutdown following an accident or transient. The UHS is typically a body of water (cooling pond, river, lake, or ocean), but it can also be a cooling tower. If the UHS temperature is too high to provide the required cooling credited in the plant's safety analysis, the plant's technical specifications will require a shutdown or downpower to maintain cooling water temperature to assure adequate cooling inventory is maintained.

The condenser circulating water system is a non-safety system that circulates cooling water through the main condenser to remove the heat rejected by the steam turbine. The heat picked up in the cooling water is rejected to the atmosphere via cooling towers or directly into a body of water such as a river, lake, or ocean. Note that not all NPPs have cooling towers, and other thermal generation plants may have the same kind of towers. Elevated air and water temperatures impact NPP thermal performance by reducing the efficiency of heat removal through the condenser. Heat transfer is reduced when there is less difference in temperature between the cooling water and the heated fluid being cooled. There may also be administrative discharge temperature limits based on environmental permits to limit the amount of heat discharged to regulated bodies of water. Potential surface water impacts to NPPs (among other power sector assets) that may occur or worsen due to changing climate conditions are covered in some detail by EPRI [38].

3.2.1 Air Temperature

Global mean surface air temperatures are projected to increase over the 21st century, with the greatest temperature increases over land and at high northern latitudes [35]. More frequent and intense extreme heat is projected, while extreme cold is projected to decrease in frequency [35]. Higher air temperatures can create higher cooling water/UHS temperatures or drought conditions. Higher water temperatures reduce the amount of heat that can be rejected to the heat sink and therefore require a reduction in power to meet permit requirements. Higher air temperatures can also create challenges for chillers, air conditioning, and heat exchangers. Higher air temperatures can also reduce the efficiency of steam turbines, resulting in lower generation output during times when demand for air conditioning is especially high. Cooling tower efficiency may also be impacted by high temperatures and humidity [1].

Higher air temperatures expected with climate change can have several different impacts on NPPs. While safety risks associated with high temperatures are low (the plant can always derate or trip offline), high temperatures may result in decreased generation efficiency and output for inland plants [27]. A 1 °C rise in ambient air temperature can reduce nuclear power output by about 0.5% due to reduced thermal efficiency. Loss may exceed 2% per degree during droughts and heat waves [19, 22]. (These losses vary by plant and design but are presented here for illustration.) Heat waves can cause premature component failure due to thermal stress or fatigue [37].

Higher temperatures can also result in employee safety issues associated with working in the heat [30]. Employee safety improvements may be needed due to more high-temperature days. These can include air conditioning upgrades and extreme heat protection equipment to support field work [30]. Vulnerabilities of worker health and safety to climate are covered in more detail in the cross-cutting topics volume of this literature review series [5].

Several adaptation measures may increase NPP resilience to a warming environment. To lessen the impacts of higher temperatures on cooling, NPPs may install additional cooling towers and modify cooling water inlets at coastal locations [27, 35]. Dry or hybrid cooling systems that require less water may also facilitate cooling in high temperatures [27]. Changing a cooling system from a once-through to a closed-cycle or hybrid system to limit water withdrawal and associated thermal releases is another potential adaptation option, though it can be challenging from a space and cost perspective [35]. NPPs may also work to develop more efficient pumps and heat exchangers [27].

In general, risks associated with very low air temperatures are not expected to increase with climate change. As cold typically improves the ability to remove heat from the plant, these temperatures alone typically do not present operational concerns. However, NPPs can be at risk from very low temperatures, particularly if they are accompanied by strong winds [14] or are of long duration. Depending on flow conditions in the bodies of water used for cooling, extreme cold and wind can contribute to the development of 1) frazil ice that can impact flow and net positive suction head in the cooling water intake structures or 2) ice on air intakes on cooling towers. Another cold weather hazard is rapid snow accumulation, which could cause a loss of offsite power, a possible blockage of ventilation air intakes, and isolation of the plant [14]. Given the regional variation of climate hazards, NPPs should consider the full range of potential changes in cold weather risks as they assess their climate change vulnerability. The Texas electric power crisis that occurred in 2021 serves as an example of risk associated with extreme cold weather [8]. The crisis could have been lessened by better planning or hardening for such a long-duration extreme weather event [8].

3.2.2 Water Temperature

Higher air temperatures can lead to warmer water temperatures in oceans, rivers, and other water bodies. Average annual sea temperatures have increased by about 0.2°C on average since 1980 and are expected to continue to rise by 0.25 to 0.65°C by the end of the century [35]. Warmer water temperatures can impact the efficiency of cooling systems at NPPs due to less efficient heat transfer. An increase of 1°C in water temperature of the cooling source (ocean, lake, or river) is expected to decrease the NPP power output by 0.44% and the thermal efficiency by 0.15% [37]. (These losses vary by plant and design but are presented here for illustration.)

Discharge into warmer water also factors into operational limits due to ecological risks [1]. Warmer seas can lead to power reduction and can alter the heat sink environment, potentially increasing incidents of marine organisms clogging cooling water intakes [35]. This increased bio-growth can lead to derating [1]. For example, organisms like jellyfish and algae thrive in warmer waters, which may result in more frequent and severe blooms and enhanced cooling water intake clogging events [35, 38].

As cooling water temperature increases, higher water extraction rates are required to keep the efficiency of the condenser at a maximum. This can present an issue in areas where water restrictions and quotas are in place, particularly for plants without recirculating cooling, which require much more water than those with recirculating cooling [39].

In the last decade, the U.S. nuclear fleet reported 12 operational experience events pertaining to extreme heat, seven related to the UHS, and five related to condenser circulating water; all required reduced output to manage temperature limits. Many of these were short-duration derates as the water temperatures typically dropped with cooler ambient temperatures overnight, allowing plant operations to return to normal power [22]. In 2022, the French energy supplier EDF temporarily reduced output at its nuclear power stations on the Rhone and Garonne rivers as heat waves increased river temperatures.

Systems cooled by the ocean, lakes, or rivers may need to be adapted to warmer temperatures. Measures include placing water intakes deeper and using improved screening systems or chemical agents to reduce organism growth [39]. In 2011, the European Commission estimated that cooling towers could cost $67 million to $130 million each, and modifying inlets at coastal plants to use deeper, cooler water could cost up to $133 million. These costs are most likely significantly, if not prohibitively, more today and could ultimately lead to a decision to retire an NPP early. New reactors can be constructed with dry or hybrid cooling systems with lower water requirements, but operational costs for these cooling systems are higher [21].

Climate change creates the potential for increasing water temperatures that will limit plant operation to satisfy environmental regulations. Adaptation measures may involve analysis and policy changes for NPPs and regulators. NPPs will need to factor climate change into their risk assessment for potential UHS limits to maintain compliance with environmental regulations. Likewise, regulators may need to evaluate how climate change will impact regulations and variance requests. Lubega and Stillwell [44] present a methodology for creating policies for thermal variances, with consideration of characteristics of individual power plants, topology and characteristics of the grid, and location of power plants within the river basin [44]. Cook et al. [45] developed a method to predict whether power plants are at risk of violating thermal pollution limits. It includes a regression model of average monthly intake temperatures integrated into a thermodynamic model of energy flows within each power plant to determine the change in cooling water temperature at each plant and the relationship of water temperature to other plants on the river system. It is used with climate models to estimate monthly effluent temperatures [45].

3.2.3 Precipitation/Flooding

Heavier precipitation events may occur more frequently in some areas of the country, creating increasing flood risk for NPPs [29]. Climate change may impact local intense precipitation, probable maximum precipitation (PMP), and probable maximum flood (PMF) values, with variations by region. For instance, a study by Gangrade et al. [46] projected significant increases in both PMP and PMF in the southeastern U.S. Changes in flood magnitudes and frequencies are also discussed in the Nuclear Regulatory Commission’s “Design-Basis Flood Estimation for Site Characterization at Nuclear Plants in the United States of America” [47]. In addition to climate change, PMF is impacted by PMP variability, land use and land cover change, antecedent moisture conditions, and reservoir storage [46]. Changes in winter precipitation may involve precipitation falling as rain instead of snow and reduce snowpack [48]. Floods can degrade cooling systems by increasing levels of mud and debris in the intake water [43]. Extreme flooding can also cause water intrusion into plant components [22] and cause accessibility issues. While the safety-related portions of NPPs are protected from current extreme flooding levels, it is not clear that all of the non-safety-related and operations portions maintain this high level of protection, or that all portions will be protected from future flood levels.

3.2.4 Sea Level Rise and Storm Surge

Sea level rise has the potential to exacerbate nuisance flooding in coastal areas and to create higher storm surges during coastal flood events. Changes in the shape of the shoreline may also create threats from erosion [1, 18, 41]. Analysis of tide gage records finds that the magnitude of extreme sea level events has increased in all regions studied since 1970 [35]. Development along the coastline may exacerbate vulnerability [18], and coastal features significantly affect exposure [35]. Sea level rise is expected to range from 26 to 81 cm by 2100, with local values varying from global averages, mostly due to the rising or sinking of coastal land [35].

Coastal vulnerability analysis is recommended for NPPs that may be subject to sea level rise coupled with extreme events such as hurricanes or tsunamis. The U.S. Army Corps of Engineers has developed guidance for incorporation of sea level change into project planning and design [47]. Other adaptation measures could include hardening investments and incorporation of increased storm events and associated tidal surge into design criteria [27]. Sea level rise adaptation measures can also include protecting pumps and sealing buildings [37]. For NPP components that are sensitive to sea level rise and coastal erosion, Wilby et al. [48] suggest modular designs that can be adjusted as conditions change.

3.2.5 Drought

The proportion of global land surface in extreme drought is projected to increase significantly by 2100 [18]. Seasonal changes in precipitation, such as reduced snowpack and drier summers, may also impact NPP operations [18]. In the western U.S., earlier snowmelt and runoff due to higher temperatures has reduced the amount of water in reservoirs available for warmer months [11]. Sixty-one percent of U.S. nuclear plants are in areas expected to face medium-high to extremely high water stress by 2030 [49]. By the 2030s, climate-induced water stress, including increased water temperatures and limited freshwater supplies, may hurt thermoelectric power production in the South, Southwest, West, and West North Central regions of the U.S. [49]. There are also energy-land-water interactions that require energy companies to compete with farmers and rangers for water rights in some parts of the U.S. In permitting new development, land use planners need to consider interactions between these water needs [29]. Drought can result in insufficient cooling water availability and quality, particularly for inland plants [27]. It can reduce cooling water levels below the inlet and can reduce cooling water flow rates, resulting in fouling and corrosion [1].

Depending on siting, those planning new NPPs should consider the availability of and growing demand for water resources [35, 49]. Around the world, there are NPPs operating or being built in water-scarce environments or very hot climates [33]. Dry cooling technology is an option that uses less water than traditional cooling technology but is costlier and less efficient [49]. Desalination can be considered to meet freshwater needs when availability is an issue [35]. Policies that both protect water resources and support energy resources will likely become more relevant in the future [43].

3.2.6 Storms

Operating experience reporting indicates that high winds from storms have been a large contributor to operational impacts at U.S. nuclear plants in the last decade [20]. Storms, tornadoes, and hurricanes tend to impact less robust T&D infrastructure, which is essential for nuclear generation in terms of not only supply of electrical output to the grid, but supply of offsite power from the grid to the plant. (When not generating electricity, NPPs require electricity from the grid to run the equipment needed to remove decay heat from the reactor core and spent fuel pool.) The offsite power system of an NPP is the preferred source of electrical power to all the station auxiliaries. Loss of the offsite power source results in a plant upset condition (usually a reactor trip) and the start of the backup power sources. With correct plant response, there would be no risk to the public; however, a large amount of equipment must function to mitigate such an event. In this case, the NPP remains available during the weather event but has no T&D infrastructure to deliver electricity, and restoring its offsite power becomes a priority for the grid.

In general, climate change is expected to affect the intensity and frequency of storm events [7]. While thunderstorms are typically too small in scale to be resolved by climate models, environmental conditions that favor thunderstorms have increased for parts of the U.S. east of the Rocky Mountains [35]. Severe storms such as hurricanes (typhoons in the western Pacific) impact NPPs and interdependent infrastructure due to the associated wind, flooding, and/or lightning. These events may damage key facilities, components, and ancillary buildings and can pose operational threats [1, 37]. NPPs are sometimes preemptively shut down due to an impending hurricane [40]. Winds can cause salt storms that can coat key facilities, especially electric switchyards, which can cause short circuits and discharges [37]. Storms can also induce flooding and move debris into water intake canals [40]. Storms or high winds combined with low water levels (droughts) can also create waves (seiche) that can create a low water level in the intake bay. Cooling towers can experience performance penalties or physical damage with high or increased wind speeds [1].

While climate change has a less clear relationship to lightning strikes than to other weather and climate events, U.S. NPPs are susceptible to lightning strikes, as shown in **Table 2**. A study similarly found limited impacts on French NPPs [50]. However, increased lightning strikes may increase operational disturbances [37]. Lightning strikes on switchyards, substations, or power lines may cause loss of internal or external power and may damage or disrupt key electronic devices [37, 40]. They could also result in fires at or near the plant. Existing preventative measures at plants include separating key buildings by a certain distance and making less important structures taller to protect key shorter structures.

3.2.7 Wildfire

In general, changes to future wildfire risk are uncertain in climate models, with regional variations [35]. Wildfire frequency and intensity are projected to increase in California [46]. Wildfires create debris and soot, which can clog air intakes and filters [37, 51]. Forest fires can impede transportation to the NPP site and can create challenging working conditions due to smoke [37]. Smoke from wildfires may enter ventilation air intakes [14]. Improved filters, screens, and stronger construction may be needed, along with an action plan for when the intake is clogged [39].

Wildfires can also cause indirect impacts to NPPs. The increase in wildfire activity associated with climate change is likely to increase maintenance costs and decrease transmission line capacity [46]. Low visibility due to smoke can obstruct accident management actions. Spot fires, breaches in firebreaks, and a short fire arrival time can shorten the grace period for accident management. Flames can also damage cables for electricity and telecommunications [51]. Okano and Yamano [51] developed a methodology to estimate plant damage frequency due to forest fire. The key parameters in their study include fireline intensity, reaction intensity, flame length, rate of fire spread, and forest fire arrival time.

3.2.8 Multiple and Other Impacts

Combinations of climate change factors can lead to other significant changes that are relevant to NPPs. Ocean acidification is occurring, and by 2100, ocean acidity is expected to change by -0.13 to -0.42 pH units. Ocean acidification will be exacerbated by the reduction in salinity associated with ice melt and excess precipitation. In the medium to long term, the increased corrosiveness of intake water could affect seawater-cooled reactors [35]. Changes in climate also create the potential for more frequent dust and sandstorms in dry areas and increased transport of sea salt due to increased storms [35]. Climate change can also impact the uranium mining sector, with flooding affecting mining activities and water scarcity impacting mining processes [35].

Many regions will experience more than one climate change effect [11]. The combination of increased temperatures, altered precipitation and runoff patterns, and more intense fire seasons may result in changes in risk at NPPs from cascading events like high runoff and debris flow events [30]. There is a need to consider the compound vulnerabilities and aggregate impacts resulting from multiple changing climate hazards [7]. Climate change is also expected to affect other infrastructure systems upon which NPPs rely. Impacts could include disruptions to supply chains, transportation networks, telecommunications, and the electric power grid [7]. A broadening of the assets considered in the vulnerability analysis may be needed to include supply chain and other infrastructure sectors on which the energy system is reliant [46]. NPP managers may need to consider participating in planning and advocacy for interdependent infrastructure systems.

Additionally, there is a human component that is important for resilience in power infrastructure. System operators need to monitor and cope with evolving system conditions. Factors that drive the level of resilience include goal-directed solution seeking, avoidance, critical understanding, role dependence, source reliance, and resource access [10]. Operator training and preparation can improve system resilience. Short-term resilience measures like monitoring, assessment, and communications before, during, and after a weather event can influence outcomes. Long-term measures including operational procedures and hardening measures are also drivers of resilience [10].

3.3 Framework for Climate Assessment

Evaluating and managing the risk of climate change consists of a sequence of assessments. It begins with assessing the hazard, evaluating potential changes in physical climate conditions (for example, potential changes in extreme precipitation, heat waves, or hurricanes). This is followed by evaluating exposure and vulnerability, and evaluating and implementing adaptation options.

Exposure assessment evaluates what assets, systems, or components could be exposed to the potential changes in climate, while vulnerability assessment evaluates potential consequences of exposure and options for responding or adapting to manage the vulnerability. The set of assessments may be applied at different scales (for example, plant component, system, plant, or grid level), with each scale having its own objectives, data requirements, analytical needs, and approaches for considering uncertainty.

Risk is determined by the likelihood and consequence of outcomes. Both likelihood and consequence are determined by a combination of hazard, exposure, and vulnerability conditions and uncertainties. Metrics need to be developed to assess physical climate risk that are fit for purpose. These metrics may be based on applicable requirements and consider risk management objectives, along with the strengths, limitations, and uncertainties of available data.

Finally, physical climate risk represents only one type of risk that companies actively manage. Physical climate risk assessment should, to the extent possible, be integrated into the company's overall enterprise risk management strategy and considered alongside other uncertainties and risks relevant to planning and operations.

Of value to the energy industry is the process in the Vulnerability Assessment and Resilience Plan (VARP) guidance [52], which was issued by the DOE in 2021 to support evaluation of its own assets and operations. The guidance was designed to be used along with the DOE Sustainability Dashboard [53] as a tracking tool. It is part of the DOE 2021 Climate Adaptation and Resilience Plan , which was prepared in August 2021 for the White House National Climate Task Force and Federal Chief Sustainability Officer [54].

This guidance provides a vulnerability screening tool (Excel spreadsheet template) for each site to evaluate climate hazards, their likelihood, and potential impacts on assets. The output of the screening tool is a risk screening matrix that allows visualizing vulnerabilities by characterizing the level of impact (low, medium, or high) of each defined climate hazard on each asset or system. An example risk screening matrix developed by the DOE is provided in **Figure 1**.

		Climate Hazards				
		Higher Average Sea Level	Increased Coastal Flooding	Increased Frequency/ Intensity of Precipitation Events	Increase Ice Storms Frequency	Increased Annual Average Temperature
Critical Asset and Infrastructure Systems	IT and Telecommunication Systems	Medium	Medium	Low	Medium	Medium
	Site Workforce	Medium	Medium	Low	Medium	Medium
	Site Specific Asset: High Performance Computers	High	High	Medium	Medium	High
	Site Specific Asset: Laboratory Research Equipment	High	Medium	Medium	High	High
	Site Specific Asset: Nuclear Waste Handling Facility	High	High	Medium	High	Medium
	Off-Site Specific Asset: Power Plant	High	High	Medium	Low	Medium

Figure 1. *Example DOE risk screening matrix*

Results from the risk screening matrix can be used to prioritize actions for implementing adaptations and ultimately mitigating the risks presented by climate change.

3.3.1 Climate Vulnerability Assessment for NPPs

NPPs are uniquely positioned to address challenges related to the potential physical impacts of climate change because they already maintain capabilities and organizational structure for environmental surveillance, asset management, adaptation to seasonal changes and extreme weather conditions, and rapid remediation in response to extreme events. These include programs such as seasonal readiness, equipment reliability, single point of vulnerability, asset management, sharing of operating experience, margin management, environmental monitoring, and post-Fukushima modifications including portable equipment (in the U.S., these are collectively referred to as "diverse and flexible coping strategies," or FLEX). Any methodology developed should leverage these existing capabilities to the extent practical, which will simplify use by plants and optimize resources (funding and personnel). The overall objective is to minimize the risk of generation disruption induced by potential future physical climate impacts while maintaining plant safety and competitive operating and asset management costs.

The potential physical impacts of climate change on NPPs involve component performance, system functionality, operational challenges, and operating and design margins. A systematic review of these impacts, as well as ongoing monitoring and trending, are essential to ensure that the impacts are understood and that actions are planned to maintain resilience.

Completing a physical climate risk assessment for an NPP involves a sequence of individual assessments (**Figure 2**) that have their own data and modeling needs. The process begins with an assessment of the climate-related hazard(s) that may affect the plant, continues with an exposure assessment that evaluates the exposure of different components of the plant to these hazards, and culminates in a vulnerability assessment that considers the interactions of the exposed assets and the climate-related hazards to understand the potential impact on plant operation.

Climate Hazard Assessment

Identify relevant climate hazards and characterize potential physical changes

Exposure Assessment

Identify components that are exposed to physical climate hazards

Vulnerability Assessment

Assess the impact of the exposure on component performance and plant operation

Figure 2. *Steps in a physical climate risk assessment*

EPRI has recently issued climate vulnerability assessment guidance [15] on the developing weather-related hazards; how these hazards are affected by climate change; what plant systems, structures, or components (SSCs) are exposed to these hazards; how to assess the vulnerabilities or margins in SSCs; and how to present the risk in a way that decision makers can use to allocate resources and plant modifications to sustain or increase resilience. Many organizations around the world are looking to develop tools and methods to assess vulnerability. There is ample opportunity to share best practices as these develop through pilot studies.

SECTION 4: APPLICATION OF RESILIENCE APPROACHES TO NPPS

General approaches towards assessing and addressing physical climate risk have been summarized in a literature review by EPRI [6]. That report reviewed literature describing general approaches to vulnerability and resilience assessment, as well as identifying resources to apply the approaches. It also covered some sources focused specifically on nuclear power applications, and these are reviewed here.

In determining an approach to assessing NPP vulnerability and resilience to climate change, it is important to set the boundary for the system. Some vulnerability assessments focus just on assets or a subset of assets. Others focus on both assets and operations [12]. An analysis can consider the entire NPP or a subset of components. The boundary can be set at the NPP boundary or include external components impacted by climate change, such as interdependent infrastructure systems (T&D, water, transportation network) and supply chain. Decision criteria can vary depending on the boundary and purpose of the analysis. In addition to resilience and reliability, criteria may include financial or economic elements, impacts to interdependent systems, impacts to customers, and environmental concerns.

McKinley et al. [55] pointed out characteristics of nuclear radioactive waste disposal management that could be used to inform climate change management. As NPP owner/operators are likely already familiar with these approaches, they could be particularly useful for managing climate change risk to NPPs. Unger et al. [37] noted that dealing with climate change at NPPs is an economic issue that involves weighing the consequences of disruption in service, power reduction, or lost revenue versus the cost of adaptation measures, with consideration of the uncertainty in climate projections.

A study by Sahlin et al. [56] evaluated two ways of combining and communicating climate projections with NPP reliability assessment of a passive containment cooling system. There are challenges in embedding climate data into a risk assessment while communicating uncertainty to avoid over- and under confidence in the risk quantification. The first method is an integrated probabilistic safety assessment conditioned on climate projections. It uses probability distributions to quantify both epistemic uncertainty associated with design variables and aleatory uncertainty associated with climate variability. This approach involves Monte Carlo simulation and is useful when the knowledge available is strong enough to quantify uncertainty by probabilities. The second approach is a risk classification based on assessment of critical temperatures. This approach classifies the system with regard to risk-relevant temperature intervals to be assessed independently of climate projections. It allows different climate models to be easily embedded into the assessment. Results are communicated as intervals of projected temperatures and either a safe or a non-safe state for each interval. Regardless of the approach used, there is a need for transparency in incorporating climate change data into the risk assessment [56].

A study by Kim et al. presents a risk analysis method for NPPs that combines flood hazard curves with fragility curves using hydrologic and hydraulics models and probabilistic flood analysis of NPPs [57]. A study by Wang et al. uses a combined model to analyze and simulate drainage capacity in a coastal NPP under combined extreme rainfall and wave overtopping. The authors note important factors, including characteristics of wave overtopping, seawall, revetments, and the pipe system [58].

Greene [59] defines a resilient NPP as one whose performance attributes and functionalities enable and enhance grid resilience. He notes two essential attributes of resilient NPPs: they enable the grid to absorb and adapt to a broad spectrum of anomalies and upsets, and they enhance the grid's ability to quickly recover from upsets and to restore service in a manner consistent with the load prioritization hierarchy [59]. Six functional requirements of resilient NPPs are noted: 1) robust load-following, 2) immunity to damage from external events, 3) ability to avoid plant shutdown in response to grid anomalies, 4) ability to operate indefinitely in island mode (without connection to external power), 5) unlimited independent safe shutdown cooling capability (without offsite power or offsite resupply of diesel fuel), and 6) ability to start with no offsite power supply from the grid [61]. Many plants do not currently possess these capabilities, but they could be considered for new plants and possible future upgrades.

Robust design features to optimize performance and resilience in future NPPs are described by Greene [59]. These include a DC-DC or variable-frequency transformer (VFT) interface with the grid; robust seismic isolation and below-grade siting; high-capacity load switching and heat rejection; multi-module NPP architecture; small reactor size; adaptive turbine-generator systems; passive shutdown cooling; inherent reactor system energy storage capacity; optimized reactor core physics design; robust nuclear fuels; GMDc/EMPd hardened electronics; and cyber secure computer and process control systems [59].

SECTION 5: GAPS IN THE LITERATURE AND RESEARCH NEEDS

In its 2013 report, the DOE notes that "there are no commonly accepted methodologies or sets of indicators to compare and prioritize risk and adaptation needs or the effectiveness of adaptation measures across the energy sector." In its Energy Sector-Specific Plan for infrastructure protection [62], the Department of Homeland Security suggests a set of general R&D needs including enhancing system design for resilience, improving preparedness and mitigation measures, improving system response and recovery, and analyzing and managing interdependencies.

A DOE [12] review of vulnerability assessments found several needs and gaps. Downscaled climate projections can be difficult to find or inadequate, making it difficult to accurately assess local-level vulnerabilities. Assessments based solely on historic data may underestimate future risks. Furthermore, these projections and assessments are needed on a local or regional basis to reflect the climate and potential changes at an NPP location. Physical risks are easier to evaluate than operational risks. Regulatory processes can negatively impact the implementation of resilience solutions, with regulated companies needing the approval of their regulators before investing in those solutions. The impact of climate change on other sectors may be important for companies/NPPs to consider. Collaboration between energy companies and other stakeholders can help facilitate awareness and action [12].

Allen-Dumas et al. [61] noted gaps in the quantification of component sensitivity functions. They note that most vulnerability quantifications are empirical and single-event driven. Environmental impacts on certain components are understudied. More attention is given to impacts associated with higher temperatures, low water availability, and wind or flooding from storms. Less attention is given to wildfire risk and cold weather extremes. The former hazards are expected to have more significant effects on NPPs, but the latter may still be considered, depending on location and regulator [36]. There is a lack of comprehensive assessments of the consequences of multiple climate events for specific and multiple grid components [61]. Multiple-hazard phenomena have been less studied than single-hazard phenomena because of inherent complexity and limited data availability [62]. Combinations of multiple hazards may be less probable than single hazards, but it is important for an NPP to maintain fundamental safety during combinations of hazards [16].

The Organisation for Economic Co-operation and Development (OECD) [35] suggests a set of R&D needs to help address climate change risks for NPPs. These include economic assessment methodologies for quantifying costs of adaptation or inaction; technologies to reduce water dependence; forecasting methods; and safety assessment methods to address future climate events [35]. Research and development could also produce advanced nuclear energy systems that could be resilient against climate change, including generation IV systems with higher efficiencies; small, modular reactors with lower cooling requirements; and submerged or floating grid reactors [35].

Research into NPP impacts from climate change lacks robust and reliable tools and often involves oversimplified models or strong assumptions. Some issues noted with available models include the need to consider interdependent infrastructure systems, complex networks of dependencies, and low-probability, high-impact events. Interdisciplinary expertise is needed for improved models [63]. Further research into climate change risks to both specific NPP components and NPP systems as a whole is needed. This should include catastrophic risk and tipping points evaluation to identify low-probability, high-consequence scenarios for NPPs. In addition to risks associated with physical NPP features, operational or managerial processes should be reviewed to ensure that NPPs are regularly reevaluating climate change risk and preparing for potential new emergencies.

SECTION 6: CONCLUSIONS

Climate change is expected to bring changes in natural hazard risks to NPPs. Impacted hazards may include air and water temperature, precipitation and flooding, sea level rise and storm surge, drought, storms, and wildfires. Combinations of these changing hazards may create additional risk. NPP cooling systems are susceptible to changes in air and water temperature and water availability. Risk varies with geographic location since climate change will impact different regions in different ways. Climate change risks associated with geographic characteristics should be evaluated when siting new NPPs. Other infrastructure systems upon which NPPs rely, including offsite power and transportation and supply chain networks, may face climate change risk that will impact NPPs. In addition, indirect impacts may occur related to worker health and safety, environmental justice considerations, and changes to ecological patterns. These topics are not reviewed thoroughly here but are addressed in more detail in a related EPRI literature review [5]. As air temperatures are projected to increase in many parts of the world, examples of cross-cutting topics relevant to NPPs include additional heat stress concerns for outdoor workers and increased risk of cooling water intake blockages from enhanced biological growth in warmer source waters. Assessment of vulnerability and resilience should consider the whole system, including the electricity grid and the environment [35].

NPPs typically have high availability, even during extreme weather events that force the shutdown of other energy generation assets [59]. However, once shut down, they become priority loads for service restoration and require high energy loads to restart [59]. Climate change resilience analysis is needed to address the resilience of NPP components and also of the NPP itself as a component of a regional electricity infrastructure system.

While adaptation and resilience improvements may be needed to address these challenges, there are barriers to improving climate resilience [6]. These barriers include:

1. Limited understanding of vulnerabilities based on climate change probabilities and significance: There may be a lack of information or understanding about the potential impacts of climate change, making it difficult to assess vulnerabilities and prioritize adaptation strategies. In general, NPPs have a good understanding of extreme events and plant risk, but they are less knowledgeable about how these events will change in the future.
2. Lack of robust economic assessments for adaptation options: It can be challenging to assess the costs and benefits of different adaptation options across different asset classes, making it difficult to determine which options are most effective and efficient.
3. Lack of a comprehensive suite of adaptation technologies: There may be a limited range of adaptation technologies available or a lack of understanding about which technologies are most appropriate for specific contexts.
4. Lack of a policy framework or adequate market signals for resilience investments: The absence of supportive policies and market signals can create a barrier to private sector investment in climate resilience, limiting the resources available for adaptation efforts.
5. Varying perceptions of risk that influence key stakeholders: Different stakeholders may have varying perceptions of climate risks, which can influence their support for adaptation efforts and their willingness to invest in resilience.

To overcome these barriers, established approaches and frameworks can be used. For example, risk assessment and management frameworks can help to identify and prioritize adaptation strategies, while economic analysis can help to assess the costs and benefits of different approaches. Additionally, policy frameworks and market incentives can help to encourage investment in resilience, while stakeholder engagement and communication can help to address varying perceptions of risk and build support for adaptation efforts.

The review of vulnerability and resilience frameworks in the literature revealed that there is a large set of frameworks that have been developed to address climate change vulnerability [6]. These frameworks focus on different applications and systems, but most have similar elements. Four elements were generally evident: 1) scoping and screening, 2) decision criteria and data, 3) risk modeling and assessment, and 4) adaptation assessment.

The development of a framework to assess climate change risk and vulnerability at NPPs would guide an organized, thorough, and efficient approach to identify and manage climate change risk. Additional thought should be given to how to communicate specific climate hazard risk to the system operator and planners. The framework elements identified in this report, along with some of the findings from NPP-specific climate risk studies, could be used to develop a framework specific to NPPs. This framework should consider and complement existing risk management measures at NPPs. In conjunction with the framework, a set of suggested climate change adaptation measures would also benefit NPP managers in identifying ways to reduce risk. Lastly, climate risk assessments not only can be used to understand the relationship of the regional climate risk to an existing asset but also should guide the siting of new builds.

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